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ORIGINAL RESEARCH PAPER

The concept of a disruption index: application to the overall impact of the July 9, 1998 Faial earthquake (Azores islands)

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Abstract The earthquake that struck Faial, Pico and São Jorge in 1998 has allowed the collection of an unprecedented quantity of good-quality data on damage to construction, costs of repair and other variables. A general overview of the impact of the earthquake is presented, and its effects on the population, housing, monumental structures and economy 10 years after its occurrence are analysed and briefly reported in this paper. We present the overall results obtained from multiple sources of information, primarily from an integrated database containing all the data gathered. The results that describe the inflicted damage, costs of repair and other variables are presented both statistically and geographically. This information was valuable for the construction of an overall earthquake impact based on the systemic analysis of the urban area through the identification of criteria and definition of descriptors leading to a disruption index. The paper is developed as follows. First, we introduce the descriptions of the earthquake effects on the broader set of existing urban systems. In the second part we present the main methodological aspects leading to the disruption index, as well as analysing and discussing the data to provide a clearer picture of how the analysed systems and their disruption affect an urban area.

Keywords Azores · Disruption index · Overall seismic impact · Systemic analysis

1 Introduction

The Faial-Pico (Azores) July 9, 1998 earthquake (M_W6.2) caused the deaths of eight people, injured a further hundred, rendered 2,500 homeless, destroyed a large number of houses and interrupted socio-economic activities for several months. The annual August "Week of the

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Sea" event in Horta city (the capital of Faial Island) was cancelled following the earthquake, with a clear impact on the life of the island. Ten years after the occurrence of the earthquake, many things in Faial and Pico Island are different. Specifically, there has been an increase of the earthquake safety procedures for building construction, and the development of new urban areas has accounted for consequences of earthquakes and other natural hazards. The earthquake prompted a new set of infrastructural and service initiatives. However, several other initially intended improvements were not implemented, although they were recommended by various bodies engaged in the reconstruction process, causing negative impacts. This paper shows the direct impact and also some indicators of the indirect impact of this event, including its social, economic and cultural impacts.

The data reported in this paper come from several chapters of the book "Sismo 1998—Açores. Uma década depois", (edited by Oliveira et al. 2008), which was written by a wide range of professionals, academicians and guest scientists who were directly involved with the earthquake.

We have used this important information to calibrate earthquake impact models that are being developed to measure the disruption induced by this type of event in urban systems viewed as a whole. One of these metrics is the disruption index (DI), which considers all direct and indirect impacts and their propagation effects within each system and from system to system in a "cascade" fashion. The full theoretical development of these concepts can be found in Mota de Sá (2011).

2 The earthquake of July 9, 1998

Faial is located in the Central Group of the Azores Archipelago, where the North American, Eurasian and African plates meet along the Azores-Gibraltar Fault Zone; consequently, significant seismic and volcanic activity has a periodically devastating effect. The seismic crisis that began on July 9, 1998 lasted approximately 4 months, and nearly 10,600 aftershocks were recorded, many of which were felt by the population. The larger event, 05h19, $M_W = 6.2$, caused a great deal of the damage inflicted on the islands of Faial and Pico, though it presented reduced intensity and frequency of damage on San Jorge island. This earthquake was preceded by a premonitory quake at 05h01 with its epicentre near the main shock, which awoke some people in parishes nearer to the epicentre and in the city of Horta. The maximum intensity registered was a value of VIII in NE Faial, as shown in Fig. 1.

The location of the epicentre has not been determined beyond the identification of a large area, and difficulty in assigning a source mechanism still exists nowadays as a result of an "inaccurate velocity-model and/or location procedures for this particular region of the Earth and lack of good instrumental coverage at the time of the event. However, the main shock relocation based on a one-dimensional velocity model suggested an epicentre about 8 km North East, offshore of Faial Island" (Zonno et al. 2010).

3 Overview of the existing data on the building stock and population

Unfortunately, the Government/State did not prepare a systematic detailed survey to collect information about the state of damage to the entire building stock after the event. The immediate post-event actions were dedicated exclusively to providing decisions about habitability, and those decisions were provided only for housing which the owners formally requested to the authorities. However, during the first 2 months, a simplified survey ("Auto de Vistoria",

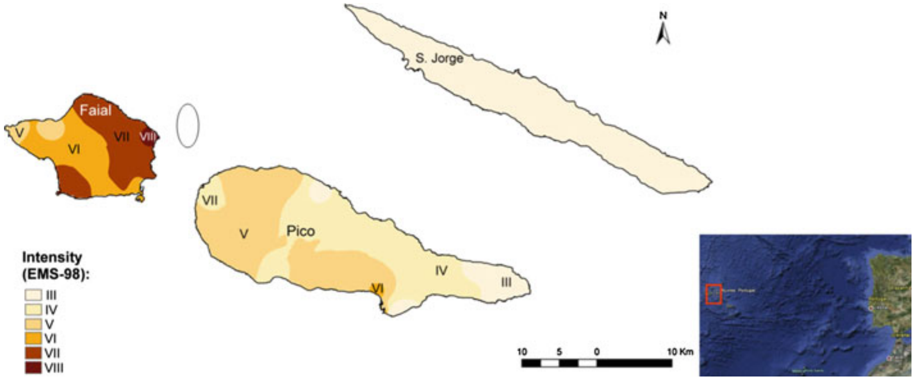

Fig. 1 Seismic intensity map (EMS-98) obtained from damage classification using EMS-98 (Ferreira 2008). *Ellipse*: possible epicentral location

Neves et al. 2008) without an accurate process of damage evaluation was conducted for all buildings in Faial, the western part of Pico and a few houses in San Jorge. This simplified survey was the basis for the creation of an "Integrated Database", which provides the basis for most of the results presented in this work. This survey was also the main tool used by the authorities to define the plan for homeless accommodation and to establish the initial policy for reconstruction.

