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ORIGINAL RESEARCH PAPER

QuakeIST® earthquake scenario simulator using interdependencies

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Abstract Earthquakes are a permanent threat to urban environments worldwide. The communication of the related risk demands accurate damage model simulations and an interactive visualization of results. The aim of this paper is to provide a realistic problem-solving environment for earthquake discussions among decision makers, stakeholders, and the general public. QuakeIST® is an integrated earthquake simulator developed by Instituto Superior Técnico (Lisbon University), oriented towards the performance of risk calculations concerning damage propagations that use the Disruption Index concept. This software imports data stored in a GIS environment, handles different ground motion scenarios, and deals with a complex situation of different soils and vulnerabilities of various layers of civil structures (buildings, lifelines, and other urban structures). It models interdependencies between several infrastructures and between infrastructures and the urban tissue. The computer programme is very versatile, written in separate modules, allowing an experimented user to incorporate new formulations. Results can be treated with any statistical application and most common GIS commercial environments can produced their geographic visualization. Current progress and new upcoming are briefly described at the end of the paper.

Keywords Seismic risk · Earthquake scenario simulator · Interdependencies · Impact assessment · GIS input/output

1 Introduction

There are currently many earthquake simulators on the market (see Oliveira et al. 2014a), such as LNECLoss (2010), GEM1 (2010), SELENA (2010), CAPRA (2014), ELER (2014), MAEviz (2014), OpenQuake Engine (Silva et al. 2014) and QALARM (2014), and many papers supporting them, such as Pagani et al. (2014) and Silva et al. (2014).

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However, as far as we know, none of these earthquake simulators addresses the problem of interdependencies (also referred as cascade or domino effects).

QuakeIST® is an integrated earthquake scenario simulator, programmed in C++, developed by Instituto Superior Técnico (IST), University of Lisbon. It is structured on a geographical information system (GIS) and performs risk calculations concerning damage propagations using the concept of the Disruption Index (DI) (Ferreira et al. 2014). It opens up new territory for earthquake science and engineering, with the goal to reduce the potential for loss of life and property.

The QuakeIST® output helps the user to identify the most important factors and system components (buildings, lifelines, etc.) that contribute to the main urban disruptions, thereby providing plans and guidance for short-, medium-, and long-term investment projects to reduce risk.

The key features of QuakeIST® software, illustrated in Fig. 1, are the following:

- The simulator (QuakeIST®) can handle different ground motion scenarios provided by the user: the epicentre geographic coordinates and the magnitude value; ground motion values (PGA, EMS-98, etc.) at a grid of points containing the geographical units under analysis; or other external scenarios obtained from programmes, such as SASHA (ĎAmico and Albarello 2008) and EXSIM (Motazedian and Atkinson 2005). It also can deal with response spectra variables.
- QuakeIST® contains a large number of well-known attenuation relationships that may be selected; alternatively, the user can decide to apply his own GMPE's.
- The loss and damage models require shaking intensity, macro-seismic intensity, PGA, PGV, or PGD as one of the input parameters. The simulator has mechanisms to proceed with all necessary conversions between ground shaking variables and units, leaving to the user the choice of those more convenient to him. Soil information can be handled

Fig. 1 QuakeIST® main characteristics

through Eurocode EC-8 (2004) that deals with classes A to D. Any specific response spectra can be used as well. The EC-8 (2004) and USGS Spectra (2015) are already internally coded in the simulator.

- Different types of assets, with no limit to the number of layers (buildings, schools, bridges, networks, population, etc.) can be modelled.
- QuakeIST® contains algorithms for propagation effects and impact assessment.
- QuakeIST® uses a display platform (GIS) to create maps and to measure the possible impact caused by earthquakes in urban systems. Maps for a given asset typology, or groups of typologies, and corresponding losses, can be plotted at any given scale, either for individual or aggregated situations.
- The DI output is prepared for illustrating the interdependency effects and can be plotted in GIS environment.

In what concerns validation or calibration (i.e., checking that the results match observed information), a set of tests were performed in the UPStrat-MAFA (2012) Project, using real data gathered in the occasion of Lorca 2011, Faial 1998, and Iceland 1998 earthquakes.

For a copy of QuakeIST® please contact one of the authors.

2 QuakeIST® architecture

The architecture of QuakeIST® consists of four modules: (1) an urban geo-database, (2) a library module, (3) a simulation module, and (4) an output module. The urban geo-database, with information at the level of the geographical unit used for analysis (a region, a county, or a block), provides basic spatial and statistical data used in the GIS platform for earthquake scenario simulation. The library module contains four sub-models (ground motion, vulnerability, damage and loss, and DI models), which correspond to the key stages involved in earthquake scenarios. The simulation module is an operation center that integrates data and models. The output module consists of tables containing the various results at the level of the geographical unit selected. These results can then be exported to any statistical environment and visualized in most GIS.

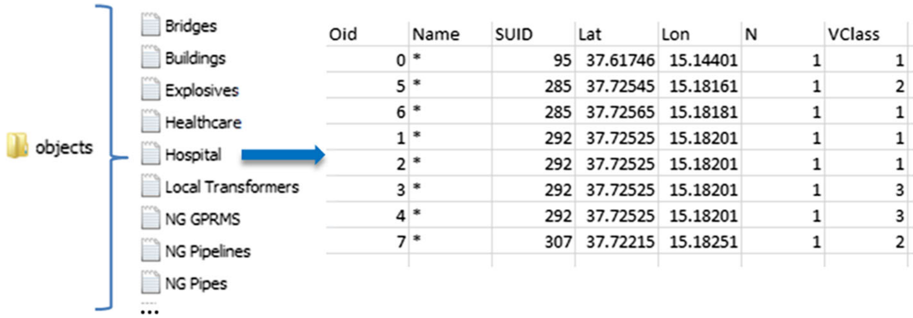
2.1 Urban geo-database

Before starting the simulation, the spatial features and attributes of all elements (assets) must be set up.

The urban elements (or “objects” organized in .txt files) already considered in the present version of the programme are (if available): residential buildings, healthcare facilities, schools, security facilities, power stations, local transformers, natural gas pipes, natural gas pressure reduction and measurement stations (PRMS), pipelines, water pipes and wastewater pipes. Other objects could be added once their geographic characterization and attributes are known and defined. The attribute information of each object should be prepared in a table format as shown in Fig. 2.

2.2 Library module

The library module contains geo-referred information needed to compute the various sub-models on ground motion, vulnerability, damage and disruption index.



