Probabilistic seismic assessment of health-care systems at regional scale

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SUMMARY
This paper presents a model to estimate the impact of an earthquake on the regional health-care system and to evaluate its capability to cope with the demand of medical care arising from a seismic event. The probabilistic methodology recently developed for the seismic assessment of a single hospital facility (Lupoi *et al.*, 2008), whose performance is measured in terms of the number of functioning operating theatres and of beds available, is integrated in this work within a larger analysis framework for the seismic vulnerability assessment of interconnected infrastructural systems, designed to account for interdependencies between transportation, utility networks and the buildings hit by a seismic event, as well as for all relevant uncertainties, especially in terms of distributed seismic hazard and physical vulnerability of the systems. The proposed model is applied to a sample infrastructure, made up of a regional health-care system and a road network.

Keywords: hospital, road network, probabilistic assessment, uncertainty, seismic risk

1. INTRODUCTION

When a major earthquake occurs, the victims distributed over the area struck by the quake need to be transferred in one of the hospitals within the region. It is well known that the mortality rate of casualties is substantially reduced if they receive care in a short time.
This study presents the probabilistic seismic assessment of a health-care systems at regional scale. Hospitals play a key role in coping with the emergency. They are, typically, highly vulnerable facilities due to age of construction, types of equipment, occupancy rate, services provided, etc.. The seismic assessment of hospitals has been studied in detail in (Lupoi *et al.*, 2008), modelling them as a system made of sub-components.
The response of a regional health-care system is however function not only of the hospitals performance but also of other factors, among which the response of the road network is of primary importance. The road network serves the purpose of connecting the hospitals in a regional health-care system: damages to the network may cause an increase in the distance to be covered because of interrupted links as well as a decrease in the transportation speed. Therefore, in the present study the road network is explicitly modelled and damages in vulnerable elements are evaluated and accounted for.
The large uncertainties affecting this complex problem require the use of a probabilistic approach. The variability due to the seismic hazard, to the response of the vulnerable components of the system and to the number of victims is accounted for.
With respect to the time-frame of a disaster (emergency, recovery, reconstruction), this study focuses on the short-term, emergency period after the seismic event (24/48 hours). The main goal is to forecast the expected impact in terms of: a) victims that cannot be hospitalised; b) hospitals that cannot provide medical care to the victims; c) city/villages that are not served by a functioning hospital within a "reasonable" distance. An example application to a hypothetical small region with eight towns and three hospitals, highlighting the important aspects of the methodology, is presented.
The Emergency managers (e.g. Civil Protection), the Hospital managers as well all the Authorities in charge of future planning are the reference stakeholders which should be interested in the results of

this study. The proposed methodology may also serve as a tool for planning risk mitigation measures, by considering alternative strategies (new hospitals, field hospitals, retrofitting bridges, etc.) and comparing the corresponding performances of the upgraded system. Along the lines of the proposed study, example applications can also be found in Nuti and Vanzi (1998) and in Franchin *et al.* (2006); an application to a different system can be found in (Cavalieri *et al.*, 2012).

2. METHODOLOGY

2.1 Components and functioning of the system

The system under evaluation is composed of hospitals, area districts and a road network. The seismic event has both direct and indirect consequences on each component of the system. The response of the system depends not only on the performance of each component but also on their mutual interactions. The identification and the evaluation of interactions is a difficult task, which unavoidably involves a number of assumptions and simplifications.

The consequence on a hospital facility is a reduction of the available medical services; this is due not only to physical damages to the building, but also by the performance of non-structural elements, by the response of the staff and by the effectiveness of the emergency procedure (e.g. understaffed medical personnel, lack of adequate emergency procedures, etc.).

Damages to the road network, and in particular to bridges, are also included. They affect the capability of transportation of the victims to hospitals, both by a reduction of the travel speed and by the closure to traffic of the collapsed bridges.