3.1 Population and housing census

Figure 2 shows the evolution of the population, housing and buildings over the past 15 years in the territory of the Faial and Pico islands, according to the population and housing Census (INE 2002). The population surveyed in 2001 on the islands of Faial and Pico amounted to 29,239, representing a decrease of 2.9% between 1991 and 2001. This decrease may be related to the earthquake, a connection that is reflected in the mobility of the population of these islands, observed through the increase in emigration or internal migration, both within the Azorean region and to other parts of the country. The last few years (after 2001), however, already showed a slight growth of the population because of the process of reconstruction and rebuilding after the earthquake. Indeed, the urgent need for reconstruction created a huge number of jobs for the local population and immigrant workers, contributing to the economic growth of the islands. The housing stock of Faial and Pico had already increased by 2.5% between 1991 and 2001 as a consequence of the reconstruction process, which did not reach its peak until the years between 2001 and 2005 (Fig. 2b).

3.2 Databases on the building stock produced after the Faial earthquake

3.2.1 "Auto de Vistoria" and database I

A survey called "Auto de Vistoria" was prepared by the Regional Laboratory of Civil Engineering of Ponta Delgada (San Miguel Island) and implemented by the Centre for the Promotion of Reconstruction (CPR). It constitutes the first survey on the housing stock of the islands of Faial, Pico and San Jorge after the 1998 earthquake. This survey was created to obtain information about households and housing damage, as well as the habitability and reparability of the buildings affected by the earthquake.

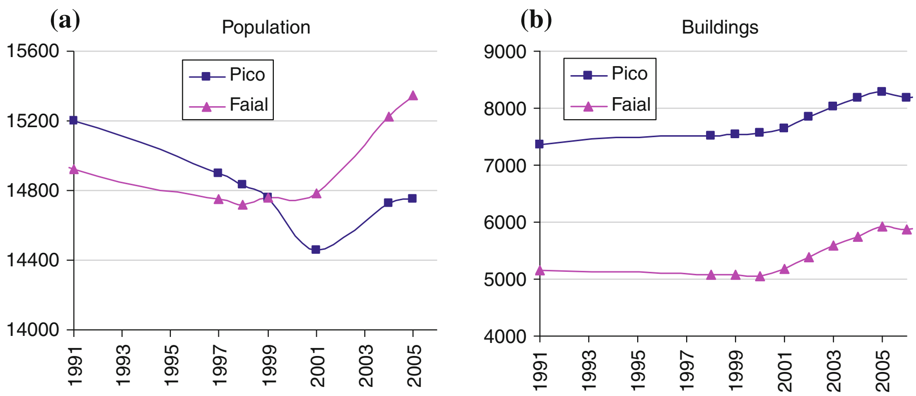

Fig. 2 Distribution of (**a**) the population and (**b**) the buildings between 1991 and 2007. *Source* National Statistics Institute—Portugal (INE 2002)

Fig. 3 *Left*: percentage of contracts and direct awarding on the islands of Faial and Pico (universe 2,543); *Centre*: types of intervention by direct awarding on the islands of Faial and Pico (universe 2,543); *Right*: types of intervention by contracts on the islands of Faial and Pico (universe 2,564)

The "Auto de Vistoria" survey has generated a database (Database I) that, in addition to other information (Neves et al. 2008), contains fields to quantify the percentage of damaged to exterior and interior walls, flooring and roofing. However, the survey did not explain the type of damage that occurred to each of the elements, and, consequently, it is difficult to translate this classification into a degree of damage.

This survey also contains a field named "personal sensitivity to global damage", although this parameter was difficult to understand in relation to our analysis of each individual building because the overall sensitivity value given (0–100) often did not coincide with the percentages of walls that could be recovered or were beyond repair. This information was supposedly obtained in the same inquiry. However, this parameter "sensitivity to global damage" allowed the reconstruction of the housing stock to be split into 3 large groups (Fig. 3):

(a) new construction (represents a major intervention in buildings that suffered severe damage, usually with total collapse of walls and gables);
(b) rehabilitation (interventions with budgets of more than 15,000 EUR, requiring a type of intervention characterised by seismic reinforcements in structural elements) and
(c) repair (repairs were defined by an amount of funding lower than 15,000 EUR).

