Quantitative assessment of socio-economic performance measures accounting for seismic damage to buildings and functional interaction with infrastructural systems

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SUMMARY:
This paper presents a model to evaluate systemic performance metrics, such as casualties, fatalities and displaced population, that are of interest to emergency managers in planning response measures to an earthquake. These quantities are the necessary input to multi-criteria decision analysis models that estimate the impact on the regional health-care system and the shelter planning. The model is an integrated one, since the buildings damage state, the combined residual service level in the utility networks, as well as the weather conditions, all together play a role in the evaluation of the performance metrics. This novel feature is possible since the model is included within a larger analysis framework for the seismic vulnerability assessment of interconnected infrastructural systems, designed to account for interdependencies and for all relevant uncertainties, especially in terms of distributed seismic hazard and physical vulnerability of the systems. A simple application illustrates the model capabilities.

Keywords: displaced population, uncertainty, functional interdependence, buildings, utility loss

1. INTRODUCTION

This paper presents results of work carried out within a European collaborative research project funded by the European Commission (SYNER-G, 2011), with the overall goal of establishing an integrated methodology for systemic seismic vulnerability and risk analysis of buildings, lifelines and infrastructures. The focus of this paper is to present a quantitative assessment of social losses such as the number of casualties and displaced persons in the aftermath of a seismic event at the regional/urban scale. In evaluating the number of displaced population, the physical damage to buildings is just one of the components in a larger picture, where damage to lifelines and tolerance for utility service loss for different weather conditions are additionally considered. In particular, the methodology encompasses probabilistic modelling of distributed seismic hazard (Weatherill et al, 2012), and of the vulnerability of multiple infrastructural systems, as well as modelling of the numerous interactions occurring between components and systems. Within the overall methodology, a Multi-Criteria Decision Analysis (MCDA, Khazai et al, 2012a,b) framework is used to also account for indirect socio-economic factors that lead to an assessment of shelter needs and health impacts. However, the focus of this paper is on the first part of this methodology, i.e. on the quantitative assessment of direct social losses, which are an input to the MCDA.
The novelty of the methodology is in the distributed seismic hazard model, in the integration of multiple infrastructural systems within a consistent computational framework where the consequences of their interactions affect each and every assessed performance measure, and in the way large extents of buildings are modelled for the purpose of the systemic analysis.
Buildings are a central portion of an Infrastructure, a set of distinct man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services (PCCIP, 1997). In this sense the Infrastructure is a super-system

comprising all systems (buildings, lifelines, critical facilities, etc) and constitutes the physical layer supporting the functioning of a Society.
Systems composing the Infrastructure can be categorized according to their “geometrical” properties in:

- Point-like components: single-site facilities whose importance for the functionality of the Infrastructure makes them critical, justifying a detailed description and analysis. Examples include health-care facilities, power-plants, hazardous industrial plants;
- Line-like components: distributed systems comprising a number of vulnerable segments/edges (e.g. pipes) as well as point-like sub-systems in their nodes, and strongly characterised by their flow-transmission function. Examples include Electric Power Networks, Transportation networks, Water Supply Systems, etc;
- Area-like components: this is the category specifically intended to model large populations of residential, commercial and industrial buildings that cannot be treated individually.

This distinction translates in different descriptions of the vulnerability and the hazard to each system type. The focus of this paper is on how the area-like portion of the Infrastructure can be modelled. The framework within which this model is developed, however, is much more comprehensive and includes also the other two typologies (Franchin and Cavalieri, 2012).
The scope of the presented model can be further constrained along three dimensions, i.e. *time*, *space* and *stakeholders*. The impact of an earthquake on the Infrastructure evolves in space with the time elapsed from the event, whereas different stakeholders have different interests and play distinct roles in the various phases of the disaster. Correspondingly, they look at impact assessments according to their own particular needs and mandates. Along the time-dimension, three periods, or time-frames, of a disaster – emergency, recovery and reconstruction – can be identified. The first period constitutes the immediate aftermath of the event and its short-term consequences where the damaged Infrastructure operates in a state of emergency. In this phase, emergency managers must deal with the demand generated by damaged Infrastructure in terms of temporary shelter needs or hospitalisation and treatment of victims. In the mid-term recovery period, while the Infrastructure progressively returns to a new state of normal functionality, the disruptions to businesses might be of interest to stakeholders in the insurance sector. In the long-term reconstruction period, national governments and multi-lateral organizations have to grapple with the costs of permanently rebuilding or upgrading/retrofitting damaged infrastructure, and mitigate the risk from the next event.
Furthermore, the position on the “time axis” of the analyst/observer with respect to the time-frame changes the goal of the systemic study:

- Before the time-frame: the goal of the system analyst is to forecast the impact in order to set-up preparedness, planning and mitigation measures. It is important to underline how the information basis in this case can be considered as constant.
- Within the time-frame: the goal of the system analyst is that of providing decision-makers with a real-time decision support system, which updates the Infrastructure state based on the continuously incoming flow of information.
- After the time-frame: the goal of the system analyst is to validate through back-analysis the models against occurred events.

The developed methodology focuses on the short-term only, with Emergency managers as the reference Stakeholders, and with the goal of forecasting, before the event occurs, the expected impact in terms of dead, injured and displaced population, for the purpose of planning and implementing risk mitigation measures. In particular, these mitigation measures are selected on the basis of MCDA which requires the above impact measures as an input.
Section 2 gives an overview of the larger system vulnerability assessment framework and illustrates the building-specific aspects. Section 3 provides an example application to a hypothetical small region with three cities/towns, highlighting the important aspects of the methodology.

2. METHODOLOGY

2.1. Systemic analysis framework

Figure 1 illustrates in very general terms the methodology. The figure shows how the *Environment* induces *physical damage* to the components of the Infrastructure (utilities, critical facilities and buildings) through the *Hazards*. In the figure, physical damage to the utility networks is represented in terms of *Utility Loss*, which is a compound measure of the functional consequences (in this sense it goes beyond pure physical damage) in each network and, as shown later, accounts for all their interactions. Focusing on buildings, the figure shows explicitly how the level of induced physical damage depends also on the fragility. The latter is a function of the *Typology*, which is an information usually obtained from the building census. Direct damage determines whether the buildings are usable after the event (*Usability*, defined in §2.2). Usability is a necessary but not sufficient condition for *Habitability* of the buildings, which, depending on current *Weather* at the time of the event, is also a function of the residual service level in the utilities. Damage and habitability of buildings are the first two of the three factors entering in the evaluation of the selected social indicators of loss. *Displaced population* and *Casualties/Fatalities* are also a function of the *Occupancy* at the *Time* of the event. Occupancy in turn is a function of the *Built-up area*, the *Population* and the *Use type*. The latter information is retrieved from the relevant data bases. For instance, in Europe a harmonised source for physical data on the buildings and socio-economic data on urban areas, in the form of the Building Census (BC) and European Urban Audit (EUA), respectively, is EUROSTAT. The information on usage is usually provided in the form of a Land Use Plan, maintained from a local source (e.g., the Municipality).