Oid	Name	SUID	Lat	Lon	N	VClass
0	*	95	37.61746	15.14401	1	1
5	*	285	37.72545	15.18161	1	2
6	*	285	37.72565	15.18181	1	1
1	*	292	37.72525	15.18201	1	1
2	*	292	37.72525	15.18201	1	1
3	*	292	37.72525	15.18201	1	3
4	*	292	37.72525	15.18201	1	3
7	*	307	37.72215	15.18251	1	2

Fig. 2 QuakeIST® input data. The objects are composed by: object ID (OID); Name (hospital name or other facility); Spatial Unit Identifier (SUID: identifies the cells where the exposed objects are considered and where a constant value of surface ground motion exists, as defined by macroseismic intensity, peak ground acceleration, peak ground velocity, or other), Latitude, Longitude, N (number of objects in the same cell), and VClass (vulnerability class)

Ground motion can be assessed in different ways as described on the Simulation Module. In all cases, soil categorization, which is a very important issue for a more correct analysis of site-effects, is considered. Data on this item can be derived from microzoning studies or from macro modelling based on general surface geological mapping. The present module considers soil amplification following the classification and formulation given in EC-8 (2004) with four classes A to D. The geographic unit of work depends on the detail of existing information, as it happens in all other cases (objects, assets, etc.), and in QuakeIST® the information is associated to the centre of mass of that particular unit. To assess the consequences and impacts of earthquake scenarios, we need tools to predict the physical consequences on given "objects" in urban areas, as well as access to the vulnerability and thus potential damage to the surrounding environment, infra-structures, and population.

"Building objects" are separated from "non-building objects". Information on the first category is obtained essentially from building Census, and damage estimations are often derived from procedures such as:

- Spectrum capacity (ATC 40 1996);
- Spectrum capacity with bilinear capacity spectrum (ATC 40 1996);
- N2 Procedure (Fajfar in EC-8 2004 and 2005);
- Macroseismic method (Giovinazzi and Lagomarsino 2004);
- Fragility functions, often gathered from Damage Probability Matrices (DPM's).

"Non-building objects", mainly lifelines, industrial components, and other special objects, are often managed by specific procedures, such as customized:

- Fragility functions;
- Loss functions;
- Repair rate functions.

All the above mentioned procedures are internally coded in QuakeIST®.

Building typologies and the corresponding vulnerabilities must be provided by the user. We have examples of use of few classes in the application of QuakeIST® to Mount Etna (Meroni et al. 2015), or of hundred classes in the Lisbon case (Mota de Sá 2016).

With QuakeIST® it is easy to compare the results produced by different methodologies and better understand their differences. As an illustration, Fig. 3 presents the capacity

Typology	Floors	Slabs	(s) T_y	(m/s2) Sa_y	(cm) Sd_y	(-) μ	(cm) Sd_u
Simple Stone masonry with 3D wooden truss, (1755…1870)	4	Wood	0,440	1,890	0,927	2,680	2,484
Simple Stone Masonry (1870…1930)	6	Wood	0,640	1,060	1,100	3,060	3,365
Unreinforced Masonry (1940…1950)	3	Wood and RC	0,240	1,920	0,280	8,730	2,446
Reinforced Masonry (1950…1960)	3	RC	0,350	3,490	1,083	2,820	3,054
RC Moment Frame (1960…1986)	7	RC	1,055	1,933	5,450	1,337	7,286
RC Moment Frame (1986…2000)	7	RC	1,001	2,247	5,703	1,786	10,186
RC Moment Frame (2000…)	9	RC	1,067	2,830	8,161	1,570	12,813

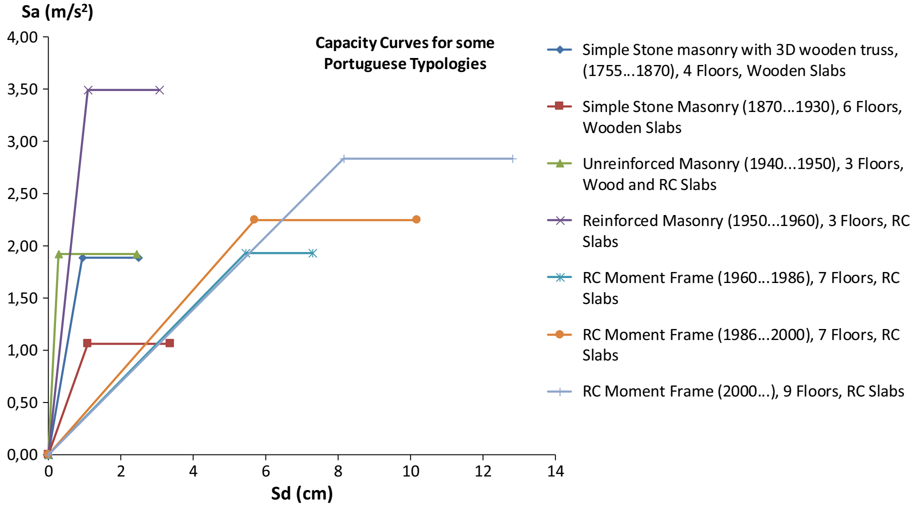


Fig. 3 Example of capacity curves used to obtain vulnerability functions of seven different typologies related to the Portuguese building stock

curves adapted from ATC 40 (1996) of a few typologies used to study vulnerability of the Portuguese building stock.

Other vulnerability or fragility relationships for various components or elements at risk subjected to ground shaking [EMS98, PGA, PGV, PGD, Sa(T), etc.] can be obtained from published information, as shown in Table 1. QuakeIST® provides many of the conversion laws to deal with different ground motion parameters (conversions from/to Intensity–PGA, etc.).

Figure 4 presents fragility curves developed for the most common traditional masonry buildings in Portugal, considering four floors. These curves are already part of the database of QuakeIST®. Similar curves are available for a different number of floors and for reinforced concrete structures (Mota de Sá 2016). Other fragility curves can easily be added to the library module.