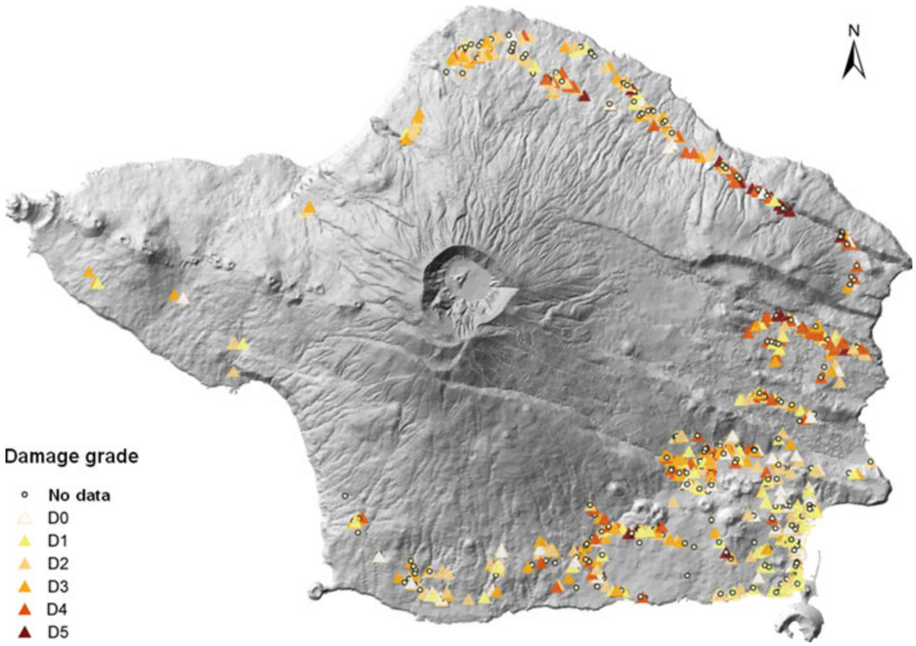

Fig. 4 Damage distribution on Faial Island

The victim or "injured party" (a person whose house was destroyed or damaged by the earthquake) opted for the type of repair work, which could be accomplished by a direct financial award or by contract.

3.2.2 Integrated database

In 2006 and 2007, it was possible to access Database I and its building photos, which permitted the characterisation, in great detail, of the type and degree of the most serious damage that occurred to each building. A new classification of damage was then proposed (Neves et al. 2011) for the exterior walls (gables and facades), the corners of the structure, the interior walls and the floors and roofs. This information and consequent characterisation led to a new Integrated Database. The analysis of the Integrated Database, as well as the various surveys conducted on the island of Faial over the years, have allowed some conclusions, which are presented here, to be drawn regarding what happened to the housing stock, people and economy as a result of the earthquake. Figure 4 shows the geographic distribution of damage (from D0—no damage to D5—total collapse) (Ferreira 2008) on Faial island, clearly indicating the zones with higher concentrations of housing and population, as well as the damage inflicted.

4 Overview of the impact on patrimony, education and health facilities, infrastructures, economy and social systems

A general overview of the earthquake impact was obtained during the various contacts and activities pursued to understand the immediate aftermath of the earthquake and the reconstruction phase and from the descriptions contained in the book "Sismo 1998" (edited by Oliveira et al. 2008). This information is discussed in this section and provides an opportunity to recognise the key elements used to assemble the disruption index described in Section 6.

4.1 Religious patrimony

The Catholic religion plays an important role in the Azores that is not only ceremonial, but is also important to social life. Large and small churches are present everywhere, one per parish. On Faial Island, of the existing 13 churches, 4 collapsed or partially collapsed and 4 others suffered serious damage; as a whole, 9 were unfit for the celebration of worship, directly or indirectly affecting approximately 8,700 inhabitants, or 58% of the population of the island.

Of the 18 churches on Pico Island, none collapsed, but 3 suffered severe damage, and a small church, despite its relatively recent construction, was in a precarious situation because of its modest construction; this church was considered for reconstruction. On this island, approximately 6,000 inhabitants (40% of the population) were affected.

Overall, 11 large churches and 3 smaller ones were affected, with direct impact on approximately 14,700 citizens, which corresponds to approximately the entire population of either island.

4.2 Education

From the analysis and observation of the damage distribution in 21 Primary and Secondary school buildings of Faial, it was realized that the extent and type of damage depended strongly on the structure of the building. Little damage was detected in all schools, apart from the collapse of the exterior wall of a nursery school (Salão), and two schools that were considered potentially dangerous were demolished (Espalhafatos and Ribeira Funda). Because the summer school holidays take place in July, pupils did not have their education interrupted, and schools were used as temporary shelters and emergency response centres—Consul Dabney's School was used as an infirmary, for example.

Between 1998 and 2000, several investments (totalling 4 million EUR) in educational facilities were made, which included remodelling work, repairs and expansions, exterior arrangements and the construction of a new school. In our opinion, the new school offers a building configuration and construction that could be very vulnerable (Fig. 5) to future earthquakes.

4.3 Health facilities

Fortunately, the main (and only) hospital in the island was not affected (excluding block C, which suffered minor damage) and remained operational after the earthquake. The hospital emergency plan was immediately launched after the event, and 128 patients were observed, of whom 104 were classified as personal accidents, the majority with minor injuries and psychotic trauma. Eighteen patients were kept in the hospital for observation. The 8 deceased were also observed in the hospital.

4.4 Infrastructure and lifelines

The overall performance of the infrastructure and lifelines was reasonably good when compared with the performance of the masonry structures that were severely damaged in this earthquake.

Fig. 5 Vista Alegre primary and nursery school

Fig. 6 Damage to pavement and retaining wall

The earthquake caused the total disconnection of the electrical system and a 1-day stoppage of the diesel groups. The following 3 days required intense work for the restoration of minimum conditions for the supply of energy to the population.

The damaged areas of Cedros, Salão and Ribeirinha (NE Faial) remained without water for 3–4 months, and its water distribution was provided by fire-fighters. Most areas are essentially rural, and the destruction of water catchments affected local livestock.

4.5 Roads and logistics

Some roads and bridges near the affected area (NE Faial, in the intensity VIII zone) were blocked with fallen stones and soil, forcing the creation of alternative paths to reach victims due to the occurrence of numerous landslides. Longitudinal cracks in the pavement were a common type of earthquake damage found on NE Faial roads, along with the collapse of retaining walls (Fig. 6), and the collapse of two bridges was also reported.