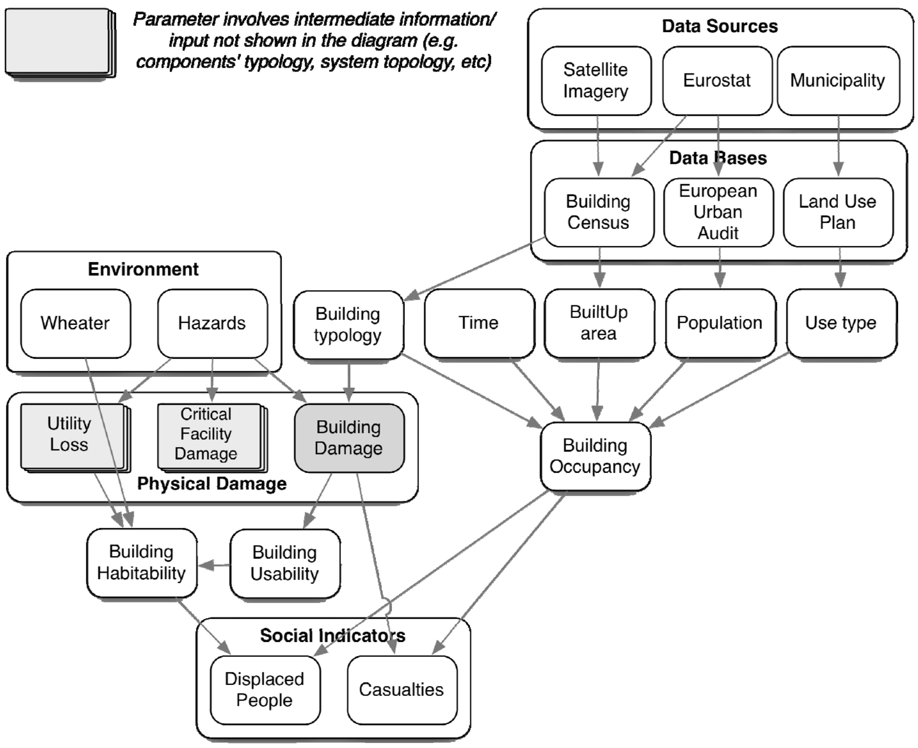

Figure 1. Integrated evaluation of physical and socio-economic performance indicators.

Evaluation of the quantities in the above scheme requires a model of both the hazard and the complex system of infrastructural systems. Such a model has been developed according to the Object-Oriented Paradigm (OOP) (Booch et al, 2007). This modelling paradigm is particularly attractive to tackle the problem at hand, since it allows emulating the behaviour of the Infrastructure as it emerges from that of the individual objects and their interaction, and the atomization of the system into its parts allows tackling gradually the complexity of the Infrastructure, and developing the model in a distributed manner. Details on the developed OO framework can be found in (Franchin and Cavalieri, 2012) and (Cavalieri et al, 2012), with a description of the classes defined to model the problem of seismic vulnerability assessment of an Infrastructure.

2.2. Model of large building groups: the "InhabitedArea" class

The very large number of buildings to be considered in a study at the urban or regional scale prevents, in all but exceptional cases, a detailed individual analysis of all buildings. Thus, the approach adopted within SYNER-G is to model buildings in "statistical terms" as groups (of size depending on the refinement of the analysis and varying from a single block – or a geo-cell – to a larger extent of the territory, comparable e.g. to a district), with information given in terms of total number of buildings and distribution by typology, with associated fragility models, and of total population, with distribution in classes of income, education, etc. The only buildings that are not modelled with this approach are those classified as Critical facilities, or those belonging to one of the Networks.

As already mentioned in §2.1, the input information is usually fragmented in several databases, such as the Building Census and the European Urban Audit, or the Land Use Plan. Hence, the first problem to be solved is that of "mesh compatibility". Each of the above sources adopts a different meshing of the urban territory, according to its own criteria. For example, in the EUA a city is subdivided into sub-city districts (SCD) which are areas sufficiently homogeneous in terms of some socio-economic indicators (e.g. income). The Land Use Plan, on the other hand, subdivides the city in homogenous areas per use type (green, industrial, commercial, residential). The approach adopted to arrive at a set of mutually exclusive and collectively exhaustive cells that cover the study region is a "raster" approach, which is most convenient from a numerical point of view. In this approach cells are defined in a multi-scale rectangular grid (see **Figure 3** top), and the intersections between these cells and the polygons from each database are used to project the corresponding data onto the cells using a simple area ratio rule.

In order to model *interactions*, each cell maintains a *link* to nodes in the other systems of the Infrastructure. In particular, each cell "knows" its reference node in each of the lifelines, i.e. the EPN substation feeding power to it or the WSS node supplying water, the RDN junction where incoming and outgoing traffic transits into the transportation system, etc. Conversely, nodes in the networks maintain a list of links to all *tributary* cells. This is an important feature of the adopted modelling strategy, since it makes the meshing refinement of each system within the Infrastructure independent of each other. For example, if a model of the RDN is set up, that has a coarser resolution with respect to the building cells, this will translate into a larger number of cells per RDN node. The accuracy of the analysis results will of course be affected by large differences in the meshing refinement. However, the approach has the advantage of allowing for different meshing, which may be the only possibility in some cases, due to the inhomogeneous quality of available data, and it is convergent upon mesh refinement.

In order to assess the *physical damage* to the built-up area, the damage state (DS) within each cell and by typology is determined by using sets of fragility curves: one set per typology, with two fragility curves each, for the "yield" and "collapse" limit-states/performance levels, respectively (delimiting three damage states: *intact* or *none*, *damaged* or *yield*, and *collapsed*). It is observed that according to this approach, all buildings of a given typology within a cell are assigned the same damage state in any given simulation run (i.e. a scenario event). This can lead, depending on the adopted mesh (cell size) for buildings, to an overestimation of the likelihood of extreme damage states (e.g. none and collapsed). However, as shown in Bal et al, this problem is important only for really coarse meshes and its influence is secondary when compared with that of the uncertainty associated with the regional hazard, when this is included in the simulation as in the case at hand. The employed fragility functions have been derived through statistical elaboration of existing models, for a given classification of buildings in Europe within the SYNER-G project (Crowley at al, 2012).

