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Scenario-based seismic performance assessment of a Chilean hospital

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ABSTRACT: Hospitals are critical facilities that are essential for providing first-aid response to communities in the aftermath of disasters such as earthquakes. The seismic performance of these facilities is highly dependent on the structural behaviour and the vulnerability of non-structural contents to damage. However, earthquake-induced structural damage has not yet been considered directly when assessing hospital loss of functionality. Our approach uses inelastic structural analysis to compute the earthquake response, fragility functions to assess non-structural and component damage, and a discrete event model to simulate the response of the emergency room of the hospital. Further, the seismic performance of the hospital is characterized by the increase of patient waiting times after the earthquake. The model is then tested with the 2014 M_w 8.2 Pisagua earthquake, which struck off the coast of northern Chile. Analyses show that hospital performance is mainly affected by two factors: the arrival rate of patients and healthcare unit downtime. The proposed model is applicable to a wide range of seismic scenarios, which is key in estimating risk for the loss of performance of hospitals during an earthquake.

1 INTRODUCTION

Healthcare facilities play a key role in the emergency response of communities struck by earthquakes since they must provide normal healthcare services in addition to treating patients affected by the seismic event. Earthquakes decrease the performance of these facilities by: (i) increasing the demand of healthcare; and (ii) decreasing the functionality of the system. Earthquake-induced injuries are mostly related to infrastructure damage (Peek-Asa et al., 1998), which depends on the intensity of ground shaking, and increase the patient arrival rate at hospitals (Malavisi et al., 2015). On the other hand, the services provided by hospitals may be disrupted after an earthquake due to structural damage, non-structural and medical equipment damage, disruption of utilities and lifelines (water, power, etc.), and lack of personnel. The causal dependencies between the failure of these components and the functionality of the hospital have been represented previously using fault trees (Jacques 2014, Lupoi 2014). Hospitals in countries with modern seismic building codes normally do not suffer severe structural damage. However, non-structural damage can still be extensive, as evidenced by the M_w 6.7 1994 Northridge earthquake (Myrtle et al., 2005), the 2010 M_w 8.8 Maule earthquake (Mitrani-Reiser et al., 2012), and the 2011 M_w 6.2 Christchurch earthquake (Jacques et al., 2014). Moreover, non-structural damage also occurs for smaller more frequent earthquakes.

Hospitals may reduce their seismic risk by carrying out mitigation measures, such as adding base-isolation (Nagarajaiah and Xiaohong, 2000), reducing downtimes, and increasing the capacity of non-structural elements. Assessing the effectiveness of these measures should guide the decision-making process, and hence a comprehensive methodology for hospital seismic performance assessment must be used. A simple way of assessing this performance is using empirical data from past earthquakes. For example, Yavari et al. (2010) used data from historic events in California to predict performance levels of the structural, non-structural, and lifeline systems, to then assign a qualitative hospital functionality class (performance). The prediction depends only on the local ground motion intensity, characterized by the spectral acceleration at 0.3 s, and the year of design. This model does not consider hospital-specific characteristics, such as the structural design, spatial distribution of non-structural components, and number of medical units, and is therefore better suited for a regional scale.

Other efforts have focused in estimating the hospital treatment capacity index, defined as the number of patients per unit of time that the hospital is able to treat surgically (Minati and Iasio, 2012; Lupoi et al., 2014). The index takes into account the structural, non-structural, and organizational aspects of the hospital in its calculation. However, this assessment is not time dependent, and hence it gives no insight on the evolution of patient waiting time after the earthquake event.

Yi et al. (2010) proposed assessing seismic hospital performance by modelling the emergency department using discrete event simulation. This approach includes the increase of patient arrival rate, but does not account for possible loss of functionality. The methodology was then extended by Cimellaro et al. (2011) to account for a reduction in the number of beds, operating rooms (surgical capacity), and operations per operating room per unit of time (operating efficiency), due to physical damage. However, the reductions were performed with a single penalty factor for the complete hospital, and hence did not consider the local damage of each healthcare unit independently.

This study presents a methodology to assess the seismic performance of hospital emergency departments. It consists in using inelastic dynamic analyses to compute the structural response of the hospital to specific ground motions. Inter-story drift ratios and floor accelerations are then related to non-structural damage by the use of specific fragility curves. Then, this damage is linked to the functionality of the different emergency units in the hospital. Finally, the increased waiting time of the patients is estimated by running several Monte Carlo simulations of a hospital discrete event model, and is assessed to measure the seismic performance of the hospital. The model is then applied to the regional hospital in the city of Iquique, Chile, after the 2014 M_w 8.2 Pisagua earthquake.