For population affected by a given scenario, Human Losses estimation was adapted from previous works, resulting in the values H and L shown below. More precisely, these expressions were at first adapted from LNECLoss (2010), Tiedemann (1992), HAZUS (2010), and Coburn et al. (1992) and later modified and adopted in the “Algarve Seismic Simulator” (ERSTA 2008) and published in the WP22 Final Report (Mota de Sá 2009).

$$H = 0.65 \times P[Ds = 4] \times Tr \times Pr \times A \times n/100$$
$$L = 0.32 \times P[Ds = 4] \times Tr \times Pr \times A \times n/100$$

where H, total number of persons estimated to be severely injured; L, total number of estimated Life Lost; P[Ds = 4], probability of some system attaining damage degree (Ds) equals to 4; Tr, time occupancy rate, defined by the % of time of human presence in the

Table 1 Different methodologies to derive damage and losses in different assets [taken from Ferreira et al. (2014)]

Element at risk	Vulnerability	Function of	Damage algorithms
Buildings	Macroseismic method Capacity method	Intensity EMS98 or PGA	P [dg $\geq$ k]; LogNormal or Beta Distributions
Healthcare buildings	Macroseismic method	Intensity EMS98	P [dg $\geq$ k]; LogNormal or Beta Distributions
School buildings	Macroseismic method	Intensity EMS98	P [dg $\geq$ k]; LogNormal or Beta Distributions
Security buildings	Macroseismic method	Intensity EMS98	P [dg $\geq$ k]; LogNormal or Beta Distributions
Bridges	"ERSTA" project (2008)	PGA	P [dg $\geq$ k] = LogNormal
Power stations	"Syner-G" project (2010a)	PGA, PGV	P [dg $\geq$ k] = LogNormal
Local transformers	"ERSTA" project (2008)	PGA, PGV	P [dg $\geq$ k] = LogNormal
Natural gas pipes	"Syner-G" project (2010b)	PGA, PGV, PGD	Repair rate: RR [R/km] = ko $\times$ k1 $\times$ PGV^{k2} [PGV in cm/s]
Natural gas PRMS	"Syner-G" project (2010b)	PGA, PGV, PGD	Repair rate: RR [R/km] = ko $\times$ k1 $\times$ PGV^{k2}
Pipelines	"Syner-G" project (2010b)	PGA, PGV, PGD	Repair rate: RR [R/km] = ko $\times$ k1 $\times$ PGV^{k2}
Water pipes	HAZUS model (2010)	PGA, PGV, PGD	Repair rate: RR [R/km] = ko $\times$ k1 $\times$ PGV^{k2}
Waste-water pipes	HAZUS model (2010)	PGA, PGV, PGD	Repair rate: RR [R/km] = ko $\times$ k1 $\times$ PGV^{k2}

ko, k1 and k2 values were taken from Syner-G (2010b)

PGA peak ground acceleration, *PGV* peak ground velocity; *PGD* peak ground displacement; *Sa*(*T*) spectral acceleration

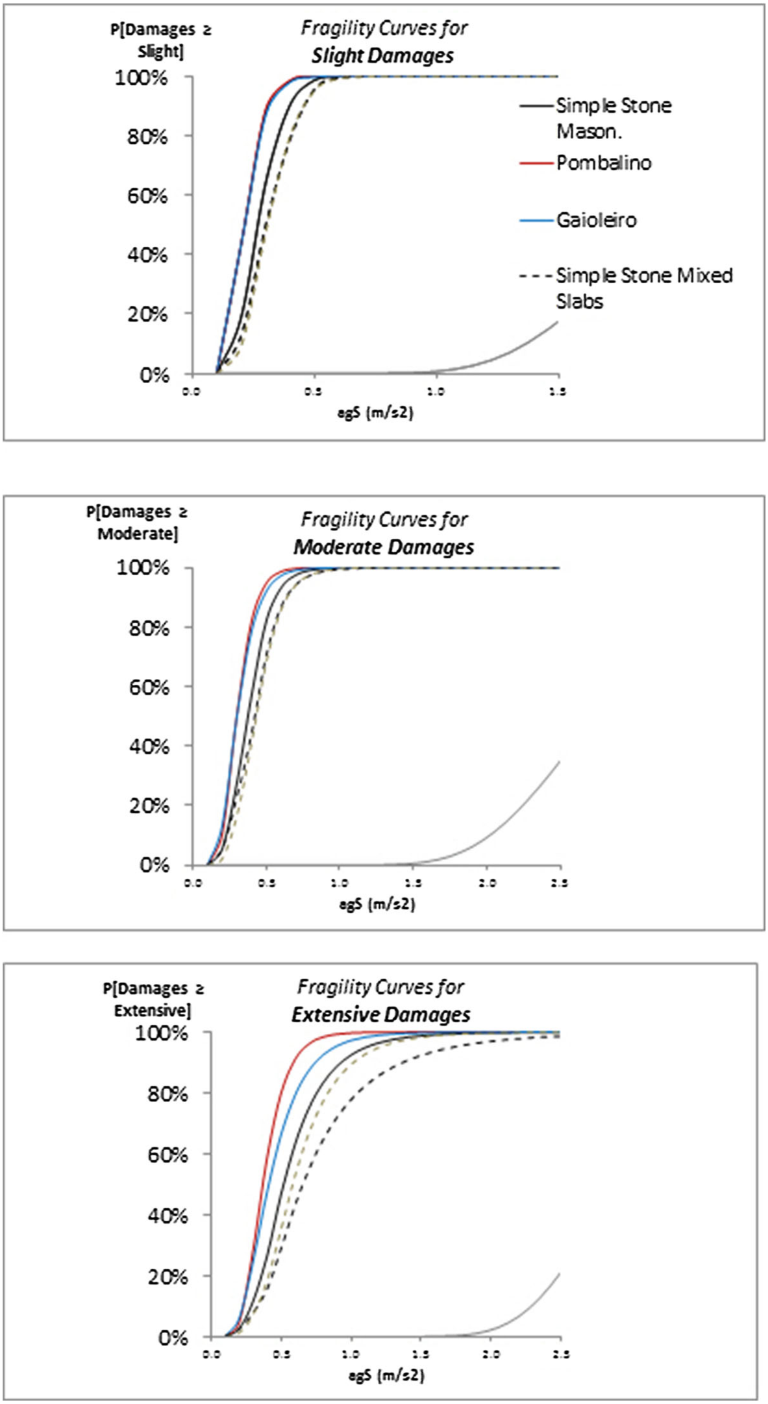


Fig. 4 Fragility curves for various masonry buildings (four floors) in Portugal (Mota de Sá 2016)

DI												
Impact level	**Impact descriptor** *Indirect descritor that measures 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.*	Environment		Housing		Food		Education		Employment		Health care
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.	> III	OR	> IV	OR	> II	OR	-	OR	-	OR	-
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.	> II	OR	> III	OR	-	OR		OR	> III	OR	-
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.	-	OR	> II	OR	> I	OR	> III	OR	> II	OR	> III
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	OR		OR	-	OR	> II	OR	> I	OR	> II
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.	-	-	> I	-	-	-	-	-	-	-	-

Fig. 5 Qualitative descriptors of DI and dependency rules from the six dimensions of fundamental human needs

building during a normal week; Pr, average number of persons per 100 m^2 of floor area, herein assumed to be 3.3, in accordance with Portuguese statistical data published by INE (2011); A, plan floor area of the building (m^2); n, building number of floors.

