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A first order evaluation of the capacity of a healthcare network under emergency

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Abstract: Immediately after an earthquake a healthcare system within a city, comprising several hospitals, endures an extraordinary demand. This paper proposes a new methodology to estimate whether the hospital network has enough capacity to withstand the emergency caused by an earthquake. The ability of healthcare facilities and to provide a broad spectrum of emergency services immediately after a seismic event is assessed through a metamodel that assumes waiting time as main response parameter to assess the hospital network performance. The First Aid network of San Francisco subjected to a 7.2 M_w magnitude earthquake has been used as case study. The total number of injuries and their distributions among the six major San Francisco's Emergency Departments have been assessed and compared with their capacity that has been determined using a survey conducted by the medical staff of the hospitals. The numerical results have shown that three of the six considered San Francisco's hospitals cannot provide emergency services to the estimated injured. Two alternatives have been proposed to improve the performance of the network. The first one redistributes existing resources while the second one considers additional resources by designing a new Emergency Department.

Keywords: resilience; hospital networks; earthquake; injured; performance; San Francisco

1 Introduction

It has been predicted that a large-scale earthquake will shake the region of the Bay Area sometime within the next 30 years. When the earthquake occurs, the city of San Francisco will suffer from severe consequences. Even if it is almost impossible to predict the exact location and time of earthquake occurrence, it is not equally impossible to predict its effects on the city and act consequently to make San Francisco more resilient in the face of this disaster. In this sense, hospitals play a critical role providing essential medical care during any type of disaster (Cimellaro *et al*., 2010; Wada *et al*., 2018). Any event that causes casualties and injuries (e.g. earthquake) requires a solid hospital network for a rapid and effective response. In fact, the level of preparedness for an extreme event is critical for saving lives and reducing post-disaster consequences (Greco *et al*., 2016). Thus, the hospital network should be able to immediately analyze the situation, coordinate the emergencies, and manage resources right after a hazardous event (Downey *et al*., 2013).

All the systems may be designed to behave in a predetermined way under normal circumstances. When a disruptive event occurs, the performance of the system will deviate from its design level (Wada *et al*., 2018). In this context, resilience is becoming increasingly important since is defined as the ability of a system to properly adapt to changes in its equilibrium status (Cimellaro *et al*., 2014). Bruneau *et al*. (2003) define a resilient system as the system which reduces failure probabilities and their consequences in terms of lives lost, damage, and negative economic and social consequences and limits also the time to recover its "normal" level of functional performance.

Wada *et al*. (2018) suggested guidelines for enhancing the seismic resilience of large cities, including preparation and implementation of emergency response after earthquakes.

Recently the attention in research has been shifted toward definition of methodologies aimed to evaluate the resistance and functionality of critical systems (Tang *et al*., 2011). Earthquake hazard mitigation have received

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much attention which resulted in appreciable reduction of the effects based on the important lessons learned from past earthquakes (Marano *et al*., 2008, Nakashima, *et al*. 2014; Wang and Lee, 2009). Kammouh *et al*. (2018) introduced an indicator-based approach to assess the resilience of communities based on post-disaster data, evaluating the functionality of each network for the whole community.

Some particular systems, such as a hospital emergency department, are designed to adapt to highly variable and uncertain inputs. Analyzing how these systems are able to cope with potentially changing demands and studying how they adapt to an emergency scenario can reveal a great deal about how to design resilient organizations (Anders *et al*., 2006). Lupoi *et al*. (2013) proposed a probabilistic framework to assess the effect of a seismic event on a healthcare system at the regional scale. In this study, the short-term period has been considered as a reference time and the estimation of an earthquake impact has been provided in terms of the number of un-hospitalized victims, hospitals functionality, demand of medical care, and hospitalization travel time. Furthermore, a single hospital has been described as a coupled system made of physical, human, and organizational dimensions. The operating conditions of healthcare facilities after a natural disaster have been explored by Achour *et al*. (2014). A pluralistic qualitative and quantitative research approach has been used to measure the impact of healthcare supplies interruption during an emergency. A discriminant function analysis has been performed using the information collected from 66 different hospitals after three major seismic events occurred in Japan in 2003. The performance of the Canterbury hospital system to the 2011 Christchurch Earthquake has been analyzed by Jacques *et al*. (2014) using a holistic approach. The functionality of healthcare services has been evaluated through a fault-tree analysis considering the hospital's staff, structure, and stuff as main factors. Estimation of the functional curve at the regional level has shown that the services' redundancy has increased the resilience of Christchurch Hospital of 12%.