The number of victims is evaluated on the basis of demographic data by means of casualty models. Victims are evaluated per area districts, whose spatial extension may vary from a small neighbourhood to a whole town depending on the scale of the study and in the detail of the available information. Victims are classified according to the severity of their condition. Among the “severely injured” victims that need hospitalisation, two classes are identified: those that need a surgical treatment, which form the *Hospital Treatment Demand* (*HTD*), and those that need a medical care and a bed. Victims that need to be hospitalised are transferred from the origin area districts to a hospital located in the region of study. The analysis is concluded either when all the patients are hospitalised or when all the hospitals in the region are saturated.

The system performance indicators are: a) the number of severely injured patients that will not be able to receive a surgical treatment or a bed (expressed in terms of mean annual frequency of exceedance or return period); b) the maximum travel time for hospitalisation; c) the risk that hospitals are not capable of providing the required surgical treatment (*HTC*/*HTD*) if an earthquake in the region occurs; d) the hospitalising rate and travel time disaggregated per area districts. The fist two indicators measure the resilience of the regional hospitals network; the third indicator measures the adequateness of each hospital of the region to cope with the seismic emergency; the last indicators provide an indication of the quality of the medical services under emergency condition for each area district. The comparison of the hospitalisation travel time for different seismic retrofit/upgrade scenarios with the baseline distribution may give useful indications for the allocation of resources.

The components of the system and the “hospitalisation” model developed for this study are described in some more detail in the following sections.

The system described above can be viewed as a part of the general framework developed in (Franchin and Cavalieri, 2012), where an integrated approach for the assessment of the systemic seismic vulnerability and risk analysis of buildings, lifelines and infrastructures is developed.

2.2. Hospital Facility and Treatment Capacity

This section presents a brief summary of the probabilistic procedure for the seismic assessment of a single hospital facility, developed in (Lupoi *at al.* 2008) and employed in the present study.

The hospital is described as a system made of three vulnerable components: *human*, *organisational*, *physical*. These components, of different nature, jointly contribute to provide an output: the *medical services*, which are standardised procedures established to guarantee an adequate treatment of patients.

The physical component is the facility where the medical services are delivered. It is made of

structural elements and *non-structural elements* (architectural elements, basic contents and equipment). While the former are critical to preserve the life-safety of the building occupants, the latter are fundamental to preserve the hospital functionality. The human component is the hospital staff: doctors, nurses and in general whoever plays an active role in providing medical care. The organisational component is the set of standardised procedures established to ensure that medical services are delivered under adequate conditions.
The performance of the hospital results from the contribution of each component and their mutual interactions, which have to be appropriately accounted for. From the consideration that the basic function of a hospital is accommodating the incoming flow of patients requiring hospitalisation, a functional analysis in emergency condition has been carried out and the following major conclusions derived:

1. The sub-set of medical services that have to remain operative after the seismic event in order to guarantee the adequate treatment of patients and victims, classified as *essential* medical services;
2. The system performance con be expressed by *the number of patients with serious injuries that the hospital can treat in one hour*, i.e. the hospital treatment capacity (*HTC*)
3. The *HTC* index can be quantitatively measured by the number of functioning operating theatres, which represent the bottleneck of the health-care system after a mass-casualty event that produces trauma victims;
4. The influence of the organisational and human components on the *HTC* can be estimated only empirically on the basis of experts judgement;
5. The relationship between the damage state of the physical component and the *HTC* is (analytically) evaluated by means of engineering-based methods.

The expression for the *HTC* index is:

$$HTC = \alpha \cdot \beta \cdot \frac{\gamma_1 \cdot \gamma_2}{t_m} \tag{2.1}$$

where α accounts for the efficiency of the emergency plan (organizational component), β accounts for the quality, training and preparation of the operators (human component), γ_1 is the number of operating theatres which remain operative after the hazardous event, t_m is the mean duration of a surgical operation (measured in hours). The factor γ_2 is a Boolean function equal to 1 if the system "survives" and to 0 otherwise, with the survival condition defined as:

a) the *operational performance level* is met (after the seismic event) for the area where the *essential* medical services are located;
b) the *safeguard of human life performance level* is met for all the other areas of the hospital, where the medical services other than the *essential* ones are provided.

Condition a) depends on the response of both structural and non-structural elements, while condition b) depends on the response of structural elements only.