The earthquake, the terrain morphology (low stable areas with very large slopes) and the geological structure (volcanic material) existing on the island of Faial favoured the occurrence of a large number of landslides, the majority of which were in the following locations: (i) in the coastal cliffs, (ii) in fault scarps, (iii) on the inner walls of the central caldera; (iv) on the NW side of the central volcano, and (v) in clinker areas (small sliding). A large

Table 1 Direct costs of the 1998 earthquake (as of 2006)

Housing stock Faial and Pico	220 M€ (160 M€ + 60 M€) without VAT
Infrastructure related to the stock	30 M€
Churches (rehabilitation and new churches)	37 M€ (new churches = 10 M€)
City Hall (infrastructures)	10 M€
Schools	4 M€

mud and rock flow composed of volcanic ashes ran down a hilled riverbed for more than 3 km, destroying all debris in the flow path.

4.6 Economic impact

The economic activities of Faial and Pico were affected in general, whether indirectly by the effects of the earthquake on housing, public facilities and infrastructure, or directly, with livestock, trade and tourism being the hardest hit sectors.

The estimates of the total direct cost of the earthquake (housing stock only) evolved over time, especially in the early months. The first estimate of 60 million EUR, made on the day of the earthquake, rose to 125 million EUR by August 1998, 1 month later. Estimates made in December 1999, based on the information introduced in the database (including a detailed architectural survey for reconstruction design and budget) and the cost per m^2 of new construction, confirmed the same value.

The final cost of reconstruction for a sample of 1,041 cases was analysed in great detail (considering housing). Although the data show a wide dispersion, it appears that the costs are approximately 50% higher than the estimates made at the time of the architectural surveys, although there is a notable subset with values that are only 17% higher.

The total direct cost of the earthquake (as of 2006) for all urban facilities may be estimated to be approximately 300 million EUR (Table 1) distributed over a number of categories (data adjusted from SPRHI, S.A. 2006).

Many other economic areas were affected by the earthquake, and it is difficult to estimate its impact. The impact on trade and tourism is of particular interest. Specifically, the Week of the Sea, an event that brings thousands of visitors, was cancelled in August 1998, as mentioned in the Introduction. The summer months (July to September) bring a significant increase in sales across all trades as a direct consequence of domestic and foreign tourists, emigrants and the return of students for the summer holidays. This consideration increases the apparent negative impact of the earthquake, in this season in particular, along with all the negative impacts (mainly of a social nature) of these kinds of disasters. Employment has suffered great changes. Immediately after the event, a significant decrease was observed, but this decrease was reversed when the process of reconstruction was launched 2 years later. A new social/economic movement was brought to the affected islands.

4.7 Social impact

Damage and fear of aftershocks (or another large earthquake) has displaced over 2,500 people from their homes. After the event, the main concern of the civil protection and fire brigade was to provide temporary housing and basic services to the victims. One of the most common shelters was tents, provided by the local and national authorities and installed next to the damaged houses.

The population was collected in multi-use buildings, named “Casa do Povo” (Houses of the People), because these were recently constructed buildings with seismic design, a doctor’s office, equipped kitchens and sanitary facilities that are fundamental for the reduction of the traumatic state in which the population found themselves. Because they were close to their homes, the stress on the population was reduced. Multi-use structures were preferable to schools because they were able to present better living conditions.

The regional government almost immediately provided prefabricated homes. Four months after the earthquake, the tents were no longer used, and the entire population was resettled in prefabricated homes; this relocation was made necessary by the late-summer weather.

5 The post-earthquake process: decisions and actions

The earthquake and the subsequent reconstruction process allowed an immediate response to the substantial damage that occurred on both islands; it also allowed the rehabilitation and improvement of the habitability of buildings that were not damaged by the earthquake.

The earthquake brought innovation and modernisation; for example, the sanitation that was long awaited by the people of Faial was a project the implementation of which was directly influenced by the earthquake. In this project, at the high-supply network level, the project envisaged the introduction of 11 km of new pipelines and the construction of 13 water reservoirs with a reserve capacity of approximately 4, 700 m^3. The rainwater collector network provided for the introduction of 25 km of new pipelines, the installation of 13 sea discharges and three water line discharges, as well as the placement of a new collector network. The rainwater collector network required the laying of 30.9 km of new pipelines, the installation of seven lift stations, a wastewater treatment plant and a submarine emissary (Castro 2008).

Because of the lack of pre-defined response strategies or policies for the reconstruction process, a few errors were committed. Among them, there were several cases in which reconstruction has led to an “unfolding” of houses. For example, economic independent victims (parents, sons, brothers, etc.), living in the same house, led to the construction of multiple properties. Thus, it appears that the number of affected buildings given by certain entities is higher than that presented here. Another problem arose from the lack of attention paid to vernacular construction because such buildings were allowed to deteriorate over the years as a result of lack of financial support.

6 Disruption index: the concept of disruption of livelihood systems

In Sect. 4, we see that there are main activities or basic necessities that are always supported after an earthquake because they are of extraordinary importance to human life. The damage to community infrastructure and the collapse of the relevant institutions has impacted all spheres of community life, and this disruption will continue. Basic services, such as clean water supply, power supply and access to markets can be disrupted; consequently, economic activities also suffer. In general, the major impacts on the affected communities are as follows:

- Disruption of electricity, which impacts security and the provision of health care and other essential services. For example, during a power outage, the water supplied to a home may no longer be safe to drink without treatment—pumps used to pressurise water mains may fail, and parts of the water treatment plant necessary for water purification may not operate properly;

- Disruption of water service for drinking/domestic use and for irrigation purposes, hampering agriculture;
- Health problems caused by the lack of access to health service providers or the lack of sewage collection and treatment;
- Impediments to access to and from home to jobs, markets and other communities because of rubble accumulation (debris) or structural collapses;
- Disruption of school or temporary relocation of students out of the earthquake zone because of safety concerns regarding school buildings and housing;
- Disruption of communication within and between communities, impacting security;
- Increased prices of commodities and transportation;
- Disruption of communal functions (social, economic and religious) and breakdown in routines, resulting in high-risk behaviour.