Building *usability* is derived from a simplified semi-empirical approach as a function of severity of observed damage to structural and non-structural elements of buildings. The usability model was developed based on a detailed survey of 305 buildings in the densely packed suburb of Pettino obtained from the Italian Department of Civil Protection after the 2009 L'Aquila earthquake (Elefante et al, 2011). The six usability classes considered during the survey were reduced in this model to just three: buildings which are immediately *non-usable* (*NU*), *partially usable* (*PU*) or *fully usable* (*FU*). Using the Pettino database, Usability Ratios (*UR*) for buildings were derived for each of the three usability classes as a function of the damage data, reported according to six damage states DS0 to DS5, which were also reduced to three DS only (the above mentioned none, yield, collapse). Such usability ratios allow to estimate the number of persons in each of the three building usability classes (N_{FU}, N_{PU}, N_{NU}).

Building *habitability* is different from its usability. Non-usable buildings (*NU*) are also non-habitable (*NH*). If a building is fully or partially usable, depending on the level of residual service in the utilities and the prevailing weather conditions at the time of impact, it can be habitable (*H*) or non-habitable. For each utility, the level of residual service is satisfactory when the Utility Loss (UL_i), defined as one minus the ratio of satisfied to required demand, is lower than a threshold value ($UL_i < UL_{Ti}$). The threshold values depend on Weather conditions and Building Usability and due to the subjective nature of perceptions, the Utility Loss Threshold (UL_{Ti}) should be established on a context-specific basis by the analyst. The total Utility Loss (*UL*) is a weighted average of UL_i on each of the utilities, with weights w_i provided by the analyst. The percent fully or partially usable buildings that are non-habitable (NH_{FU} or NH_{PU}) is thus determined as the portion of buildings which have utility losses greater than the total utility loss threshold value ($UL \geq UL_T$).

The total displaced population (*DP*) is finally calculated as the portion of occupants of buildings that are uninhabitable according to the following relationship:

$$DP = N_{FU} NH_{FU} + N_{PU} NH_{PU} + N_{NU} - N_d \tag{2.1}$$

where:

- N_{FU} = number of occupants in buildings that are fully usable
- N_{PU} = number of occupants in buildings that are partially usable
- N_{NU} = number of occupants in buildings that are non-usable
- NH_{FU} = percent fully usable buildings that are non-habitable, where $UL \geq UL_T$
- NH_{PU} = percent partially usable buildings that are non-habitable, where $UL \geq UL_T$
- N_d = number of dead persons estimated in the casualty model (as a function of physical damage)

An initial (direct) casualty estimate for occupants of buildings at the time of earthquake can be obtained based on an original idea developed by Coburn and Spence (1992). The casualty model employed here is one of those developed or adapted in SYNER-G, and uses the rate of death (*QD*) and rate of injury (*QI*) calibrated for the 2009 L'Aquila event by Zuccaro and Cacace (2011).

2.3. Treatment of uncertainties

Alternative approaches to the evaluation of the performance of a distributed system with uncertain input and parameters can be found in the literature. With specific reference to the case of infrastructural systems three main alternatives can be identified: simulation-based methods, usually enhanced with some variance reduction techniques, e.g. (Jayaram and Baker, 2010); the so-called matrix system reliability method (MSRM), applied, for instance, to road networks with bridges as vulnerable components in (Kang et al, 2008), which is, however, limited to connectivity problems (to the knowledge of the authors); the Bayesian network (BN) approach, presented in (Der Kiureghian, 2009) and applied again to a road network problem in (Straub et al, 2008), which, however, finds its ideal field of application in the near-real-time evaluation of an infrastructural system with a continuously varying information base due to incoming observations of its components' states (a valuable capability that comes with the requirement of a complete knowledge of all possible system states and associated probabilities beforehand, i.e. an extremely intensive simulation of the system run "off-line" to span all its possible components' states combinations.