The vulnerability analysis of a hospital consists of the following actions:

- Verifying that the hospital is provided of all the *essential* medical services, identifying their location in plan, defining the appropriate performance level for each area of the facility.
- Assessing the quality of the emergency plan to provide, by expert judgement, an estimate of the coefficient α in Eqn. (2.1).
- Verifying the existence of adequate resources and assessing the *skill* and the *availability* of operators to put in practice the emergency plan. This results in assigning, by expert judgement, a value to the β factor in (Eqn. 2.1).
- Building up the fault-tree of the physical component to establish the relationship between the state of the vulnerable elements and the state of the system. The sub-systems fault-trees have to be appropriately "assembled" to build up the "system" fault-tree of the whole physical component. A generic fault-tree based on the distinction between essential and basic medical services is illustrated in **Figure 1**. Since the fault-tree is hospital-dependent, it has to be customised on a case-by-case basis.
- Deriving the fragility curve for the *HTC* index, i.e. the relationship between the number of functioning operating theatres and the intensity of the ground motion. The techniques for

deriving system-specific fragilities are based on detailed structural analyses (Lupoi *et al.*, 2008), (Pinto *et al.*, 2004). The employment of a probabilistic approach is an almost inevitable choice due to the large uncertainties characterising most of the quantities that contribute to the system response. The relationship between structural response quantities and the ground motion intensity measure is derived by means of a reduced number of numerical analyses; the fragility curve is then evaluated by standard simulation techniques, e.g. Monte Carlo: if the system survives (γ_2 = 1), the hospital resources are measured in terms of the functioning operating theatres γ_1. A detailed description of the procedure is illustrated in (Lupoi *et al.*, 2008).

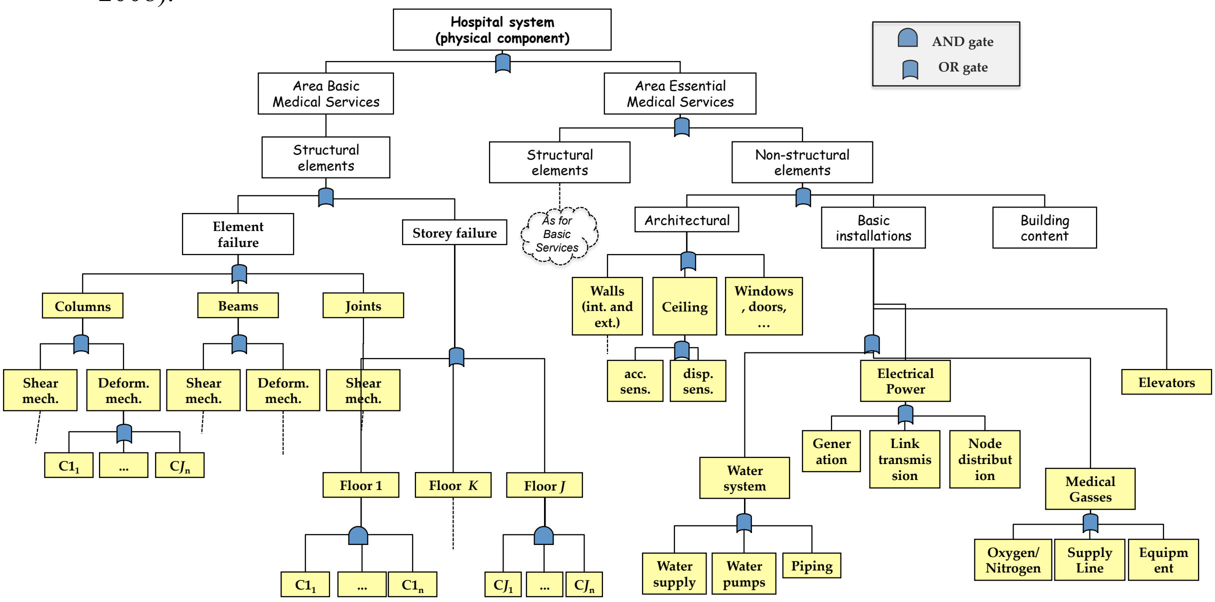

Figure 1. Example of a fault-tree for the physical component of a hospital.