The earthquake "simulators" that have been developed show the direct physical damage to victims, buildings, essential facilities and transportation systems, but they do not include the estimation of indirect losses or propagated effects (functional interdependencies). As many disruptions in the systems and networks increase, the "urban performance" decreases, and the dynamic system is replaced by a static system. When they are aware of the likely impacts of future hazards, communities can make informed decisions about what they need to do, and they can plan appropriate strategies to reduce their losses and protect their livelihood systems, including infrastructure.

The topic of systemic approaches that include social and economic dimensions has been developed in recent years by a few researchers and schools. This field of study includes the work of Granger et al. (1999), Menoni et al. (2002), Bruneau et al. (2003) among others. Other authors have also approached vulnerability and risk analysis from a systemic perspective with different results, and developing different frameworks.

In this paper, we propose a DI to quantify the state of disorder induced by the disruption of urban structure and its functions.

Our efforts to understand this complex system have relied not only on the observation and assessment of the impact of the July 9, 1998 Faial earthquake (described in previous section) but also on the observations collected in several earthquake field missions in different regions of the world, including the Azores (Oliveira et al. 1992), China (Costa et al. 2010), Italy (Proença and Ferreira 2009), Haiti (Oliveira and Ferreira 2010) and Spain (Ferreira 2011), which have guided and delimited the first steps of this research. The information and experience gained from earthquake missions were based on contact and discussion with the affected population, as well as various entities and agencies, in order to identify the most important effects on a society, its economy and other sectors. Existing reports and studies relating to other earthquakes were also analysed.

From the above considerations, it is clear that a functional urban taxonomy forms the basis for the evaluation of earthquake impact. Therefore, functions were defined and classified using seven *criteria*, or dimensions of human needs, the most fundamental of which are the following: Environment, Housing, Food, Safety and Security, Health, Education and Employment.

In Table 2, we present the descriptors associated with each criterion.

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 2 Criteria and consequences impacting individual criteria

Criteria	Descriptors
Environment	Assesses the environmental impacts due to soil contamination, water, aquifer or spills. 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
Food	Evaluates if the food is accessible to the majority of the population and identifies alternatives to their supply (coping strategies)
Safety & security	Evaluates the level of security (people, property, businesses, etc.) in a particular area
Health	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

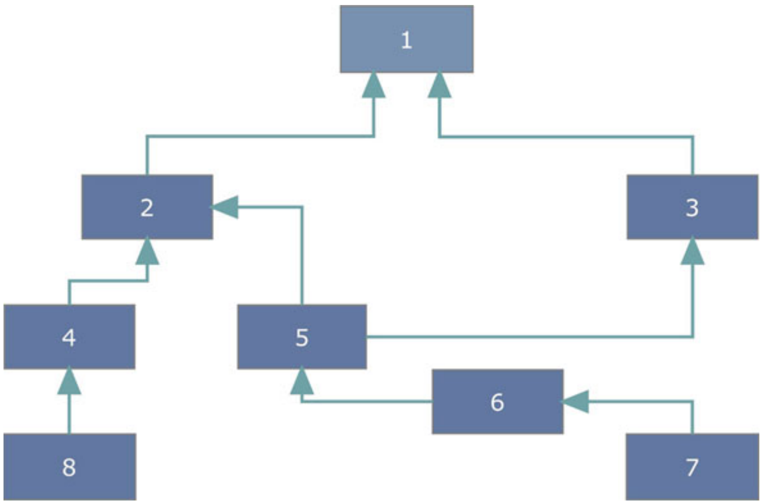

Fig. 7 A typical graph representation (where dependencies are represented by arrows)

We could also use a digraph structure, in which the logical representation might look something like Fig. 7.

Figure 7 illustrates a complex network in which nodes play the roles of sources and sinks, interacting in an interdependent fashion. For nodes connected by oriented arrows, a conditional probability (the probability that the end node is affected if the initial node is affected) is assigned. Applying tools from graph theory, it is possible to characterise the global features of the system, including dependencies and incidences. Further information is given in Mota de Sá (2011), in which a detailed account on these theoretical developments is presented.

In our study of an urban area, each player (urban function or physical asset) has its unique dependence and interaction behaviour. The graph in Fig. 8 shows the entire system dealt with in this paper with 7 criteria (referred above in Table 2) and 19 interrelated components,

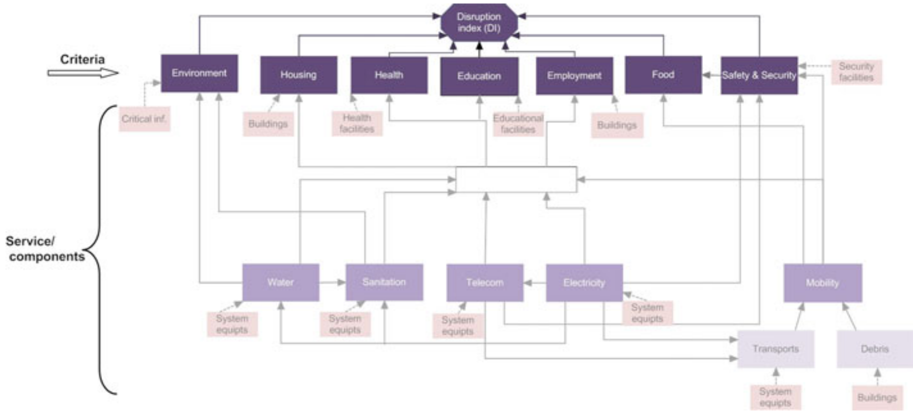

Fig. 8 Graph representation of vital urban functions and their dependencies and incidences

services and equipment (all rose and lavender boxes that connect to each criterion). The empty box in the middle of the arrows represents the path connecting the lower level boxes with the upper level boxes (criteria) or dependencies. The discontinuous rose arrows represent the equipment associated with each service or component.