2 HOSPITAL MODEL

Discrete event simulation (DES), a powerful method for modeling systems with strong queueing structures, has been assessed as being well-established for simulating hospitals (Gunal, 2012). The system dynamically evolves in time in a discrete manner. The studied system is the emergency department (ED) of a Chilean hospital. Patients entering the ED can pass through four types of healthcare units (stations): triage, examination box, operation room, and hospitalization. The triage unit is composed of a nurse measuring vital signs and classifying patients into four categories, namely, C2 to C5. Category C1 is allocated to patients needing immediate attention and are categorized outside of the hospital (e.g. in the ambulance). Category C2 is assigned to patients needing fast attention (< 30 minutes), C3 to patients needing attention within 1.5 hours, C4 to patients needing attention within 3 hours, and C5 to patients needing general consultation but no urgent attention. The second station is the examination box, where a physician attends patients. The third station is the operation room (OR), where patients undergo surgery. Finally, patients occupy a bed for recovery in the hospitalization unit.

The DES model requires the definition of the daily variation of patients arriving at the ED (Fig. 1a) and the characterization of the healthcare path followed by patients in the ED (Fig. 1b). The healthcare path of the patients depends on their C1 to C5 categorization (Gutiérrez 2013). The model assumes that C1 patients skip the triage in the ED and go directly to an examination box, and that C5 patients only pass through the triage station before being redirected to other medical services independent of the ED. Based on historic data, it is also assumed that 100% and 22% of C1 and C2 patients, respectively, undergo surgery and need hospitalization, and that 3.4% of C3 patients need hospitalization.

The patient treatment time in each of the healthcare units is sampled from probability distributions, fitted with historical data from the large Barros Luco hospital located in Santiago. The time patients stay in the examination box follows a truncated normal distribution with a mean of 0.6 and a standard deviation of 0.09. The truncation limits are 0 and 2 respectively. The time patient stay in the OR follows a lognormal distribution with a mean of 0.5 and a standard deviation of the variable's natural logarithm of 0.6. Exponential distributions were fitted for hospitalization time depending on the patient category, say with scale parameters 8.7, 13.5, and 21.5 for categories C1, C2, and C3, respectively. The triage time is assumed to follow a uniform distribution with bounds of 0 and 5.5/60. Based on a Chilean governmental report of three hospitals in the Maule region during a two-year period, the model sets the categorization probability of each patient entering the emergency department as: 0.45%, 10.60%, 52.20%, 31.95% and 4.8% for C1, C2, C3, C4, and C5, respectively (MINSAL 2013).

The total time that patients are waiting is an important indicator that summarizes well the quality of service provided by the ED (Maxwell 1984). The waiting time is defined in our model as the time patients are not being attended in a healthcare unit. The total waiting time of each patient is calculated as the sum of waiting times during the patient´s stay in the ED. The daily mean waiting time is used to quantify the daily performance of the hospital.