2.3. Casualty model and Hospital Treatment Demand

The number of casualties due to an earthquake event and of those who need a surgical treatment are estimated combining epidemiological studies and casualty models.
In current medical practice, a patient's condition is classified by a colour tag according to the *triage* scheme: red tag for patients who require immediate care, yellow tag for those who require delayed care, green tag for those who need minimal care, black and blue tags for the deaths or for those who are not expected to survive despite any treatment.
Casualty models provide estimates of the "severely injured" people (i.e. those requiring to be hospitalised) and of the deaths: red-tag, yellow-tag and black/blue-tag patients. The lightly injured people (green-tagged) are ignored. The casualties expressed as percentage of the population can be evaluated by the expression (Coburn and Spence (1992) as simplified by Nuti and Vanzi (1998)):

$$C(I) = k\cdot (I - I_{min})^4 \tag{2.2}$$

where I is the intensity measure of the seismic event, k and $I_{\min}$ are the model parameters which take into account both the vulnerability of the building stock and the occupancy rate. The model parameters have to be calibrated as function of the environmental conditions; the extent of damages to buildings has to be estimated by means of appropriate vulnerability functions.
The number of the victims, N_{r+y+bb}, is given by:

$$N_{r+y+bb} = C(I) \cdot \varepsilon_{cas} \cdot N_{pop} \tag{2.3}$$

where N_{pop} is the population in the area affected by the earthquake and ε_{cas} is an error term, having lognormal distribution, unit median and coefficient of variation equal to 0.3, introduced to account for the large uncertainty which affects the casualty model.

The *Hospital Treatment Demand*, *HTD*, defined above as the number of people that require a surgical treatment, is a sub-set of the red-tag and yellow-tag patients:

$$HTD = \zeta \cdot N_{r+y} \tag{2.4}$$

with N_{r+y} the number of red-tag plus yellow-tag patients and ζ a factor whose value is typically in the range between 1/3 and 1/2. The actual value has to be defined on a case-by-case basis by expert opinion. The proportion of "severely" injured people over all casualties is derived form epidemiological studies, which assess the "medical severity" of a hazardous event by two *severity* indexes: $S_1 = T_{bb} / (T_r + T_y + T_g)$ and $S_2 = (T_r + T_y) / T_g$, where T_r is the percentage of red-tag patients, T_y the percentage of yellow-tag patients and so on. The index S_1 gives an indication of overall severity of the event (deaths over injured), while the index S_2 measures the severity of the injuries caused by the event (seriously injured over lightly injured). Data from past earthquakes have shown that the value of S_1 is comprised between 0.1 and 0.5, while the one of S_2 between 0.15 and 0.6.
The estimate of N_{r+y} is obtained combining N_{r+y+bb}, from Eqn. (2.3), with the expression of the severity indices S_1 and S_2. After some manipulations: $N_{r+y} = [\ S_2 / (S_1 + S_1\ S_2 + S_2)\ ] \cdot N_{\mathrm{r+y+bb}}$.
The final expression for *HTD* is:

$$HTD = \zeta \cdot [\ S_2 / (S_1 + S_1\ S_2 + S_2)\ ] \cdot C(I) \cdot \varepsilon_{cas} \cdot N_{pop} \tag{2.5}$$

2.4. Road Network

In this study the function of the Road Network is to allow the transportation of the injured to hospitals. The analysis is carried out in terms of *pure connectivity*, i.e. the traffic flows are not modelled. This is coherent with the time-frame of the study, limited to rescue operations in the aftermath of the seismic event. The interest is the identification of the portions of the network critical with respect to the continued connectivity of the network: damages to the vulnerable elements of the road network are evaluated and accounted for.
This approach requires a simple description of the network in terms of a graph; analysis tools are limited to basic graph theory results. The road network is represented as a graph consisting of n nodes or vertices, connected by n_a arcs, or links or edges. The relationship between nodes and arcs is described by the adjacency matrix $\boldsymbol{B} = [b_{ij}]$, which is a n x n Boolean square matrix, whose terms are either 0, when no connection exists between nodes i and j, or 1 when a connection exists.
The graph is directed (also known as digraph), which means that the existence of a link from nodes i to j does not imply the presence of a link between nodes j and i (e.g. some roads are one-way only); as a consequence, the adjacency matrix is not symmetric. When for every directed arc the opposite one exists, the graph is said to be symmetric, or non-directed or simply a graph. Two different types of connectivity are involved: strong and weak. The latter does not consider the edges directions, actually treating the network as non-directed. Of course, for non-directed graphs only the weak connectivity can be considered. In general, a graph is composed of one or more (strongly or weakly) connected components (i.e. groups of connected nodes).
Given a graph, a finite or infinite sequence of links such that the origin node of each arc coincides with the destination node of the previous one is called a path P. The order of the path is the number n_p of links making up the path. A free-flow travel speed is assigned to each arch of the graph.