As an example, to explain the meaning of the graph in Fig. 8, which corresponds to the final product of this complex analysis, we see that the dependencies of Environment are the following: Water, Sanitation and Critical Infrastructure. Water depends on the operation of the Water system equipment and of the Electricity supply, which depends in turn on the Electric system equipment. Similar reasoning can be seen in the Sanitation supply.

Mathematically, the graph shown in Fig. 9 can be represented by its *adjacency matrix* A, in which the element a_{ij} equals 1 if row i *depends* on column j and is zero otherwise (see Fig. 8).

Figure 10 shows the availability of water (potable water). The purpose of this diagram is to provide an adequate quantity of domestic water for drinking and for the proper operation of plumbing fixtures used for personal health and hygiene. This system is associated with Water equipment (including pumps, valves and piping, water treatment, tanks and reservoirs) and the electric supply system with the corresponding electrical equipment.

Figure 11(left) presents the same matrix as A, but without the variables that support the 15 functions and services. Those variables correspond to the physical impact on the engineering structures affected by the earthquake. In the present study, these variables correspond to the directly observed damage described in Sect. 4. In other cases, these variables could be obtained from earthquake "simulators". The same analysis can be performed with the *incidence matrix* B, where b_{ij} equals 1 when row i *impacts* column j and is zero otherwise (Fig. 11, right). Note that the binary "0, 1", used in this approach can be upgraded in future work to intermediate values representing the strength (or weight) of the relationships defined above.

The modelling of interactions within and between systems and their propagation effects (Fig. 11, right, dysfunctions) can be based on Dijkstra's algorithm (1959), which is a graph search algorithm that solves the shortest-path problem or any other algorithm that serves the same purpose (Path finder). In this case, a slight modification was performed on the relaxation condition of the algorithm in order to allow it to calculate the path of maximum probability rather than the path of least cost. With this procedure, it is possible to find nodes (systems,

	DI	Environment	Food	Housing	Security	Heathcare	Education	Employment	Mobility	Electricity	Telecom	Transportation	Debris	Water	Sanitation	Critical infrast.	Electric power equipments	Transport infrastructure	Water equipments	Sanitation equipments	Telecom equipments	Educational facilities	Healthcare facilities	Security facilities	Residential buildings	Non-habitational buildings	Buildings in general
1 DI		1	1	1	1	1	1	1																			
2 Environment														1	1	1											
3 Food					1				1																		
4 Housing									1	1	1			1	1										1		
5 Security									1	1	1													1			
6 Heathcare									1	1	1			1	1								1				
7 Education									1	1	1			1	1							1					
8 Employment									1	1	1			1	1											1	
9 Mobility												1	1														
10 Electricity																	1										
11 Telecoms										1											1						
12 Transportation										1	1							1									
13 Debris																											1
14 Water										1									1								
15 Sanitation										1				1						1							
16 Critical infrast.																											

Fig. 9 Adjacency matrix A. In columns, we represent the graph elements. The square matrix contains the 7 criteria; the other *black rows* contain the services and components, and the *lavender columns* show the equipment that supports all other functions

sub-systems and infrastructures) with greater potential to induce a generalised dysfunction in the global system, allowing for their prioritisation from a functional perspective.

Summing all values in a column provides the level of dependence of each element, leading to a hierarchy of propagation. For example, if the sum is 0 (we subtract the case of self-dependency), the service depends only on itself, as is the case for Electricity, Debris and Critical infrastructures. If the sum equals 1, that service is considered next in the hierarchy of propagation, as is the case for Transportation and Sanitation. For a large sum, the dependence of the system is complex, and it depends on many other factors.

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 and identify their reference levels (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). Our aim is to clarify the way in which a chain of failures overwhelms systems and develop a set of principles that are able to define and measure impact.

Table 3 shows the impact descriptors for Housing criteria and their corresponding impact levels.

Each impact level is correlated with the severity or grade of damage to either the equipment or function connected with the Housing function (Fig. 12), so that a specific "picture" of the impact is given. For example, if we look at impact level IV, we see that each component that contributes to this function must be at a certain level to produce a Housing impact of IV; there are several requirements that differentiate the levels:

- Housing buildings should present an impact level greater than III, which means that in the affected area, the majority of buildings are heavily damaged. Buildings are unusable or dangerous; or,
- alternatively, mobility should present an impact level greater than II, which means that it is "strongly disturbed at regional and local levels". This requirement is obtained from