In order to assess the seismic vulnerability of a hospital system, an integrated methodology has been proposed based on the theory of complex system analysis through input–output inoperability model of Leontief and rapid seismic vulnerability assessment (Miniati and Iasio, 2012). The Leontief model allows defining the input failure vector, which describes the impact of an earthquake on the different elements of the hospital, causing their inoperability. The initial levels of inoperability are evaluated through a rapid seismic vulnerability approach which is based on the World Health Organization (WHO) evaluation forms. The approach proposed by Miniati and Iasio (2012) has been applied to a system of five hospitals located near Florence, in central Italy and subjected to a $M_w = 6$ earthquake scenario.

After a disaster, hospitals have to provide emergency services to the injured setting of restricted resources through an accurate and effective collaboration with other healthcare facilities. The capacity of a healthcare system to coordinate the rescue and deliver emergency services after a disaster has been studied in several works (Zhong *et al*., 2014). Based on the 2008 Wenchuan Earthquake, Zhou *et al*. (2014) studied how to build a valid communication system to ensure an effective flow of health information during major crises. According to Garshnek and Burkle Jr (1999), sharing knowledge and experience during and after disasters is extremely important to develop a more effective emergency communication system. Furthermore, there is a strong need to integrate risk analysis into public health management at both the methodological and theoretical levels (Löfstedt and 6, 2008).

In this research, a simplified methodology has been described in order to evaluate the performance of a hospital network during emergencies. In particular, the main purpose of this study is to analyze San Francisco's hospital network after a strong earthquake. A 7.2 M_w magnitude earthquake on the San Andreas Fault has been assumed as the seismic scenario. The minimum targets indispensable to ensure adequate health care services during and after the earthquake has been compared with the effective response of each hospital. The ability of San Francisco's healthcare facilities to coordinate the emergencies and to provide services to the injured is evaluated. The organizational aspects of healthcare facilities are essential to measure the quality of services provided during the emergency. The quality of the assistance provided by the San Francisco's hospitals has been defined using the waiting time (WT) spent by patients in the waiting room before receiving care (Cimellaro *et al*., 2017). Thus, the WT has been selected as the main criterion to check how the hospital network responds to the earthquake. The evaluation of the performance of the healthcare emergency network is a key to identify opportunities for improvement.

In this paper, two different methodologies have been adopted to guarantee that hospital network can provide emergency care to all the patients within the acceptable WT. The first methodology is based on the patient's redistribution considering the existing resources. In this approach, injured who cannot be treated are directed into the nearest hospitals to exploit the capacity of the other healthcare facilities. This necessitates providing an Operative Center to manage the flow of patients between the hospitals. The second methodology is conceptually a mitigation action contemplating construction of a new hospital equipped with an efficient emergency department. The first section of this paper provides a detailed description of the proposed simplified methodology, while the second part illustrates its applicability through the San Francisco healthcare network as a case study. Lastly, the two different approaches used to improve the resiliency of the emergency network are described.

2 Description of the methodology

During emergencies, the number of patients increases significantly with respect to the normal condition. It is essential that the entire network of hospitals will be able to respond to all the demands. A methodology for hospitals performance measurement has been provided to assess the response of a hospital network during a seismic event. An earthquake scenario has to be selected in order to assess the consequences on the emergency framework of the considered city. The number of injured has been estimated considering the damage level induced by the earthquake. The number of injured persons in each Emergency Department of the hospital's framework has been evaluated assuming that patients during emergencies are directed to the nearest hospital. The estimation of an Emergency Department response is a complex procedure. The Emergency Plan, resources, location of the internal spaces, and paths should be considered and a simulation approach has to be used. A numerical simulation requires a long computational time to analyze the simulated scenario and it produces a significant amount of complex output data. Thus, an approximation of the simulation model is a preferable strategy to study the response of the Emergency Department within the healthcare network. The proposed methodology is based on the utilization of meta-models that are capable to assess the functional relationship between system behavior and selected input data parameters.