2.5. Transportation and Medical Treatment Model of the victims

Transportation is assumed to take place by private vehicles on the damaged road network. The selection of the hospital, made by users, is affected by both objective constraints and subjective choices. The closure of a road represents one of the former; the user "familiarity" with a specific facility is one of the latter. This section briefly addresses the proposed model for the transportation of casualties to the hospitals of the region of interest.
In Section 2.3 an expression has been derived for *HTD*, considered as a fraction of red-tag plus yellow-tag casualties. The complementary portion of casualties with respect to N_{r+y} is made up of the

injured (called $\overline{HTD}$ in the following) that do not need a surgical treatment, but only a bed for medical care.

The implemented algorithm is iterative, since patients arrived at a hospital might not receive medical care if such hospital is severely damaged (not operative, $\gamma_2 = 0$) or has its capacity saturated, either in terms of available beds or of number of functioning operating theatres (*HTC*).

At the beginning of the first iteration, the availability of all the region hospitals is checked, both for $\overline{HTD}$ (by counting the number of available beds) and for *HTD* (verifying that the *HTC* of the damaged hospitals is greater than zero). Unavailable facilities are excluded. Then, the estimated victims of all area districts (or *Traffic Analysis Zones*, TAZs) are moved to the hospital closest, in terms of minimum travel time computed on the damaged road network, from their area district. Once they reach their "first-choice" hospital, they are allocated based on their arrival time, i.e. following the "first-come, first-served" criterion. If the hospital capacity is reached, separately for the two types of victims, the not-allocated casualties are forced to move to the next closest hospital facility. The second and subsequent iterations are similar to the first one; the only difference stands in the fact that casualties are moved only between hospitals, since all of them left their origin area districts. The analysis is concluded either when all the casualties are hospitalised or when all the functioning hospitals in the region are saturated (all available beds are used or $HTC \leq HTD$, depending on the type of casualties).

In this model a possible choice could be to assume that the injured victims that do not need surgical treatment, i.e. $\overline{HTD}$, can always receive medical assistance at the first operative hospital which they reach. This is coherent with the emergence procedures activated in the case of a natural disaster, where the number of medical treatments may be doubled with respect to standard, "every-day" condition (eventually by field hospitals). In the computation of the travel time to reach the hospital, an unreduced free-flow speed is assumed for highways, while a 50% reduction in speed is considered for the urban portions of the road network in order to account for the potential damage to buildings (and hence road blockage) and other possible random events.

3. TREATMENT OF UNCERTAINTIES

The probabilistic assessment of the regional health-care system is carried out employing a standard simulation-based method. This approach is characterised by robustness; the computational efficiency may be enhanced by means of a number of variance reduction techniques, e.g. (Jayaram and Baker, 2010).

The described system 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 (Franchin and Cavalieri, 2012). 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.

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. 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.
Uncertainty in the physical vulnerability of components is described by a set of lognormal fragility functions. The physical damage state of all components, D, is sampled as a 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, detour to reach hospitals from area districts due to the closure of damaged portions of roads).
The basic random variables typically involved in the derivation of fragility curves are the strength of materials, the amount of reinforcement in RC structures, the capacity models for structural and non-structural elements, etc. The derivation of fragility curves for the system components is out of the scope of the present study. The uncertainty in the estimation of the victims is described in section 2.3.
This typical simulation run is carried out as part of either a plain Monte Carlo simulation or a more effective importance sampling scheme.