QuakeIST® was designed not only to combine seismic hazard, vulnerabilities, physical damages and the loss of service from lifelines, but also to integrate the DI about urban and societal impacts (Oliveira et al. 2012; Ferreira 2012; Ferreira et al. 2014, 2015).

The purpose of the DI is to condense, in a concise and easy way, complex problems and multi-dimensional situations involving the earthquake impact in the urban system and livelihood, and identify interdependencies and connections among them. The development was based on extensive bibliographical research about the physical and social impacts of severe events, and on the experience gained in several earthquake field missions in different regions of the world.

More than 70 Primary Concerns were found to be systematically present in all texts and reports. They were aggregated into 14 Fundamental Criteria (using the rules of decision problem structuring), which translate the urban functions and dictate what we see as an urban system's ability or disability to respond to the observed demands (Ferreira 2012). Each one of the 14 Fundamental Criteria is characterized by an impact descriptor (Ferreira et al. 2014). Urban functions were then defined and classified using the following six Dimensions of human fundamental needs: "Environment, Housing, Healthcare, Education, Employment, and Food". These six Dimensions are affected by several other main functions/systems, such as mobility, electricity, water, and telecommunications, which, in turn, depend on the reliability of several buildings, equipment system facilities, and critical or dangerous facilities, in a bottom-up construction. As an example, in a top-down description, Fig. 5 presents the global DI impact descriptor and the dependency rules from the six Dimensions of fundamental needs;

Figure 6 shows the impact descriptor of one of these six fundamental needs (in this case, the Environment and the dependency rules from lifeline behaviour); and Fig. 7 presents the impact descriptor of the physical damage states of the critical infrastructures, one type of facilities influencing the Environment (Fig. 6).

The other dependencies and tables setting the algorithms are described in Ferreira et al. (2014). An example of the application of DI to three areas of the Algarve region (South

Environment						
Impact level	**Impact descriptor.** *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.*	Critical infrastructures		Water supply		Sanitation supply
IV	Explosion danger, nuclear, chemical, biological, radiological accidents, etc. Contamination of air, soils, water and/or aquifers. Could occur phenomenon of transboundary contamination/pollution problems. Need to evacuate.	> III		-		-
III	Environmental concerns: sanitation problems with health impacts (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.	> II	OR	> II	OR	> II
II	Local pollution/contamination problems. Leaks or spills of substances such as oil, waste oil, fuel, lubricants, paints. Public health problems, substances can pose risks to people.	> I	OR	>I	OR	>I
I	No adverse effects.	-	-	-	-	-

Fig. 6 Qualitative descriptors of environment and dependency rules from lifeline behaviour

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

Fig. 7 Qualitative descriptors of critical infrastructures

Portugal) is presented in Ferreira et al. (2015), and its application to Monte Etna (Italy) in Meroni et al. (2015), (this issue).

The first approach to DI was an application made in Excel® environment related to an entire zone affected by the Faial (Azores) 1998 earthquake (Oliveira et al. 2012). It became clear that the DI methodology depended on the geographic area under analysis and on the level of interdependencies studied.

A new initiative took place to respond to these challenges, in order to make DI a tool with geographic significance. The first problem was solved by introducing the concept of geographic minimal unit with meaningful sense. It could not be the size of a building because we need to make averages, but it could not be even a large area, unless we just wanted to look to an overall measure of disruption for an entire region. We selected the block, a grid, or any other geographic unit of the census track and something which can be referred as the center of gravity of our detailed analysis. The second problem was also dealt with as the more layers or urban systems are considered, the more correct the interdependency situation is analyzed. It means that the more complete is the analysis, the more close to the upper value of interdependencies we are.

Urban centers do not function in isolation; rather they provide goods and services to the area lying beyond the urban boundary; people from the surrounding area commute to a

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

Fig. 8 *Left* criteria for delineation of the radius (*sphere*) of influence. *Right* illustration of spatial modelling and spheres of influence

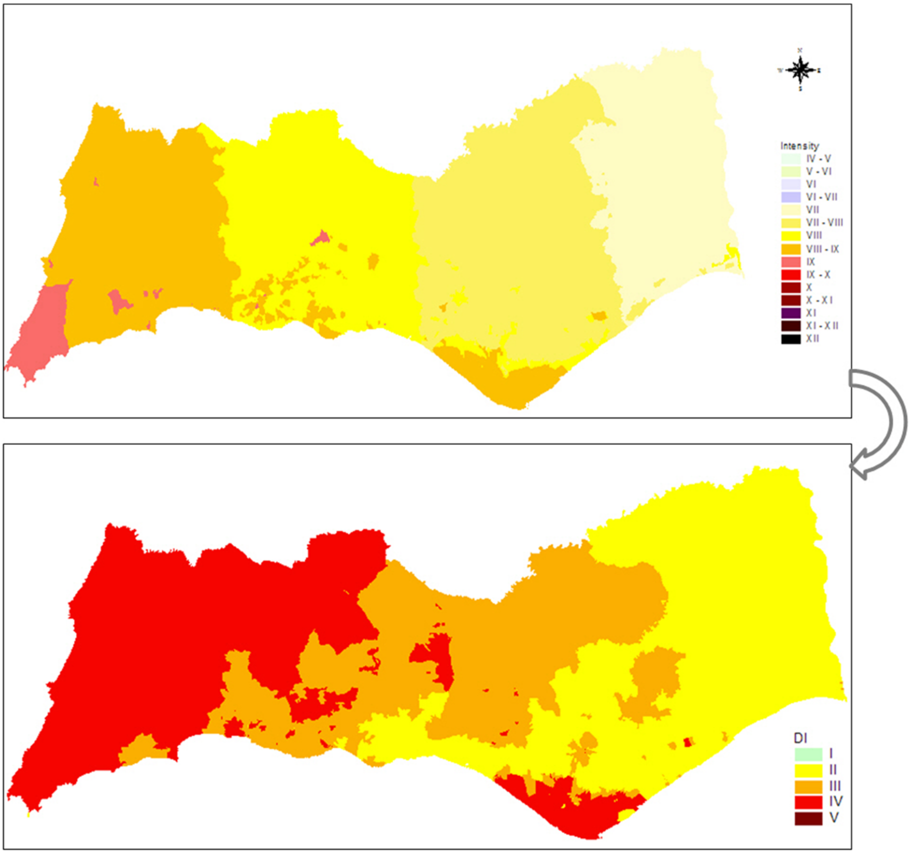


Fig. 9 Algarve region, Portugal: comparison between intensity map (*left*) and DI map (*right*)

town to access the required facilities. At this point we introduce the city's "sphere of influence" which describes its physical boundaries and the areas where facilities, amenities, and services are allocated in a fair manner within the urban center. Subsequently, urban population is found distributed among the settlements of varying sizes from smaller towns to giant cities (Pascione 2001).