Meta-model definition consists in a structured approach focusing on the generic problem definition and model generation. The statement of the problem is necessary to identify the input, output, and response parameters to be used in the meta-model development. According to Cimellaro *et al*. (2010), the patients' WT is one of the most representative parameters describing the hospital behavior during emergencies, while the time period (t), the seismic arrival rate (α), and the number of functional emergency rooms per color area (m) after earthquake occurrence are considered as input parameters (Cimellaro *et al*., 2017). After defining the input and output parameters, sensitivity analysis is performed in order to measure outputs variation due to change of the system input parameters under emergency conditions.

The meta-model has been based on numerical simulation data obtained through the Discrete Event Simulation (DES) model applied to the case study of Umberto I Mauriziano Hospital located in Turin, Italy (Cimellaro *et al*., 2017). The model has been implemented using ProModel software (Price and Harrell, 1999). The Patients' arrival rate, the path through the Emergency Department, the location of the rooms in which the patients are treated, the processing time, the resources involved (e.g. doctors, nurses, et.), and the operating conditions have been considered as input parameters in the simulation model. Some assumptions have been set to simplify the problem and to reduce the computational effort. The structural and non-structural damage has not been considered as a parameter which affects the patients' path within the hospital. Furthermore, the patients have been divided into different codes from the beginning, without considering the first treatment at the "triage". The DES models have given as output the real time average patients' WT obtained through Monte Carlo simulations for different scenarios grouped according to the number of functional rooms (m) and the seismic input (α). The closure of some emergency rooms due to possible structural damage after the earthquake has been preliminarily assumed. It consists of changing the values of m in the simulation model. Furthermore, the patient arrival rate collected in a Californian hospital after 1994 Northridge earthquake (Cimellaro *et al*., 2011) has been used as the seismic input parameter (Fig. 1).

In addition, according to Yi (2005), the seismic arrival rate has been divided in different patient codes for emergency and normal operating conditions (Table 1). The severity of an injury is represented by four different color codes: white, green, yellow, and red. *White codes* include all patients who have not urgent injuries and they are treated by a general doctor (no urgency). Patients with *green codes* have not critical situations, so their lives are not at risk, while *yellow codes* refer to the patients who have partial life-threatening injuries and then they need treatment in the Emergency Department. Finally, the *red code* refers to the patients with compromised vital functions, whose lives are at risk.

In order to consider the sensibility of the Emergency Department, the patient arrival rate has to be proportionally amplified using several scaling factors. The scaling procedure is necessary to adapt the available statistical data to the expected seismic intensity of the considered site and then provide a general definition of patients' arrival rate. A scaling procedure based on the Modified Mercalli Intensity (MMI) has been selected because it takes into account some important features such as the population density and the urbanization

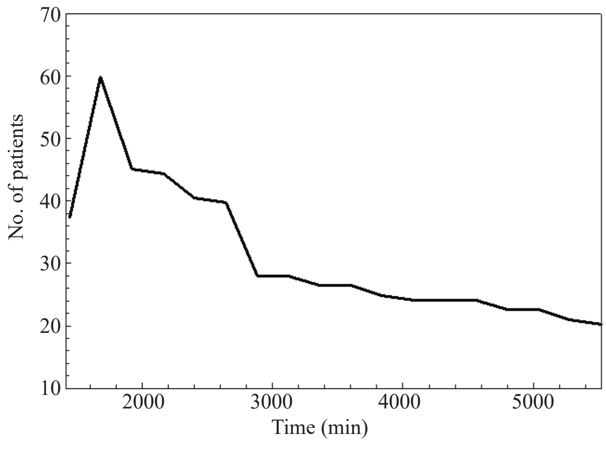

Fig. 1 Patients arrival rates for 1994 Northridge earthquake

Table 1 Percentage of patients arriving in the Emergency Department in both normal and emergency operating conditions