The present work relies on simulation, certainly the more robust of the three approaches, since the system, and in particular its network component systems, is modelled in capacitive terms (which excludes the MSRM), and the simulation is used to predict future system performances, as stated in §2.1. The described model presents multiple input uncertainties. These range from those related to the regional seismic activity and the corresponding local intensity at each site, to those related to the physical damage state as a function of local intensity, to the uncertainty on the parameters (or even the form) of the fragility models employed.

Uncertainty on the seismic hazard is modelled through two models, the *event* model and the *local intensity* model. The event model starts with a continuous variable M for the event magnitude, continues with a discrete random variable Z for the active zone, with as many states as the number of seismo-genetic zones, and ends with a random variable L for the epicentre location within the active source. Distributions vary according to the adopted sampling scheme, but that of Z is conditional on the sampled value of M, and that of L is conditional on the sample zone Z.

The local intensity model is split into sub-models. Local intensity measure (IM) at the sites of vulnerable components is described with a vector of IMs that are needed as an input to the corresponding fragility model. The vector is obtained with a multi-step procedure:

- a scalar random field of a so-called "primary IM", e.g. PGA, on rock (no amplification yet) is first sampled as a function of the sampled M and L on a regular grid covering the study region, employing a ground motion prediction equation (GMPE) with inter- and intra-event error terms η and ε. In the application to follow the employed GMPE is that by Akkar and Bommer (2010). Intra-event residuals ε are modelled as a spatially correlated random field (Jayaram and Baker, 2009) by means of an exponential auto-correlation function derived for Italian events and consistently with the Akkar and Bommer GMPE in (Esposito et al, 2010). The need for sampling on a regular grid first arises to avoid singularity problems in the covariance matrix of intra-event residuals, since sites usually occur in clusters with very similar source-to-site distances.
- the primary IM is then interpolated to all sites and "secondary IMs" (all other components in the intensity vector at a site) are sampled from their distribution conditional on the primary IM value (postulating joint lognormality of the IMs, see e.g. Bazzurro and Cornell, 2002, and using inter-IM correlation values from Baker and Cornell, 2006).
- where needed, intensities are amplified based on local soil conditions, with probabilistic amplification functions (Weatherill et al 2012).
- finally, a geotechnical hazard model is used to sample geotechnical intensity measures such as e.g. peak ground displacement for those components whose fragility model requires one. Details can be found e.g. in (Franchin and Cavalieri, 2012).

Uncertainty in the physical vulnerability of components is described either by a set of lognormal fragility functions (point-like and area-like components, such as e.g. buildings), or by a Poisson repair-rate (line-like components, such as e.g. pipes). In the former case, the variable D describing physical damage state is discrete and is sampled with probability masses function of the input intensity measures. Once D is known, the functional analysis of each system can be carried out to determine its performance. At this stage physical interactions are also considered (such as, for instance, the lack of electric power at a pumping station of the water supply system).

This typical simulation run is carried out as part of either a plain Monte Carlo simulation or a more effective importance sampling scheme.

3. EXAMPLE APPLICATION

3.1. The case study area

Figure 2 shows a hypothetical region with three cities and a number of interconnected infrastructural systems. The figure shows, for each city, the different (fictional) subdivisions into Building Census Areas (BCAs), Sub-City Districts (SCDs) and Land Use Plan Areas (LUPAs). **Figure 2** also shows three seismo-genetic area sources that can generate events affecting the region, together with their corresponding activity parameters for the truncated Gutenberg-Richter recurrence law: mean annual rate of all events in the source λ_0, magnitude slope β, and lower and upper magnitude limits M_L and M_U (values taken from real sources in the central Appenine region in Italy).

Given the illustrative character of the application several simplifications have been made: 1) only the electric power network (EPN) and the water supply system (WSS) are included, in order to evaluate

Utility Loss. Details on the topology, properties and seismic damageability of these two utilities can be found in (Franchin and Cavalieri, 2012); 2) buildings in each city belong to two typologies only, namely unreinforced masonry (URM) and older reinforced concrete (RC) buildings, which are taken as representative of pre-WWII and post-WWII constructions in the area. A much larger and quite comprehensive taxonomy of buildings for Europe has been produced within SYNER-G project (Crowley et al, 2011). Fragility curves are lognormal, in terms of PGA, with parameters: URM, $\mu_{\log} = -2.041$ and $\sigma_{\log} = 0.574$ for yield, and $\mu_{\log} = -1.269$ and $\sigma_{\log} = 0.550$ for collapse; RC, $\mu_{\log} = -1.832$ and $\sigma_{\log} = 0.474$ for yield, and $\mu_{\log} = -1.091$ and $\sigma_{\log} = 0.485$ for collapse.