4. EXAMPLE APPLICATION

4.1. The case study area

A hypothetical region with an infrastructure (system of systems) composed of a road network (RDN) and a health care system (HCS) is shown in **Figure 2**. The architecture of the RDN has been taken from the application example in Kang *et al.* (2008). Then, some modifications and additions have been made in this work to form an infrastructure that is subjected to a distributed seismic hazard and in which the RDN/HCS interaction is taken into account.
Given the illustrative character of the application, several simplifications are made. The transportation network connects eight towns by highways with twelve bridges. It is studied with a pure connectivity approach, i.e. no traffic flows are computed in the damaged network. For simplicity, it is assumed that no other roads aside from the highways exist between cities and that the bridges are the only vulnerable components, whose earthquake induced damage may cause paths to be disconnected.
As shown in **Figure 3**, left, two bridge types are considered, single-bent and two-bent overpasses. Since only network connectivity is analysed, only one fragility curve is assigned to each type, expressing the conditional probability of attaining or exceeding the collapse limit state for a given value of PGA. In other words, a bridge is assumed to be in one of the two following states: collapse/survival.
The eight towns have populations ranging from 8,000 to 20,000 inhabitants, for a regional population equal to 105,000. Such towns are considered as traffic analysis zones (TAZs), whose centroids are taken as the RDN nodes. The HCS comprises three hospitals, located in towns [1,5,8] and having a total number of beds, a number of beds already occupied in the pre-seismic conditions and a number of available beds (see **Table 1**).

Table 1. Number of beds and surgical treatments per day, for the three hospitals in the region.

Hospital # / TAZ #	# total beds	# occupied beds	# available beds	# surgical treatments per day
1 / 1	300	210	90	77
2 / 5	400	320	80	77
3 / 8	350	290	60	77

All hospitals are also characterised by a health treatment capacity, HTC, considered here as the number of surgical treatments per day, since it is assumed that casualties are allocated in hospitals within one day. The employed HTC curves, shown in **Figure 3** (right), have been derived for the real case of an existing facility located in Lamezia Terme (Italy) (Lupoi *et al.*, 2008). The hospital fault-tree is shown in **Figure 1**; uncertainties in both structural and non-structural elements have been accounted. The factors α and β in Eqn. (2.1) have been taken equal to 1 and 0.8, respectively, while the mean duration of a surgical treatment has been assumed equal to t_m = 2 hours. The mean and

standard deviation of the *HTC* index have been evaluated conditional on *PGA* by means of a Monte Carlo simulation. The mean and mean minus/plus one std curves are assigned for this example to hospitals located in TAZs 1, 5 and 8, respectively: such curves allow to compute the damaged or residual (post-seismic conditions) *HTC* for a given value of *PGA*.
The casualty model parameters k and I_{min} in Eqn. (2.2) have been set to 0.01 and 5, respectively; the severity indexes S_1 and S_2 in Eqn. (2.5) are taken equal to 0.154 and 0.625, respectively (FEMA, 1999).
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, magnitude slope β, and lower and upper magnitude limits M_L and M_U.