Color code	Normal operating conditions (%)	Emergency operating conditions (%)
White	11.47	7.81
Green	71.19	48.48
Yellow	16.78	40.1
Red	0.56	3.7

level which are important indexes for the assessment of seismic effects. Once the expected seismic arrival rate is defined, several increasing levels of seismic intensity have to be considered to cover the different possible scenario in the simulations. The numerical results obtained in the case study of Umberto I Mauriziano Hospital which has been implemented in Cimellaro *et al*. (2017) can be used to build a meta-model. The main challenge is to provide a general meta-model which is capable to analyze healthcare facilities' capacity to cope with and respond to a disastrous event, such as an earthquake. The problem is rather complex since each hospital is considerably different from another and the behavior of a healthcare facility is described by a significant number of input variables. Thus, the number of input variables has to be reduced to provide a general tool which may be applicable to any healthcare facility. Selecting the seismic input and the number of functioning rooms as input parameters allows considering a set of representative variables which generally expresses the trend of the patients' WT in a given operative conditions for any hospital. Then a sensitivity analysis has to be performed to calibrate the meta-model and a specific mathematical form needs to be defined. This assumption is a key point in the definition of the meta-model for the operative conditions of an Emergency Department after a seismic event. Using the data from the simulations, a lognormal function has been chosen as a representative to assess the patients' WT in the Emergency Department (Eq. (1)).

$$WT\left(t,\alpha,m\right)=\frac{a}{t}\cdot\exp\left(-0.5\cdot\left(\frac{\ln\left(\frac{t}{b}\right)}{c}\right)\right) \tag{1}$$

where WT and the time range t are expressed in minutes. The parameters $a(\alpha, m)$, $b(\alpha, m)$, and $c(\alpha, m)$ are the nonlinear regression coefficients dependent on α and m values calculated in the considered operating conditions. It is worth mentioning that these parameters have been calibrated based on the simulation results of ED analyses, first considering their dependency from the parameter α and then from the parameter m. Simulation results have shown a polynomial dependency between the considered parameters and the meta-model input variables. Firstly, a quadratic, cubic and quartic fitness function have been considered. Then, an objective function has been selected as ratio between the Coefficient of Determination (CoD) and the number of parameters involved. The quadratic model has shown the higher values of objective function and then it has been selected as the most effective model to be used (Eq. (2)).

$$\begin{cases} a(\alpha)=a_0+a_1\cdot\alpha+a_2\cdot\alpha^2 \\ b(\alpha)=b_0+b_1\cdot\alpha+b_2\cdot\alpha^2 \\ c(\alpha)=c_0+c_1\cdot\alpha+c_2\cdot\alpha^2 \end{cases} \tag{2}$$

Furthermore, the dependence from the parameter m has been studied considering a 4th order model to represent the coefficients a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, and c_2 (Eq. (3)):

$$\begin{cases} a_0(m)=a_{00}+a_{10}\cdot m+a_{20}\cdot m^2+a_{30}\cdot m^3+a_{40}\cdot m^4 \\ a_1(m)=a_{01}+a_{11}\cdot m+a_{21}\cdot m^2+a_{31}\cdot m^3+a_{41}\cdot m^4 \\ a_2(m)=a_{02}+a_{12}\cdot m+a_{22}\cdot m^2+a_{32}\cdot m^3+a_{42}\cdot m^4 \end{cases}$$
$$\begin{cases} b_0(m)=b_{00}+b_{10}\cdot m+b_{20}\cdot m^2+b_{30}\cdot m^3+b_{40}\cdot m^4 \\ b_1(m)=b_{01}+b_{11}\cdot m+b_{21}\cdot m^2+b_{31}\cdot m^3+b_{41}\cdot m^4 \\ b_2(m)=b_{02}+b_{12}\cdot m+b_{22}\cdot m^2+b_{32}\cdot m^3+b_{42}\cdot m^4 \end{cases} \tag{3}$$
$$\begin{cases} c_0(m)=c_{00}+c_{10}\cdot m+c_{20}\cdot m^2+c_{30}\cdot m^3+c_{40}\cdot m^4 \\ c_1(m)=c_{01}+c_{11}\cdot m+c_{21}\cdot m^2+c_{31}\cdot m^3+c_{41}\cdot m^4 \\ c_2(m)=c_{02}+c_{12}\cdot m+c_{22}\cdot m^2+c_{32}\cdot m^3+c_{42}\cdot m^4 \end{cases}$$

Table 2 summarizes the values obtained from the quadratic model based on the simulation results of the ED working when the Emergency Plan is applied.