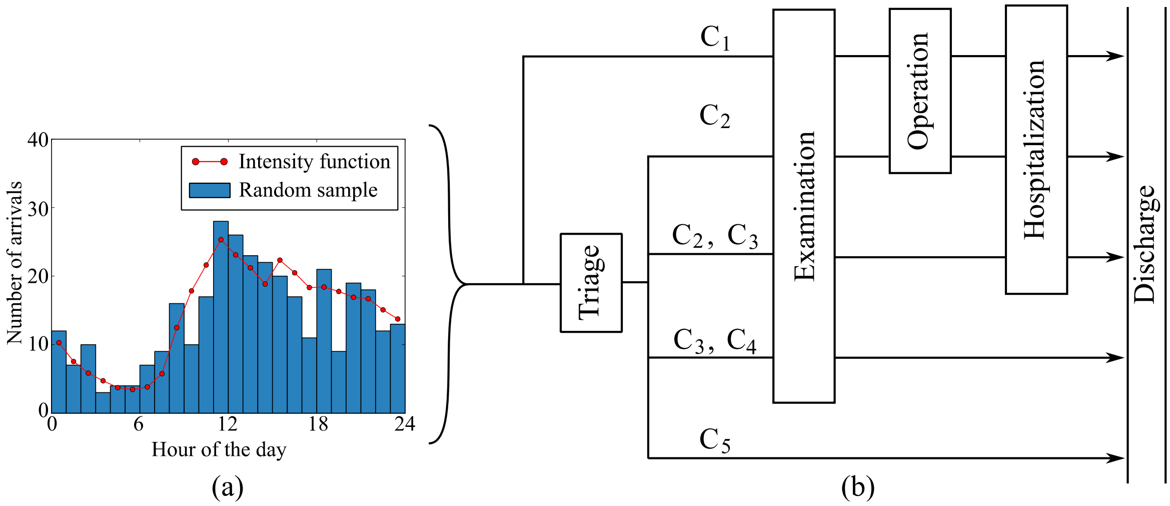


Figure 1: Model variables: (a) average number of arrivals depending on the hour of the day and a sample of daily arrivals from a non-homogeneous Poisson process; (b) schematic paths of patients in the emergency department depending on their category.

The number of patients that arrive to the emergency department in normal condition varies during the day. This variation is considered in the model by sampling the patient´s arrivals from a nonhomogeneous Poisson process with the rate parameter (intensity function), $\lambda(t)$, shown in Figure 1a. The rate parameter was obtained from the average rate observed in the hospital during a two month period. Figure 1a also presents a sample from the stochastic process of patient arrivals in a single day.

Few data are available to validate the hospital model. The time patients spent between their arrival and the end of triage in the *Barros Luco* hospital for the months of February and March 2010 were used for validation. The amount of healthcare units of the emergency department of this hospital is presented in Table 1. A normalized histogram comparing the distribution of the time between patient arrival and triage, derived from real data and from results of a run of the model is shown in Figure 2. The DES model produces a similar mean value of the time, 0.42 hours, relative to the data, 0.44 hours, that is to say an error of 5% approximately. However, the shape of the distributions show differences.

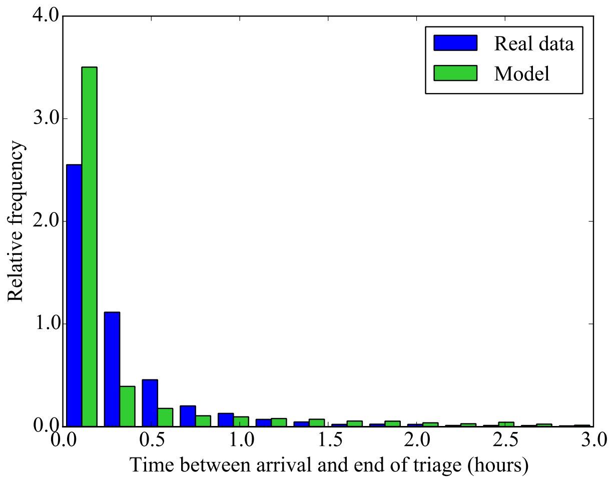


Figure 2: Daily mean patient waiting time for different conditions.

Table 1. Number of healthcare units in the emergency department of two Chilean hospitals.

Hospital	Triage	Examination boxes	Operation rooms	Hospitalization beds
Barros Luco	1	9	1	60
Iquique	1	10	7	36

3 LOSS OF FUNCTIONALITY AND INCREASE OF HEALTHCARE DEMAND

This section describes the sub-models that were used to assess the hospital loss of functionality for a given earthquake motion and how the hospital arrival rate is altered by the earthquake. It contains the description of the nonlinear structural modelling used to compute the response of the studied hospital, a probabilistic assessment of non-structural damage of components, the relationship between building damage and loss of functionality of healthcare units, and the calculation for assessing the earthquake-induced healthcare demand.

3.1 Structural Model

In order to estimate floor accelerations and inter-story drift ratios, a 3D nonlinear structural model was constructed in OpenSees (McKenna 2000). The model consists of a two-story reinforced concrete frame building, composed of 33x33 cm columns and beams 25cm wide and 55cm in height. The grid of columns is 6.6 x 6.6 m and the dimensions of the plan are 26.4x54.4 m. The story height is 3.65 m for both floors, and the slabs were modelled assuming an in-plane rigid diaphragm. The "beam with hinges" element was used for modelling beams and columns (Scott & Fenves 2006), and the Concrete02 and Steel02 constitutive models from OpenSees were used for concrete and steel fibers, respectively. The mechanical parameters of the stress-strain curve ($\sigma - \varepsilon$) used for unconfined concrete were a maximum concrete strength, $f_c' = 0.2$ ton/cm^2, unit deformation at maximum strength, $\varepsilon_0 = 0.002$, unit deformation at ultimate strength (20% of f_c'), $\varepsilon_u = 0.01$, and ratio between unloading slope at ε_u and initial slope, $\lambda_c = 0.1$. The corresponding values for confined concrete, were $f_c' = 0.26$ ton/cm^2, $\varepsilon_0 = 0.0024$, $\varepsilon_u = 20\varepsilon_0$, and $\lambda_c = 0.1$. Mass was assigned only to the 3 translational degrees of freedom of each node, and comes from the weight of structural elements, other dead loads, and 25% of live load (INN 1986). The damping matrix was Rayleigh damping, i.e. $C = \alpha_1 M + \alpha_2 K$, where C, M, and K are the damping, mass, and stiffness matrices, respectively. Parameters α_1 and α_2 were calculated such that ξ was 3% for $1.5T_0$ and $0.2T_0$, with T_0 being the first elastic period.