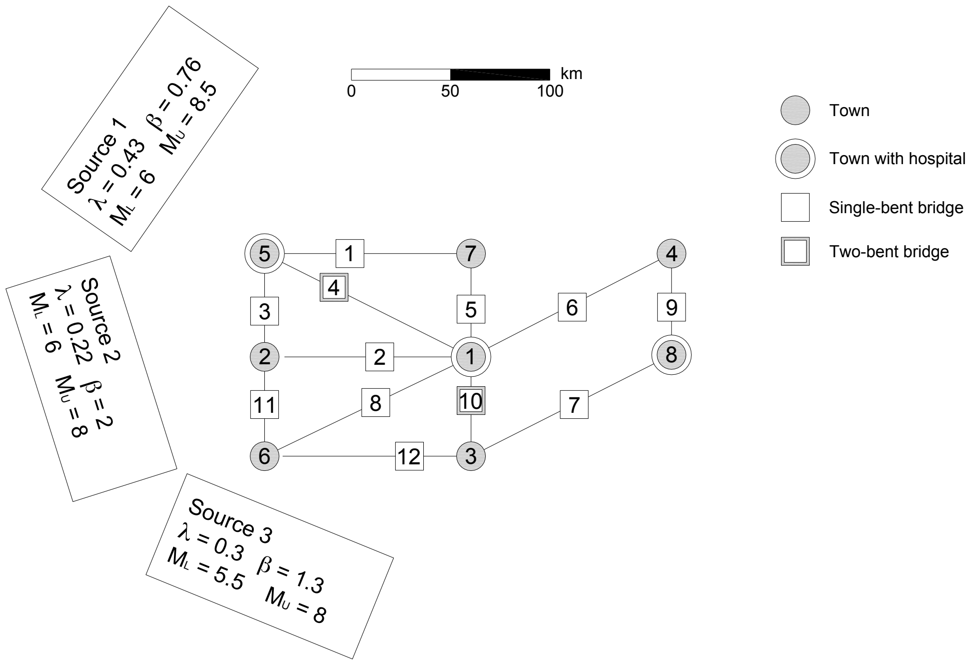

Figure 2. The hypothetical study area.

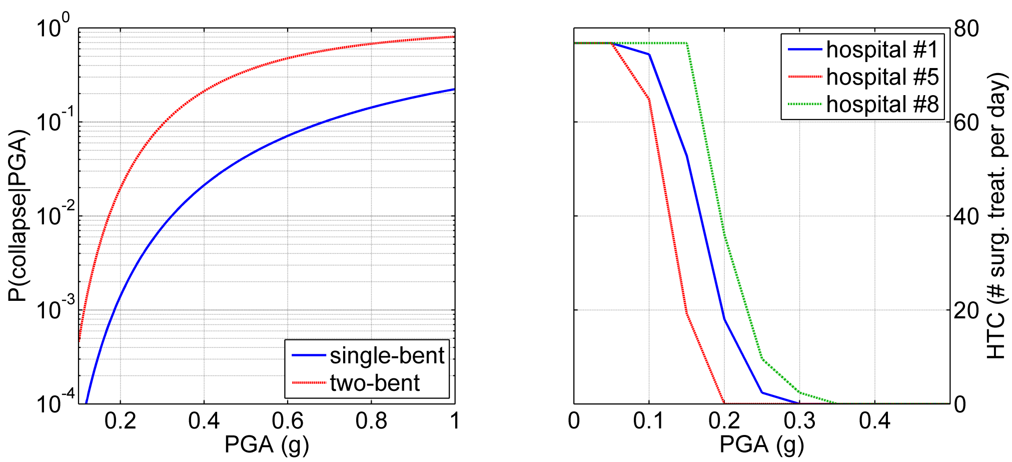

Figure 3. Employed fragility curves for bridge typologies (left) and *HTC* curves for hospitals (right).

4.2. Simulation results

A plain Monte Carlo simulation with 10,000 runs is carried out to test the proposed methodology. The

expected value of the total number of casualties, N_{r+y}, over the 10,000 runs is equal to 75 (0.07% of the regional population); among those, the expected *HTD* are 52, while the $\overline{HTD}$ are 23. Please note that these figures do not include deaths (blue and black tag) and lightly injured people (green tag).
The first indicator to measure the resilience of the regional health-care system is the number of victims that cannot receive the medical care. This is expressed in terms of Mean Annual Frequency (MAF) of exceedance (or, equivalently, of return period of the event which causes the exceeding of un-hospitalised victims). The corresponding curves for the *HTD* and $\overline{HTD}$, normalised to the regional population, are shown in **Figure 4**. For example, the return period of the event with the 0.1% of the regional population that cannot receive the (needed) surgical treatment (red curve) is 100 years.

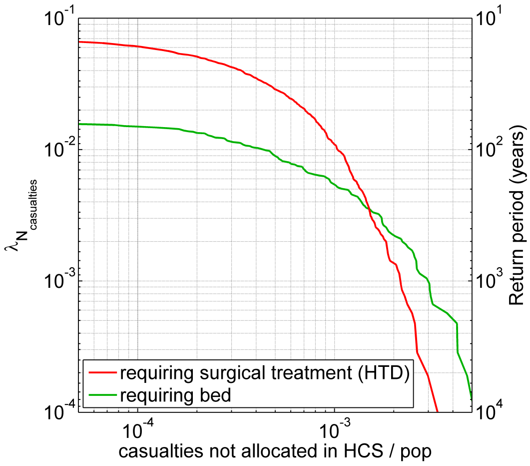

Figure 4. MAF curves of normalised casualties (divided in two categories) that are not allocated in hospitals.