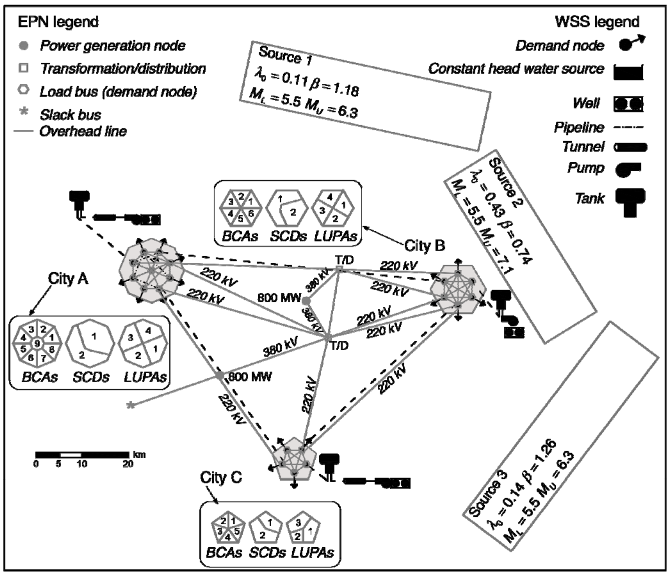

Figure 2. The hypothetical study area.

3.2. Simulation results

Figure 3, top, shows the discretisation of the study region into a multi-scale rectangular grid, used to model buildings. The developed OO software automatically discretises the study region, starting with a user defined cell size and refining the mesh locally whenever a cell intersects an urban polygon (either a SCD, a LUPA or a BCA), up to a user defined number of times. Since the grid is multi-scale, it is possible to accurately project the building data from the different databases and to closely follow the city boundaries. As already mentioned, the use of coarse meshes may lead to erroneous estimation of damage and hence losses, since the same damage state is attributed to all buildings of each typology within the same cell and the intensity predicted is that at the cell centroid, rather than an average value over the cell. As shown in (Bal et al, 2010), however, this problem is important only for really coarse meshes (cell of the size of entire districts, while already at the post-code level it is acceptable) and becomes of secondary importance when compared with the uncertainty associated with hazard within a simulation in which the entire regional seismicity is modelled, as in the case at hand.

The quantity represented by different shades of grey is the predicted displaced population (computed for *good* weather conditions) in each cell, for a single simulation run (an event of magnitude 7 on source 2, with epicentre located close to City B). Cells with non-zero (i.e. non white) values of displaced people have suffered building physical damage and/or reduction of service from utilities. As expected, the number of displaced people is higher in City B than in cities A and C (maps of physical damage per building typology for the same scenario can be found in Cavalieri et al, 2012).

With the aim of highlighting the influence of weather conditions and utility loss on the number of displaced people, **Figure 3**, bottom, shows a close-up on City B, with raster maps of displaced population computed for good and bad weather conditions in relation to having utility loss in each case. In the maps, darker colours mean higher numbers of displaced people. It is noted that the maps for the case of no utility loss (UL = 0) for all cells are identical for the two weather conditions, since they are not affected by the difference on thresholds. On the other hand, the maps for the case of utility loss present are significantly different, indicating the great influence of weather conditions on the number of displaced people. It can also be noted the important role played by the presence of utility loss (i.e. by the damage on utility networks) in increasing the displaced people, especially for bad weather conditions.