3.2 Component damage

The non-structural damage is linked to the building earthquake response by the use of specific fragility curves. These curves represent the probability of exceeding certain damage state for a given local engineering demand parameter. Depending on the component sensitivity, this demand could be floor acceleration or inter-story drift ratio at the location of each component. The model considers the fragility of three non-structural components, i.e. partition walls (Retamales et al., 2013), doors (Lupoi et al., 2014), and suspended ceilings (Badillo-Almaraz et al., 2006). The fragility curves used in the analysis are the lognormal distributions presented in Table 2, where x_m is the median and β corresponds to the logarithmic standard deviation.

Table 2. Fragility curves of non-structural component.

Component	Sensitivity	Damage state	x_m	β	Reference
Partition walls	Drift	Moderate	0.67 %	0.390	Retamales et al. (2013)
Doors	Drift	Moderate	4.37 %	0.320	Lupoi et al. (2014)
Suspended ceilings	Acceleration	Moderate	0.83 g	0.143	Badillo-Almaraz et al. (2006)

3.3 Functionality of healthcare units

Of the four types of healthcare units used in the hospital model, two can lose their functionality:

examination boxes and operating rooms. Two approaches are used to assess the effect of non-structural damage on medical functionality. Box functionality is estimated using information gathered from the M_w 6.6 2004 Chuetsu earthquake (Kuo 2008), which relates the probability that a box is functional with the percentage of ceiling panels that fell inside the box during an earthquake. The relationship is shown in Table 3, and intermediate values are obtained by linear interpolation. Operating room functionality is assessed using the fault tree of architectural non-structural elements proposed by Lupoi et al. (2014). Here, an OR stops functioning if any non-structural element inside the room (i.e. partition wall, door, or ceiling) reaches a moderate damage state. The triage station was assumed to work since it does not require substantial medical equipment, and can be easily relocated. Hospitalization beds were assumed to remain operational after the earthquake due to lack of information.

Table 3. Probability of examination-box functionality given an amount of fallen suspended ceilings (Adapted from Kuo 2008).

Fallen ceilings (%)	Prob. of functionality
0	1
20	0.38
50	0

Data on healthcare-unit downtime after earthquakes is scarce, and to the authors' knowledge, no comprehensive methodology has been proposed to assess this downtime in the literature. Therefore, the downtimes are sampled from a uniform distribution with bounds from 1 and 7 days, respectively, which was the range of observed downtimes of healthcare services after the 2010 Chilean earthquake (Mitrani-Reiser 2012). However, given the importance of this parameter in the methodology and its great uncertainty, a parametric analysis was performed.

3.4 Earthquake-induced arrival rate

The patient arrival record in the weeks following the Pisagua earthquake was lost. Thus, the earthquake-induced arrival rate was estimated scaling the data from a well-documented Californian hospital during the M_w 6.7 1994 Northridge earthquake, as proposed by Malavisi et al., 2015. The scaling was based on the Modified Mercalli Intensity (MMI) and the mean annual arrival rates. The MMI of the Northridge earthquake at the Californian hospital location was IX, and magnitude of the Pisagua earthquake at the Iquique hospital was VII. To take into account the difference of size between the Californian and the Iquique hospitals, the arrival rate was also scaled by the ratio between mean annual arrival rates for both hospitals in normal condition, which is equal to 2. The total scaling factor was obtained by multiplying both factors 7/9 and 2, resulting in a factor of 1.56.