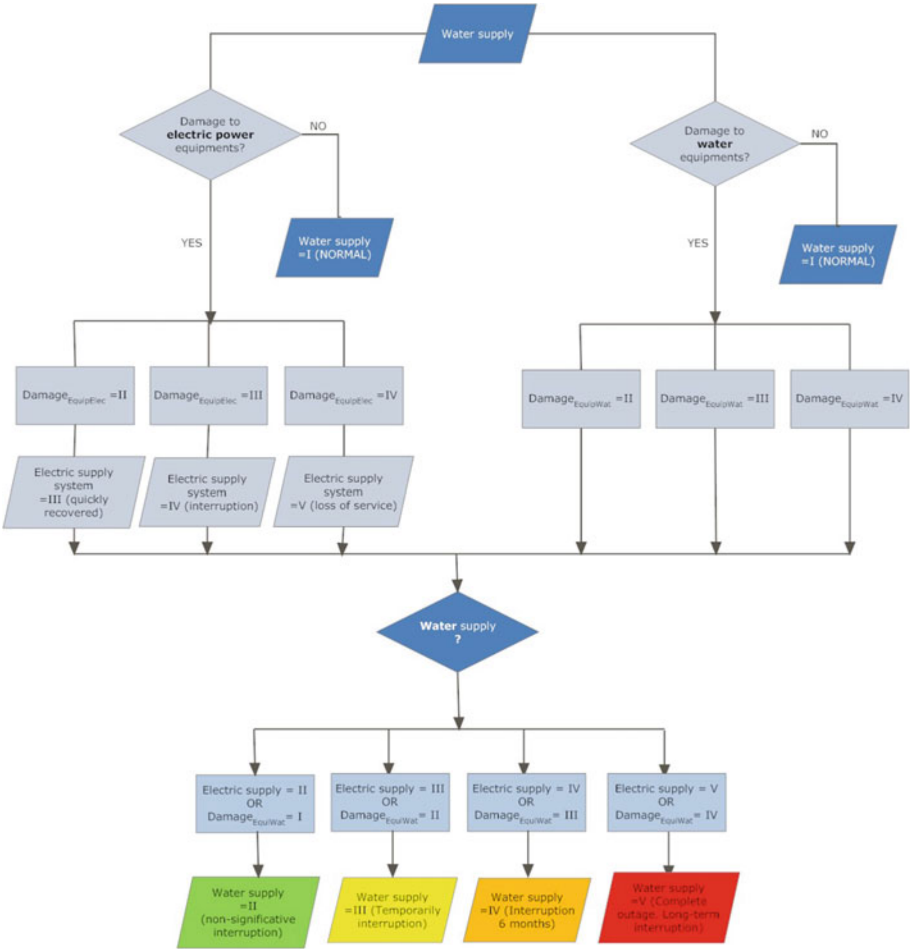

Fig. 10 Water supply diagram

	DI	Environment	Food	Housing	Security	Heathcare	Education	Employment	Mobility	Power	Telecoms	Transportation	Debris	Water	Sanitation	Critical infrast
DI ⇨	1	1	1	1	1	1	1	1								
Environment		1												1	1	1
Food			1		1				1							
Housing				1					1	1	1			1	1	
Security					1				1	1	1					
Heathcare						1			1	1	1			1	1	
Education							1		1	1	1			1	1	
Employment								1	1	1	1			1	1	
Mobility									1			1	1			
Power										1						
Telecoms										1	1					
Transportation										1	1	1				
Debris													1			
Water										1				1		
Sanitation										1				1	1	
Critical infrast																1

	DI	Environment	Food	Housing	Security	Heathcare	Education	Employment	Mobility	Electricity	Telecoms	Transportation	Debris	Water	Sanitation	Critical infrast.
DI ⇨	1															
Environment	1	1														
Food	1		1													
Housing	1			1												
Security	1		1		1											
Heathcare	1					1										
Education	1						1									
Employment	1							1								
Mobility	1		1	1	1	1	1	1	1							
Electricity	1	1	1	1	1	1	1	1	1	1	1	1		1	1	
Telecoms	1		1	1	1	1	1	1	1		1	1				
Transportation	1		1	1	1	1	1	1	1			1				
Debris	1		1	1	1	1	1	1	1				1			
Water	1	1		1		1	1	1						1	1	
Sanitation	1	1		1		1	1	1							1	
Critical infrast	1	1														1
DP's ->	14	4	5	6	4	6	6	6	4		1	2		1	2	

Fig. 11 Adjacency matrix (*left*) and incidence matrix (*right*)

Table 3 Level of performance

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
V	Buildings are unsafe to enter. Population needs to be relocated
IV	Residential buildings are partially unusable. Semi-permanent housing needed; a long-term relocation will be required
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 remotion) that wi ll reduce risk to its occupants to acceptable levels. Need for temporary relocation
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
I	Normal conditions

Impact level	Residential buildings		Mobility		Power supply		Telecom supply		Water supply		Sanitation supply
V	> IV	OR	> III	OR	-	OR	-	OR	-	OR	-
IV	> III	OR	> II	OR	> III	OR	> III	OR	> III	OR	> III
III	> II	OR	-	OR	> II	OR	> II	OR	> II	OR	> II
II	> I	OR	-	OR	-	OR	-	OR	-	OR	-
I	-	-	-	-	-	-	-	-	-	-	-

Fig. 12 Housing conditions to obtain an impact level

the 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 greater than III, which means that the supply system is disrupted, affecting critical services; or,
– the Sanitation service should present an impact level greater than III, indicating a long-term disruption of sanitation service.

By combining the conditions using the logical function OR, we are able to categorise the impact level if either component condition is true. By this procedure, each node has an associated *transition function* that transforms the input, measured by the expected performance of several other nodes on which it depends, to the expected performance (or output) that affects the behaviour or the end state of other nodes that depend on it. The benefit of the use of logical conditions is the elimination of hypothetical (subjective) utility functions and additive aggregation rules, as well as their inherent constraints that lead to well-known problems related to the weights and non-preferential independence of utilities. In this sense, a Housing impact of level IV means that in the affected area, buildings are partially unusable because of damage or difficulty in accessing them, which causes a temporary housing need.