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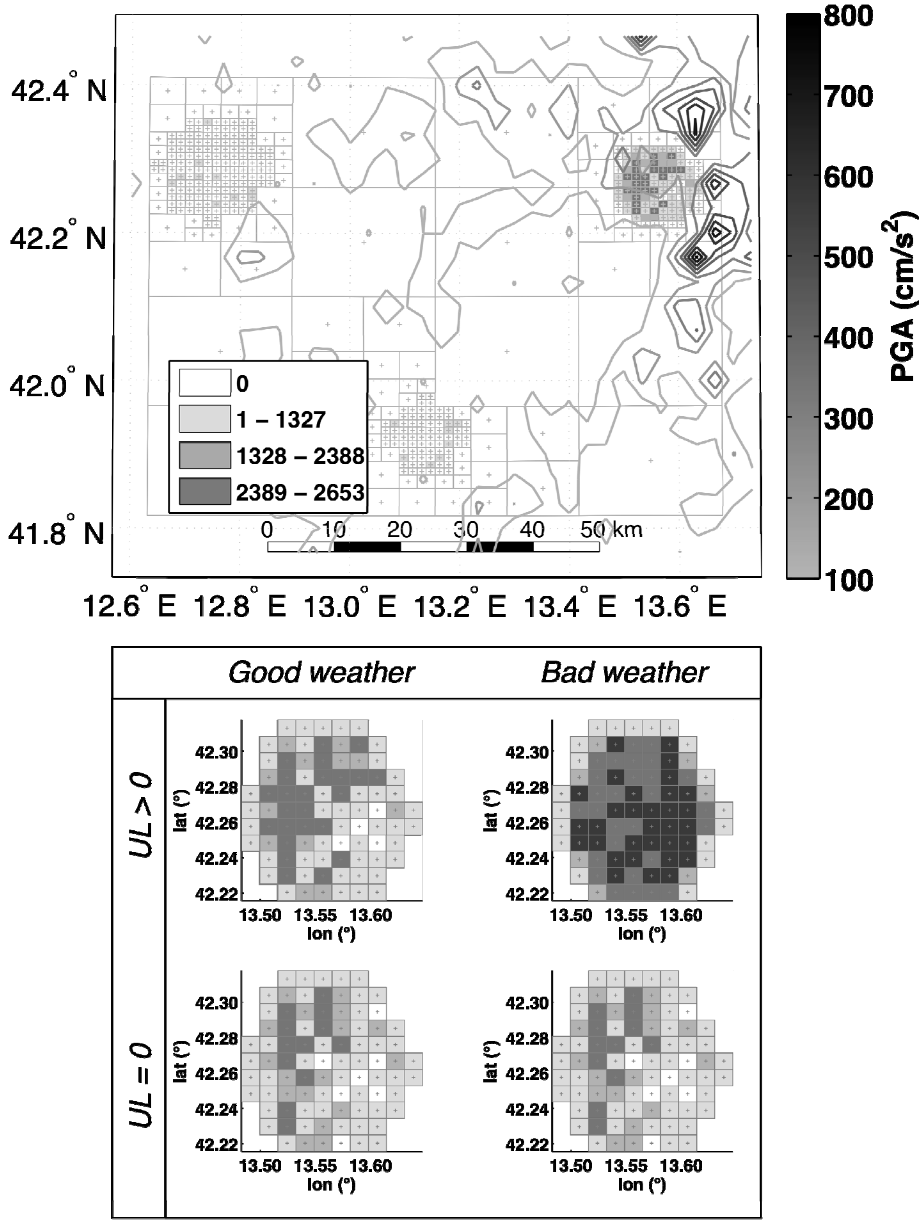

Figure 3. Displaced population in the study area (top) and close-up on City B (bottom, same color code as above with the darkest color not present in the top plot) for good/bad weather and utility loss present/not present, for one simulation run (a single scenario event with magnitude 7 on source 2).

Figure 4 presents summary results from the whole simulation, a plain Monte Carlo simulation with 10,000 runs. In particular, Mean Annual Frequency (MAF) of exceedance curves are shown for some performance metrics of interest. Plot (a) refers to fatalities, normalised to city population, with MAF for each city clearly reflecting the difference in distance from the sources. Notice how all curves present a smooth behaviour. This is not the case for the MAFs of displaced population, shown in plot (b). Similarly to the previous plot, rates are given by city and in terms of the ratio of displaced to total population. All cities, but in particular cities A and C, present a sharp transition close to the 100% value. This is due to the fact that displaced population is influenced by utility loss and for this simple