3.5 Methodological overview

In summary, the performance of the hospital for a given earthquake is assessed by the following algorithm:

1. Perform a dynamic inelastic structural analysis to compute the building's response.
2. Compute the damage probabilities of each non-structural component using fragility curves.
3. Sample the damage states of each non-structural component.
4. Assess the loss of functionality for each healthcare unit (i.e. examination boxes and ORs).
5. Sample the patient arrivals to the emergency department.
6. Execute the hospital discrete event model.
7. Repeat steps 3 to 6 several times to capture the randomness in each step.
8. Compute the waiting times using all the results from step 6, i.e. Monte Carlo simulations.

4 RESULTS

A hospital in the city of Iquique, Chile, was selected to illustrate the capabilities of the methodology. The emergency department of the hospital was studied under normal conditions and for the 2014 Pisagua earthquake. The number of healthcare units used in the analysis is specified in Table 1, previously shown in section 2. Results of the structural analysis and damage of contents are shown in Table 4. Maximum drifts and accelerations were calculated at the centre of mass of the deterministic structural model. A total of 10,000 Monte Carlo simulations were used to compute the mean and standard deviation values of the damage of non-structural components and healthcare units. Only non-structural components inside healthcare units were considered when computing the percentages shown in Table 4. Note that boxes are located only on the first floor, and ORs only on the second. The low percentage of non-structural damage compared to the percentage of damaged ORs is due to the fact that the damage of only one non-structural component is needed for an OR to lose its functionality. Doors are not shown in the Table since none of them failed during the analysis.

Table 4. Simulated mean values of structural response, non-structural damage, and healthcare unit functionality. Standard deviation values are shown in parenthesis.

	Structural response		Non-structural damage		Health care unit functionality	
Floor	**Max Drift (%)**	**Max Acc. (g)**	**% damaged partition walls**	**% damaged false ceilings**	**% damaged Boxes**	**% damaged ORs**
1	2.0	0.49	Not required	2.8 (1.7)	8.5 (8.8)	-
2	0.7	0.51	21.8 (7.7)	7.3 (1.7)	-	97.5 (5.9)

A total of 500 Monte Carlo simulations were used to obtain the response of the hospital in each condition, since the model is based on several probability distributions which need to be sampled. The simulations started 3 days before the earthquake occurred so that the flow of patients reaches a stable condition. Figure 3 compares the average daily waiting time of the patients in normal and earthquake conditions. The results show that the average waiting time reaches 30 hours 6 days after the earthquake, and returns to normal after 19 days. The two reasons why earthquakes reduce the performance of hospitals, i.e. loss of functionality and increase of healthcare demand, were also studied independently, and the results are also presented in Figure 3. In this case the increase of healthcare demand has a greater impact on the waiting times than the loss of functionality.

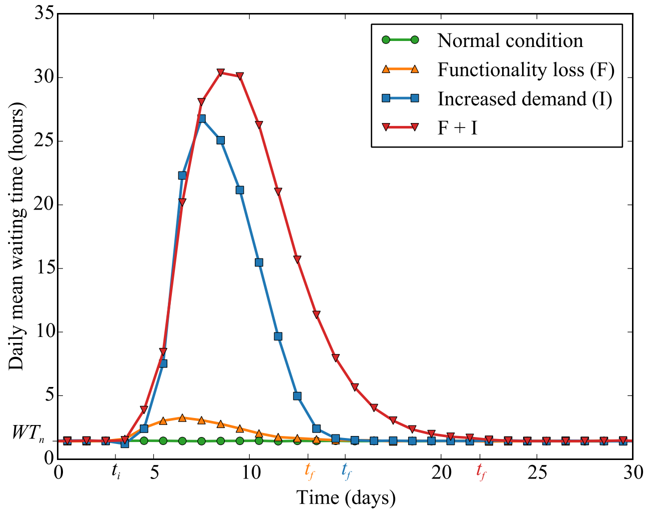
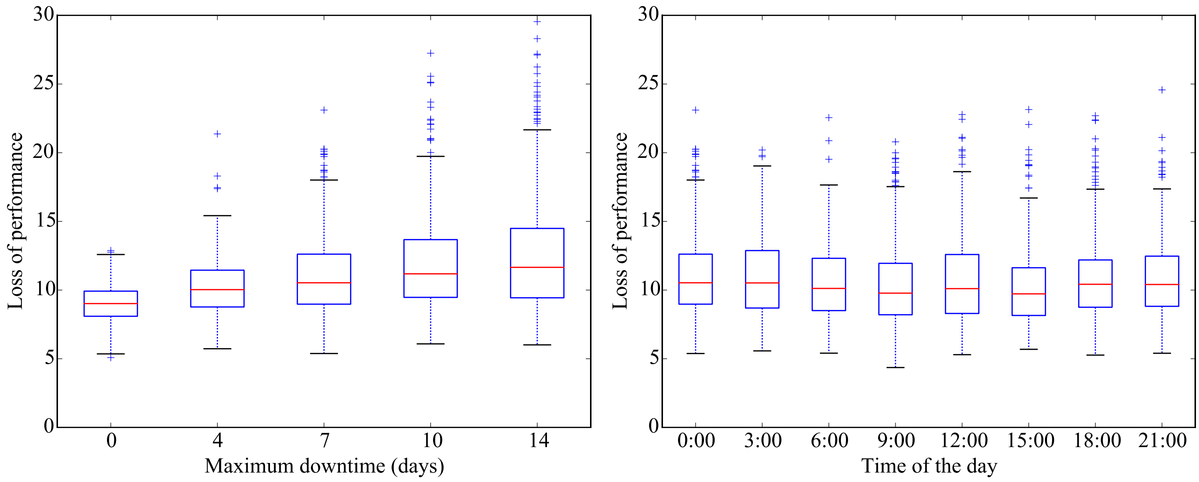