In general, firehouses, hospitals, schools, etc., should be distributed throughout the city, so that each facility has a primary service area extending within a recommended radius. From the center of each cell a circle is drawn up to an x radius distance; for example schools are located within a 1.5 km radius of each grid cell. Figure 8 presents the radius of influence for some common urban facilities and networks, and depicts the circular form of the "sphere of influence" of amenities and facilities. Those values agree with planning and urban design standards. They can be slightly changed and their influence analyzed.

DI computations are made for a grid of points or for the center of gravity of a block of buildings (or other geographic unit), applying the concept of radius of influence. Isolines of DI (isoDI, or zones of equal DI) are then drawn to obtain the geographical location of transitions between them. All this methodology was programmed in QuakeIST® and the output information is structured in shapefile format, which can be exported to any GIS platform and subsequently treated in terms of spatial and statistical information.

Consequently, it is possible to calculate isoDI areas (Ferreira et al. 2015) and understand the real propagation effect as a function of various interdependencies. The two panels of Fig. 9 clearly show how the propagation effect amplifies the region of individual responses.

Several questions may be placed at this instance about the sensitivity of the DI on the size of the grid and on the absence of information required to deal with all six Dimensions of fundamental human needs, and other sources of uncertainty. These issues are discussed at length in Ferreira et al. (2015) and in Oliveira et al. (2014a, b).

The DI concept can be extended without further computer programming to other systems having important interdependencies, such as industrial complexes. Other multi-hazard analyses, in macro or micro scale, can also be dealt with, requiring minor adjustments to QuakeIST®.

2.3 Simulation module

The simulation focuses on the impacts from buildings and assets conditions, according to different scenarios (based on attenuation conversion law, intensity to PGA conversion law,

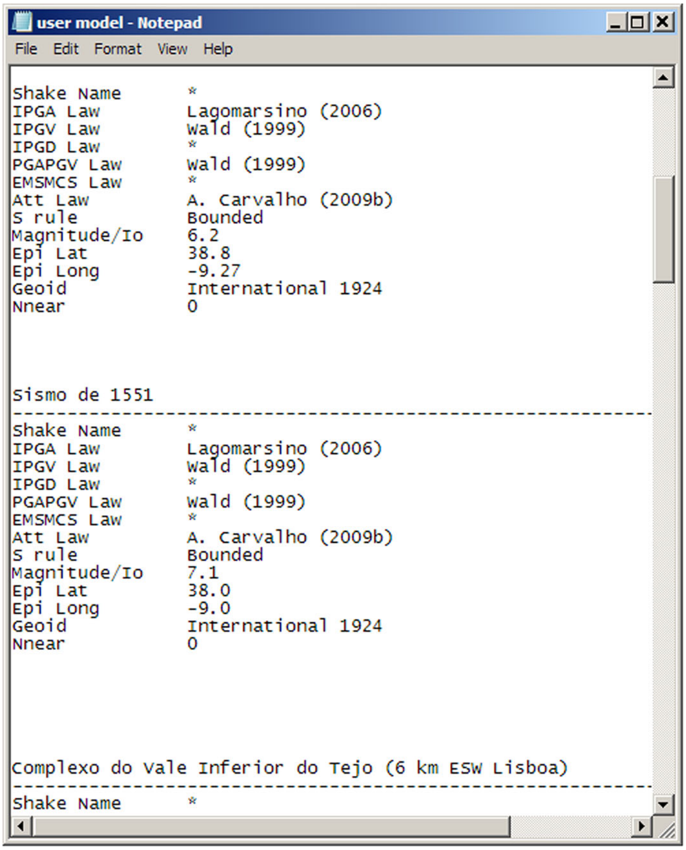


Fig. 10 User model layout for ground motion definition

Intensity to PGV conversion law, magnitude, and so on). As soon as a new scenario is developed, it is automatically added to the existing library.

Figure 10 illustrates the "user model" for scenario configuration (in this case two scenarios are prepared for simulation), where the user chooses the parameter settings for simulation, such as the attenuation model and conversion Intensity/PGA/PGV spectra, already available in the library. QuakeIST® allows two ways of specifying ground motion: (1) supplying a text file with ground motion values in some specific points defined by their coordinates, or (2) supplying epicentre coordinates and a Magnitude "Mw" or Intensity "I_o" value.

The parameters considered for simulation, presented in the "user-model" of Fig. 10 are described in Fig. 11.

A large set of attenuation formulae or of GMPE's, PGA, PGV conversions laws to EMS-98 are embodied in the surface ground motion module. Figure 12 presents a set of

line Name	line Description	line Class
Shake Name	"*" if scenario is internal; "Some_Scenario_name" if scenario is external	Text [30]
IPGA Law	Function to be used in converting ShakeV to I or PGA. Possible values	Text [30]
IPGV Law	Function to be used in converting ShakeV to PGV. Possible values	Text [30]
IPGD Law	Function to be used in converting ShakeV to PGD. Possible values	Text [30]
PGAPGV Law	Function to be used in converting PGA - PGV. Possible values	Text [30]
EMCMCS Law	Function to be used in converting IMCS to IEMS. Possible values	Text [30]
Att Law	Att. Law used to predict Ground Shaking f (Magn, R). Possible values	Text [30]
S rule	Site Effects (Soil Amplification/Deamplification rule)	Text [30]
Magnitude	Magnitude or Epicentral Intensity, Io (0 if scenario is external)	Float (Double)
Epi Lat	Epicenter Latitude in decimal degrees (0 if scenario is external)	Float (Double)
Epi Long	Epicenter Longitude in decimal degrees (0 if scenario is external)	Float (Double)
Geoid	Geoid (Theoretical surface used to compute distances)	Text [30]
Nnear	Number of near points in external scenario that should be used to obtain Gm values in other points.	Integer