Using the outputs of the damage estimation models (simulators) or an earthquake description, as we have in Azores, we are able to not only know the number of damaged dwellings (and their usability after an event) but also to understand how a damage grade affects many parts of a person's life (access to education, work, daily routines, etc.). Post-earthquake usability assessment is, at present, a way to establish the financial contribution of the gov-

Table 4 Level of dysfunction of each equipment or network

Impact level	Equipment or network	Impact descriptor
2	[1…4] Electric power equipments	Disturbance in operations. Equipment restoration (repaired or replaced) as a function of time (in weeks)
1	[1…4]Transport infastructure	No damage or minor damage
2	[1…4] Water equipments	Disturbance in operations. Equipment restoration (repaired or replaced] as a function of time (in weeks]
2	[1…4] Sanitation equipments	Disturbance in operations. Equipment restoration (repaired or replaced] as a function of time (in weeks]
1	[1…4] Telecom equipments	Normal service or minor disturbance may occur
2	[1…5] Educational facilities	Light damage. Needs post-earthquake building inspection (usable)
1	[1…5] Healthcare facilities	No damage
1	[1…5] Security facilities	No damage
4	[1…5] Residential buildings	Heavy damage. Buildings are unusable/dangerous
3	[1…5] Non-habitational buildings	Significant/moderate damage. Temporarily unusable, some buildings may require reparation/strengthening
3	[1…5] Buildings in general	Significant/moderate damage. Temporarily unusable, some buildings may require reparation/strengthening
1	[1…4] Critical infrastructures	No damage

ernment to the reconstruction, but it is also necessary to point out the consequences of losing the Housing function in a certain area, for example, in education. The greater the impact, the longer the recovery process must be, demonstrating reduced resilience.

These results could be useful for the development of an understanding of the contribution of individual dimensions to more effective disaster risk reduction. Considering the propagation effects, we could obtain an estimate of the number of homeless, the amount of semi-permanent housing needed, the number of the households affected by relocation, and the consequent loss of employment, considering the whole panoply of social, political and economic structures.

The following tables show how to apply this model to the case of the Azores. In Table 4, the first column cells translate the observed impact level for each type of equipment (or component of a criterion) after the earthquake. By the use of logical conditions (as shown in Fig. 12), we can calculate the impact level of each criterion (Table 5). To do so we compute in each step the different levels of impact within each subsystem; the overall impact is given by the maximum subsystem impact. Finally, repeating the same procedure, we obtain the disruption level (Fig. 13) imposed by a particular event.

The present methodology calculates a value of the DI = 4, which means that the disaster "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."

Throughout this paper, we have illustrated the applicability of our methodology by referring to a single case study, the 1998 Azores earthquake, and we arrived at a specific DI.

Currently, earthquake risk reduction considers only direct earthquake impact. The problem should be examined from a different perspective, as we propose in this paper, starting from

Table 5 Level of dysfunction of each function (services) and associated descriptor

Impact level	Functions	Impact descriptor
1	[1…5] Environment	Normal
4	[1…5] Housing	Residential buildings are partially unusable. Semi-permanent housing needed; a long-term relocation will be required
1	[1…3] Food	Normal food supplies
3	[1…5] Security	Earthquake response with some problems due to lack of energyj communications and mobility
2	[1…5] Education	
3	[1…5] Employment	Resumption of economic activities within a short time (2–3 weeks)
2	[1…4] Healthcare	Hospital services are continuing to provide care, some disturbance may occur
3	[1…5] Power supply system	Power supply system can be quickly recovered
3	[1…5] Water supply system	Temporary service interruption but with critical services provided. Tankers deliver water to areas without supply
3	[1…5] Sanitation system	Temporary sanitation service disruption
3	[1…5] Telecommunication system	Temporary telecom service disruption (voice, data and internet services)
2	[1…4] Mobility	Works or some debris causes disruption
3	[1…5] Transportation (road)	Interruption in local transport service due to dysfunction of normal operation
2	[1…4] Debris	Debris in some roads causing occasional interruptions

4	[1...5] Disruption index, DI	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.

Fig. 13 Final earthquake impact

the identification of the elements or services that do and do not directly impact the system and an understanding of the high level of interconnectivity (connections or dependencies) in the system. However, if the system analysis is too detailed, there are many dependencies and connections, and it is very difficult to provide all the data necessary to perform this complex analysis. Our broader perspective is coarser, but it can consider the most important components of the system. For instance, we do not contemplate patrimonial heritage, but it would be simple to add.

7 Conclusions and perspectives

After an earthquake, several services are unavailable to end users during the system failure and recovery processes, thereby causing service disruptions. For example, the lack of education in an affected area results in population movement. Malfunctions in the electricity distribution system produce electrical power outages that could be variable in time and space, generating consequences in the water distribution system or transportation infrastructure. The impact is not necessarily limited to a single country; it could also affect the neighbouring countries or regions.

The measurement of earthquake impact is the goal of this study, including all elements at risk and their inter- and intra- dependencies. 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.

The concept of a DI that is presented here and defined as the level of system performance after and prior to the earthquake allows us, in conjunction with Monte Carlo simulations and the use of *Importance-Measures*, to select the most influential system functions, leading to improved understanding of the whole system and the role of each component. In this sense, we could indicate where a community should be focusing its attention or support the community in the evaluation of alternatives that considers their effectiveness and cost.

This index was computed for a time (t_0) immediately following the event, but it can be computed as a function of time, incorporating not only the recovery process but the effects of aftershocks and the evolution of vulnerability functions, among other factors. The presented DI is a tool that can be applied to any kind of earthquake situation, using real data (descriptive) or data obtained from earthquake "simulators", allowing the comparison between different earthquake scenarios in order to develop guidelines for impact evaluation.

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.). The index can also be considered to be an enriched Macroseismic Scale.

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