Figure 3: Daily mean patient waiting time for different conditions.

The effects on the results of two parameters of the methodology, the maximum value of the distribution of healthcare unit downtime and time of the day when the earthquake strikes, were studied. The hospital seismic loss of performance, P, was characterized by

$$P = \left(\frac{WT_e - WT_n}{WT_n}\right) \quad (1)$$

where WT_n is the average patient waiting time in normal condition; and WT_e is the average waiting time of all patients that were treated from the time when the earthquake stroke, t_i, to the time of normal waiting times, t_f (Fig 3). Figure 4 shows the effect that the two parameters have on the hospital performance. It was found that the maximum downtime has a significant effect on the performance of the ED. Figure 4a shows that the median value of index *P* (Eq. 1) from the 500 simulations increases with the maximum value allocated to the downtime distribution, from 9.0 (no downtime) to 11.7 (14-day maximum value of downtime). On the other hand, the time of the day that the earthquake occurred does not have a strong influence on the loss of performance (Fig. 4b). Indeed, the median of index *P* remains in the interval [9.7, 10.5] for all hours of the day tested, i.e. 0:00, 3:00, 6:00, 9:00, 12:00, 15:00, 18:00 and 21:00. Moreover, the distributions of index *P* for each time of the day exhibit a similar shape and spreading.



(a) (b)

Figure 4: Effect on the hospital seismic loss of performance, *P*, of: (a) maximum value of the distribution of healthcare unit downtime; and (b) time of the day when the earthquake strikes.

5 CONCLUSIONS

This work proposed a seismic performance assessment tool for hospital emergency departments, which are crucial to save lives in the aftermath of an earthquake. The method includes the effect that physical damage has on the functionality of healthcare services, and the increase of healthcare demand after the earthquake. Both effects are connected to a discrete event simulation model of the emergency department, enabling the estimation of patient waiting times. Results showed that for the specific hospital analysed herein, the increase of healthcare demand had a greater impact than the loss of functionality. Meanwhile, the procedures to obtain the earthquake-induced arrival rate of people to the emergency department have proven to be a limitation for predicting reliable future hospital performances. This could be done by relating the number of injuries with the physical damage of the built environment, e.g. by using HAZUS, or better data for the patient arrival prediction.

Parametric analyses were used to quantify the impact of different inputs and assumptions of the methodology, i.e. the maximum downtime and the time of the day when the earthquake occurred. The seismic performance of the studied hospital showed little dependency on the time of the earthquake during the day. However, the selection of healthcare unit downtime has proven to be an important aspect of the evaluation. These downtimes were approximated based on a small amount of observations from the literature, but should be enhanced with more data from real events, which could be obtained by surveying medical staff.

The presented methodology does not include a possible increase in the number of healthcare units after an earthquake, such as the ones achieved by using other sections of the hospital and field hospitals. Indeed, it provides the response of the emergency department if no additional help and resources are provided. Moreover, human resources and lifelines have not been considered in this study, and their effect on the results will be studied in future work using Hazus.

Instead of a scenario-based assessment, future stages of this research will take into account the real seismic hazard of the hospital (i.e. all possible earthquakes and their probability of occurrence) to compute the corresponding seismic risk, and will extend the methodology to assess the performance of the healthcare networks at a regional scale.

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