Fig. 11 Parameter definition

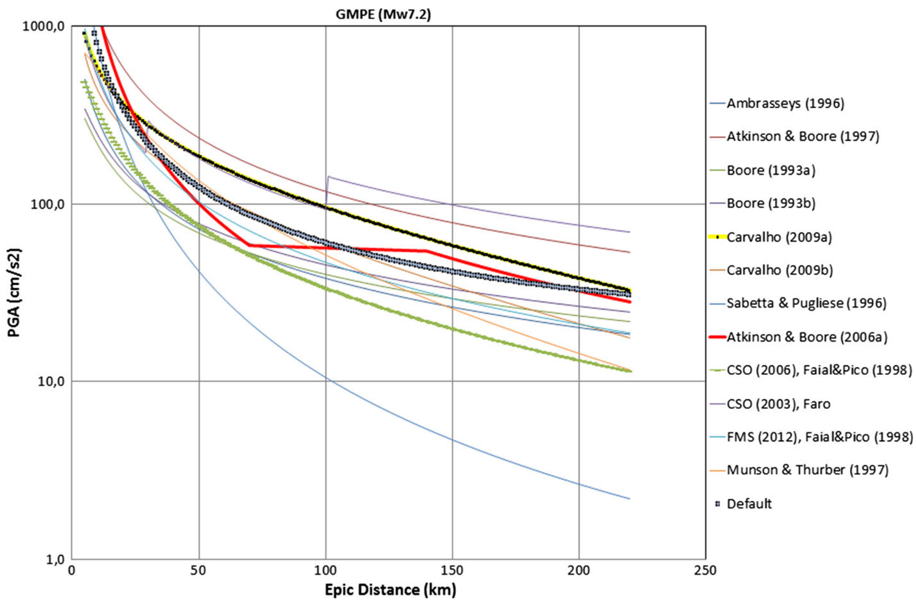


Fig. 12 Attenuation curves available in the library module. All references can be consulted in Mota de Sá (2016)

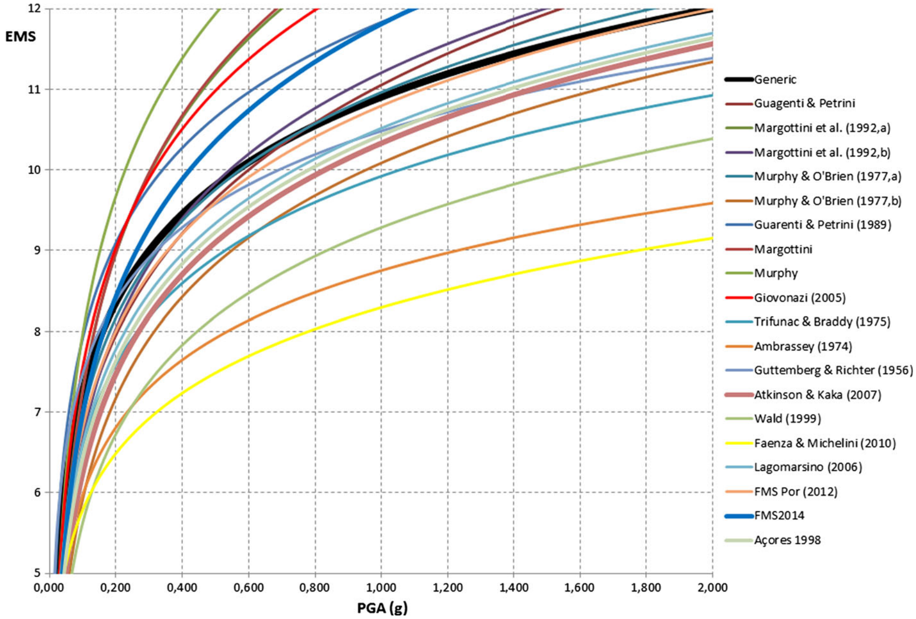
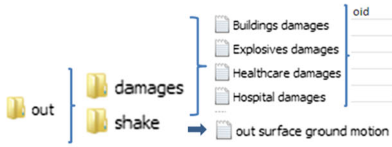


Fig. 13 Conversion between PGA and macroseismic Intensity. All references can be consulted in Mota de Sá (2016)

Field Name	Field Description	Field Class
Oid	Building_object Unique Identifier	Integer (Long)
Mean	Mean Damage Grade	Float (Double)
Mode	Most Observed Damage Grade	Integer
pp1	Likelyhood of Damage Grade 1 being achieved or surpassed, P[dg ≥ 1]	Float (Double)
pp2	Likelyhood of Damage Grade 2 being achieved or surpassed, P[dg ≥ 2]	Float (Double)
pp3	Likelyhood of Damage Grade 3 being achieved or surpassed, P[dg ≥ 3]	Float (Double)
pp4	Likelyhood of Damage Grade 4 being achieved or surpassed, P[dg ≥ 4]	Float (Double)
pp5	Likelyhood of Damage Grade 5 being achieved or surpassed, P[dg ≥ 5]	Float (Double)
n0	Number of, with No Damages, at (Lat, Long)	Float (Double)
n1	Number of, with Damages Grade 1, at (Lat, Long)	Float (Double)
n2	Number of, with Damages Grade 2, at (Lat, Long)	Float (Double)
n3	Number of, with Damages Grade 3, at (Lat, Long)	Float (Double)
n4	Number of, with Damages Grade 4, at (Lat, Long)	Float (Double)
n5	Number of, with Damages Grade 5, at (Lat, Long)	Float (Double)

(*) Case N=1, Number of = P [ ]



oid	mdg	mode	pp1	pp2	pp3	pp4	pp5	n0	n1	n2
0	0.264	0	0.242	0.022	0	0	0	0.758	0.22	0.
1	0.264	0	0.242	0.022	0	0	0	0.758	0.22	0.
2	0.264	0	0.242	0.022	0	0	0	0.758	0.22	0.
3	1.239	1	0.848	0.326	0.061	0.004	0	0.152	0.522	0.
4	1.239	1	0.848	0.326	0.061	0.004	0	0.152	0.522	0.

SUID	R	ShakeU	ShakeV	S	IEMS	PGA	PGV	PGD	SaT1
0	0	EMS	5	1	5	66.019	4.256	0	41.262
1	0	EMS	4.576	1	4.576	42.226	3.22	0	26.391
2	0	EMS	4.701	1	4.701	48.111	3.495	0	30.07
3	0	EMS	4.389	1	4.389	34.708	2.846	0	21.693
4	0	EMS	4.061	1	4.061	24.632	2.294	0	15.395
5	0	EMS	4	1	4	23.101	2.203	0	14.438

Fig. 14 Structure of output folders and results

attenuation curves already available, and Fig. 13 the conversion of ground motion parameters. Both figures show the tremendous scatter for these two issues. One has to be aware that the choice of the attenuation function and of conversion laws are very important. Customizing these functions will reduce the great epistemic uncertainties which will be present in the final results.