A second indicator is the maximum hospitalisation travel time. The moving average μ and moving standard deviation σ are computed at each simulation run. Corresponding curves of μ and $\mu \pm \sigma$ are shown in **Figure 5**. For the investigated system, the expectation of the maximum hospitalisation time is 36 min. The mean of the indicator becomes stable after about 1,000 runs, and this justifies the adopted number of runs.
The resilience of the hospitals in the region is expressed by the probability of not being able to provide the required surgical treatments to victims if an earthquake strikes the region (i.e. the *seismic risk*), as shown by the bar plot in **Figure 6**. The results are in agreement with the treatment capacity curves employed for hospitals and the assumed configuration of the study area, where the seismic sources are located in the western part. In fact, the distribution of the seismic risk reflects both the source to hospital-site distance (hospital in TAZ #5 is the closest) and the assumed vulnerability of the facilities in terms of *HTC* fragility curves (hospital in TAZ #5 has the lowest treatment capacity).

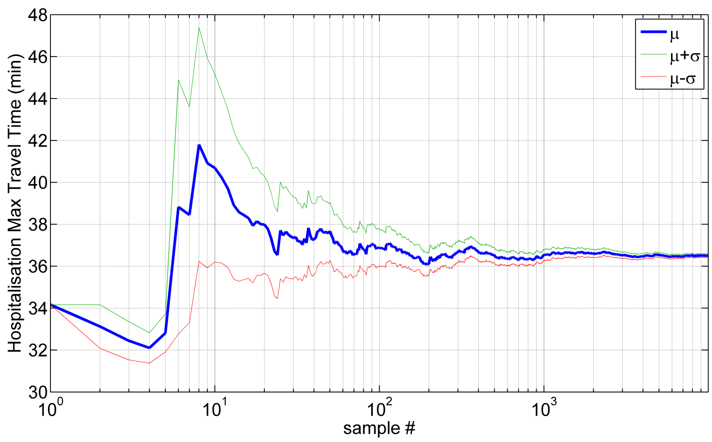

Figure 5. Evolution of maximum travel time for hospitalisation.

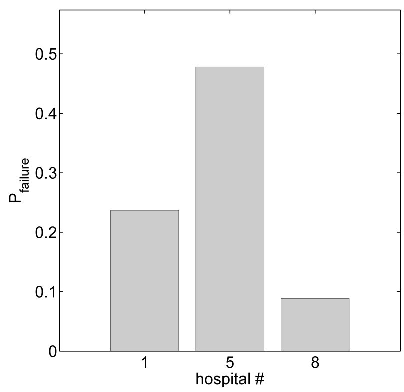

Figure 6. P($HTD \geq HTC$), for the three region hospitals.

5. CONCLUSIONS

A methodology for the seismic assessment of a regional health-care system is presented in this study. The system is composed of hospitals, area districts and road network. The road network is deputed to connect districts and hospitals allowing the transportation of injured and sick people. To properly assess the response of the system, the vulnerability of the system components, i.e. hospitals and roads, as well as the interaction among them are accounted for. This represents a novelty of the proposed methodology with respect to common applications.

A probabilistic approach has been employed to model the large uncertainties that affect the problem. In particular, the hospitals capacity and bridges physical damage are represented by fragility curves. Uncertainties in the evaluation of the casualties are also introduced. A model for the hospitalisation of the victims has been developed and implemented.

The capabilities of the proposed methodology have been tested by means of an example application to a hypothetical region. A Monte Carlo simulation has been carried out to analyse the system. Results are expressed in terms of un-hospitalised victims annual exceedance rate, hospitalisation travel time and hospitals seismic risk. The information may be useful for emergency managers and for authorities in planning the emergency operations and in developing mitigation strategies.

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