example the EPN is either fully functional or completely non-functional. In the latter case, independently of direct damage, buildings, even usable ones, become non habitable and occupants are forced to evacuate. This is more apparent in cities A and C where direct physical damage is less likely due to the larger distance from the seismo-genetic sources.
To gain further insight into this effect of interdependencies captured by the model, plot (d) shows the MAF of normalised displaced population for the most affected City B under different modelling assumptions. The solid curve is the same shown in plot (b), i.e. the case where utility loss is considered, and the lifelines are dependent (WSS on EPN, to highlight this effect all three cities have water sources that consist of a well-field and an EPN dependent pumping station). The dashed line shows what would happen if *UL* was still considered in evaluating habitability, but the WSS-EPN interaction was disregarded: the MAF would consistently decrease, and the sharp knee in plot (b) would be attenuated, since EPN-induced failure of the pumps was removed. This is clearly shown in plot (c) where the MAF of the WSS System Serviceability Index (*SSI*) is shown in the two cases. The knee in the displaced people MAF would completely disappear and the curve would more closely follow the trend of the fatalities MAF in plot (a) if displaced people were computed based only on direct physical damage (the 'no lifelines' case).

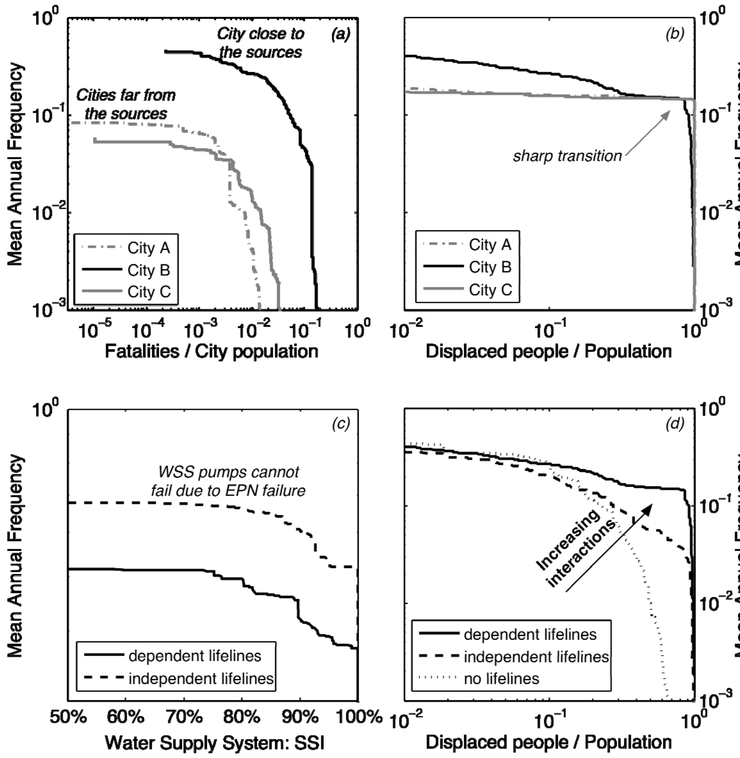

Figure 4. Whole simulation results (10,000 MCS runs). MAF of exceedance curves of (a) fatalities and (b) displaced population, as a ratio of total population, by city; different MAF of exceedance obtained considering various levels of interaction for (c) *SSI* and (d) normalised displaced population (curves refer to City B).

4. CONCLUSIONS

A model is presented for evaluating performance indicators of interest in planning the emergency response to an earthquake. Its output is the number of casualties, fatalities and displaced population. These quantities are input parameters into MCDA models for the impact on the regional health-care system and the shelter planning, which are not addressed within the scope of this paper. The model is intended for use by emergency managers at the forecasting stage and is integrated within a larger analysis framework for the seismic vulnerability assessment of interconnected infrastructural systems, accounting for relevant uncertainties and interdependencies. Thus, estimates of the output quantities reflect the uncertainty affecting all other components in the Infrastructure, as well as their interactions.

The main feature of the presented model is to account for the effect of physical damage to systems other than buildings (utilities) in determining buildings-related quantities such as displaced population. Large groups of buildings are modelled with a multi-scale grid of geo-cells that covers the study region, with each cell being automatically linked to nodes in all other infrastructural systems for the purpose of demand, utility loss, and accessibility evaluation. The adopted meshing solution has the advantage of making it possible to integrate different meshing criteria (refinement) for each infrastructural system and solves the problem of mesh compatibility among different databases.

ACKNOWLEDGEMENT
This work has been carried out within the EU-funded research program SYNER-G, grant n° 244061. Authors gratefully acknowledge the support from project partners G. Weatherill, H. Crowley, I. Iervolino, S. Esposito, L. Elefante, P.E. Pinto, A. Lupoi and I. Vanzi.

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