2.4 Output module

To understand the output of the earthquake scenarios, the results are computed for each object in the form of the fraction of buildings that reached or surpassed each damage state, $ppk = P \times [Ds > k]$. QuakeIST® can also provide a damage distribution per building typology (amount of buildings in each damage state within the same building class) or the total damage distribution (sum of all the buildings in each damage state). Figure 14 illustrates the structure of output folders and results. Linking these data to each object and facility, several maps, with damages geographically detailed in any GIS platform, are obtained.

Once all the information is compiled, QuakeIST® is ready to run and calculate the impact results for an entire region, or for a part of that region. For the case of about 220,000 buildings and lifelines, the computation time for one scenario in a portable with 3.1 GHz processer is <5 s. The simulation module is designed to depict earthquake damage states for each defined layer. In Fig. 15 we see the imported results in a GIS

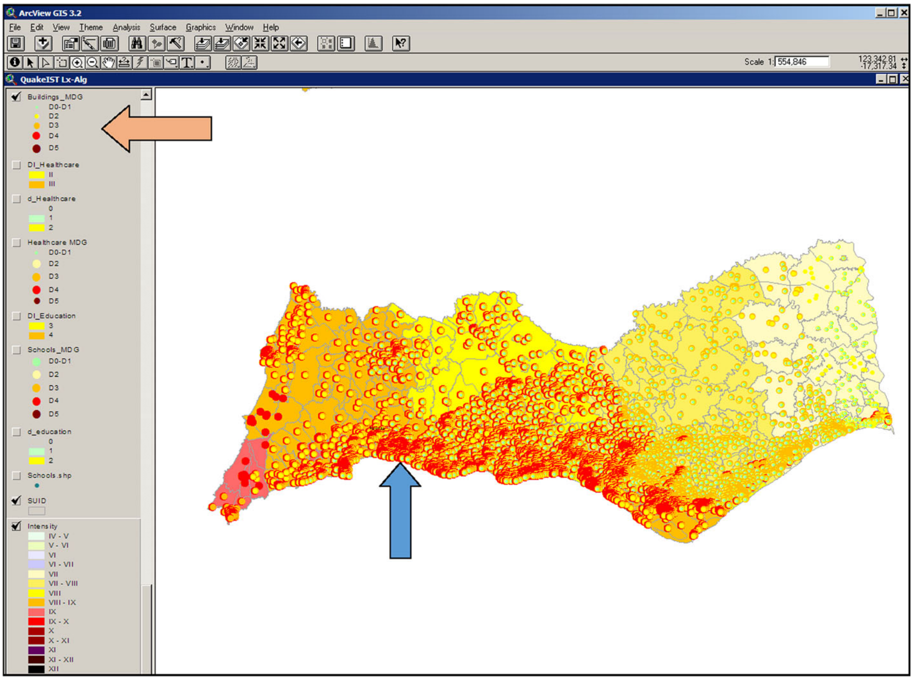


Fig. 15 QuakeIST® example of simulation in a region (Algarve, south Portugal). Output with building damage states—*brown arrow*—use superposition of *pies* designed for the centre of mass of each statistical sub-tract (unit). *Blue arrow* indicates the zoomed zone presented in Fig. 16) (Produced in ArcGIS® 2015)

Fig. 16 Output (smoothed mean damage density) plotted on a Google Map® interface, zoomed of Fig. 15 (Courtesy of João Bonacho 2016) (Produced in QGIS® 2015)

environment, in terms of "pie" representation at each geographic sub-section. And in Fig. 16, using another GIS platform, one council of the region presented in Fig. 15 is zoomed and the smoothed mean damage density is plotted by means of a "heat function" on top of a Google Map® interface. This way, visualization of more vulnerable areas are decided by the end-user operator.

3 Decision-support for disaster risk reduction: upcoming research

To be independent from the GIS platform, the simulator interacts with GIS and other software by *Tab-Delimited Text Files*. This provides freedom to use the simulator data (input and output) with many other applications offering statistical and risk analyses, or simply using spreadsheets. This is an important feature, once a better understanding of seismic risk can be achieved by the use of other software.

In Fig. 17, as an example of end-user application of the QuakeIST®, a very common characteristic of seismic risk, "skewed probability distributions", can be observed. In fact, apart very few cases where left (negatively) skewed or even bimodal distributions appear, risk probability distributions are often right skewed (Mode < Median < Mean), leading to *average values inducing a highly biased interpretation of seismic risk*. Considering scenario generated by QuakeIST® for the city of Sines, Portugal (Oliveira et al. 2014a, b), the

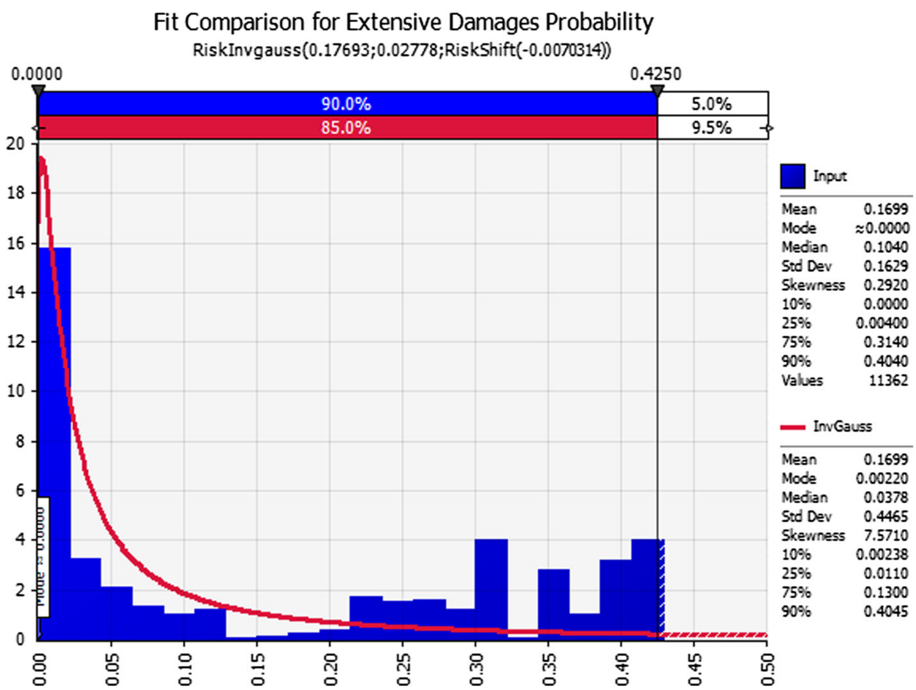


Fig. 17 Example of risk distributions often right (positively) skewed (@RISK 2014)

mean probability of extensive damages in the building stock would be about 17 %, whereas the most expected probability (the mode) is only about 0.2 %, and even the median probability is only about 3.8 %.

A second example of interaction of QuakeIST® with external applications can be observed in Fig. 18, where *Risk Importance Measures* and *Multi-State Interdependent Systems* (Apostolakis and Lemon 2005; Vesely et al. 1983) were used to identify *Potential Policies of Risk Reduction* in Faial Island (Ferreira et al. 2015, where all definitions and glossary presented below are explained).

There, the simulator was used in scenarios generation where the multiple exposed critical assets were subjected to different vulnerability modifications, simulating various possible polices interventions. Then, from the simulator results, *Risk Importance Measures (RRW* and *RAW)* were used to understand the influence of assets seismic vulnerability in the Global Disruption induced in the urban system measured by the DI. From the interpretation of the results shown herein, it was possible, beyond several other conclusions, to assert that:

- Mobility (here translated by vulnerability in the Transportation sector assets) is (besides the building stock) the most responsible for restrictions in risk containment, preventing Risk Reduction even if others sectors improving are pursued. This is observed by the R^* Indicator = 19 %.
- Again, besides an intervention in the building stock, it is also possible to conclude that improving Transportation assets resilience would bring a 22 % reduction in seismic risk. This is translated by $RRW = 1.22$, for these assets.

Faial Island after the July 9, 1998 earthquake

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

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

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

	RRW_i					RAW_i					BBi				
i	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Critical Infrasctructures	1.01	1.01	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1%	2%	0%	0%	0%
Electric Facilities & Components	1.01	1.02	1.08	1.30	4.70	1.01	1.01	1.34	2.04	4.55	2%	3%	21%	31%	38%
Transportation Facilities & Components	1.01	1.02	1.22	1.03	1.13	1.01	1.02	1.78	2.07	4.63	2%	3%	47%	27%	33%
Water Supply Facilities & Components	1.01	1.02	1.09	1.30	1.00	1.01	1.01	1.35	2.04	1.00	2%	3%	21%	31%	0%
Sanitation Facilities & Components	1.01	1.02	1.08	1.30	1.00	1.01	1.01	1.35	2.05	1.00	1%	3%	21%	31%	0%
Telecoms Facilities & Components	1.00	1.00	1.00	1.01	1.04	1.01	1.01	1.39	2.18	5.01	1%	2%	20%	29%	35%
Scools	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1%	2%	0%	0%	0%
Health Care Facilities	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.36	1.00	1.00	1%	1%	18%	0%	0%
Security Facilities & Components	1.00	1.00	1.02	1.00	1.01	1.01	1.01	1.81	2.09	4.70	1%	1%	41%	27%	32%
Building Stock	1.01	1.01	1.36	1.17	1.02	1.01	1.02	1.94	3.22	4.43	2%	2%	60%	58%	30%

Fig. 18 Using QuakeIST® with *Disruption Index* and *Risk Importance Measures*

- If degradation in Security facilities is not restricted, seismic risk can be expected to increase in about 81 %, which indicates that strong attention should be put in these sector facilities. This is shown by the *RAW Indicator* = 1.81, for these facilities.

These examples, beyond many others, show that the usefulness of a seismic Simulator such as QuakeIST® goes further beyond simple damage expectations, providing an extremely versatile and multi-objective support for seismic assessment, communication and management.

4 Conclusion

An integrated earthquake scenario model requires sophisticated software support to cope with the complexity of current engineering tasks, especially when the interdependencies among systems are included. The introduction of the Disruption Index (DI) brings new quality and special interest to understand the earthquake impact in urban areas, representing an advance in the state-of-the-art over most earthquake loss-prediction models.

The UPStrat-MAFA Project (2012) used the QuakeIST® software in several pilot-areas of Italy, Portugal, Spain, and Iceland to measure risk and quantify the impacts, considering the DI concept. The pilot-areas under study were very important to calibrate several parameters of the model and to check its reliability and efficiency. The outputs provided the spatial distribution of expected damages and were important tools to support policy- and decision-making in the context of earthquake risk management, disaster mitigation, post-earthquake emergency response, and urban planning. These applications improved, in a more comprehensive way, the capacity for defining strategies to address adverse natural events.

QuakeIST® is a very versatile software in the sense that the user can change the parameters and test different assumptions about hazards, vulnerability, exposure, and the interdependency protocol. The platform architecture has been developed to be modular, extensible, and open, enabling the possibility to include various inputs and other information. Because the core software is written in C++, inputs and outputs can be transported from/to almost any GIS environment. As a short comment within this context, we should emphasize that the simulator itself is no more a problem (the computer time and size of region under analysis are compatible with the performances of a portable computer), but more accurate results are only possible if QuakeIST® is fed with “good” inventory data.

Future developments of QuakeIST® will include other modules, namely one dealing with hazard analysis and de-aggregation and another dedicated to cost-benefit analyses. Coming versions will be designed with a more friendly architecture, so that a non-expert in GIS handling can use this software (data preparation and visualization of results) in an easier way. Further expansions will include the access to “event-tree” analysis (Lee et al. 1985) and analyses of uncertainties using Monte-Carlo simulations, through risk management software such as @RISK (2014). QuakeIST® is especially oriented towards studies requiring a great deal of runs, each one with a different input parameter. The influence of attenuation laws, the soil characteristics underlying the implantation of our facilities, the form of attributing typological classes to buildings classified in Census data, the process of aggregation typologies to the centre of mass of the urban unit, the dynamics of commuting population along the day, the week, etc., are some of the analyses QuakeIST® can perform easily and process output data in a statistical sense.

In relation to DI, several analyses along the lines stated before can be pursued to study the influence of certain parameters on the overall output. In spite of all these uncertainties, DI is a step ahead of other simulators, because it can be used as a basis to define strategic indicators for risk mitigation policies (Ferreira et al. 2015) as shown in the final example presented.

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