Therefore, all the parameters in Eq. (3) have been evaluated through nonlinear regression depending on the m values. Substituting these values in Eq. (2), the three coefficients a, b, and c are obtained. This calibration procedure leads to express the influence of the seismic arrival rate (α) and the number of functional emergency rooms per color area (m) in given operating conditions for assessing the patients' WT. Figure 2 shows the

Table 2 Meta-model coefficients for patients treated with yellow codes in emergency operating conditions

a_{00}	-89323896	b_{00}	28475.30	c_{00}	5.57
a_{10}	138734467	b_{10}	-43551.10	c_{10}	-9.34
a_{20}	-69987233	b_{20}	22726.00	c_{20}	4.89
a_{30}	14701509	b_{30}	-4684.30	c_{30}	-1.04
a_{40}	-1106445	b_{40}	338.60	c_{40}	0.08
a_{01}	132611723.00	b_{01}	-43772.00	c_{01}	-7.65
a_{11}	-233300000.00	b_{11}	74209.60	c_{11}	13.67
a_{21}	124474864.00	b_{21}	-38812.00	c_{21}	-7.34
a_{31}	-26999059.00	b_{31}	8013.60	c_{31}	1.58
a_{41}	2072754.00	b_{41}	-578.50	c_{41}	-0.12
a_{02}	16657792.00	b_{02}	11604.20	c_{02}	2.79
a_{12}	22339458	b_{12}	-18167.40	c_{12}	-4.78
a_{22}	-22646870	b_{22}	9196.20	c_{22}	2.54
a_{32}	6227391	b_{32}	-1811	c_{32}	-0.54
a_{42}	-543784	b_{42}	123.1	c_{42}	0.04

WT curve in emergency conditions, considering two functional emergency rooms m = 2 for yellow code and a seismic arrival rate obtained using a scale factor α = 1.2.

According to the numerical example, the maximum time that patients with yellow code must wait at an emergency room to visit a doctor in emergency operating conditions is 553.20 min.

The meta-model has been built based on some assumptions. The configuration of the Emergency Department does not change during the emergency and the number of emergency rooms and the paths (surrounding conditions) are considered as constant parameters. Furthermore, the number of functional emergency rooms is assumed equal to the number of doctors. Generally, this assumption may be considered reasonable because one emergency room is equipped to provide care to only one patient, so the presence of additional doctors would be ineffective. Another assumption refers to the lognormal form of the output parameters. This assumption leads to consider the same mathematical output trend for all the analyzed scenarios. The proposed meta-model describes the performance of the ED under emergency using two parameters: the earthquake intensity (α) and the number of emergency rooms (m). The structural damage is taken into account as a penalty factor on this last parameter. The maximum admissible WT has to be estimated and compared with the WT evaluated through the proposed meta-model. This value identifies whether the hospital is able to provide emergency services to the injured or not. For this purpose, several interviews with medical staff have been carried out and the maximum acceptable WT has been assessed. The questionnaire has been developed in order to quantitatively assess the disaster resilience capability of a healthcare facility. A survey has been conducted between April 2014 and July 2014. Among all the selected hospitals in the San Francisco's Bay Area, 16 complete questionnaires have been collected which represent about a 69% response rate. The 16 hospitals are shown in Fig. 3.

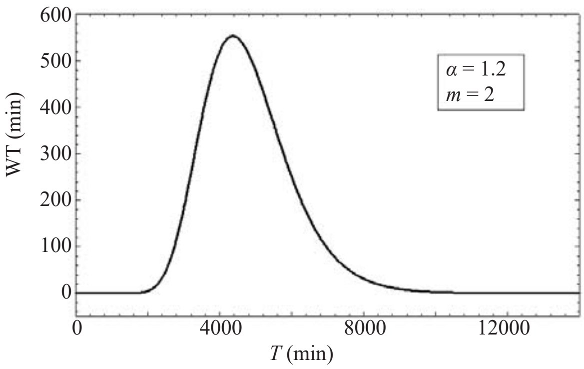

Fig. 2 WT in emergency operating conditions for m = 2 and α = 1.2 for yellow code patients

The survey has been conducted by interviewing in person hospital's emergency staff or by sending the questionnaire by e-mail (Cimellaro *et al.*, 2018). For each hospital, the person who is familiar with emergency planning has been selected to fill out the questionnaire (in most cases the emergency department director). The collected information has been categorized into 8 sections: hospital safety, disaster leadership and cooperation, disaster plan, emergency stockpiles and logistics management, emergency staff, emergency critical care capability, emergency training and drills, recovery and reconstruction represented through 33 questions.

All the questions are associated with a specific item which does not contribute equally to the overall

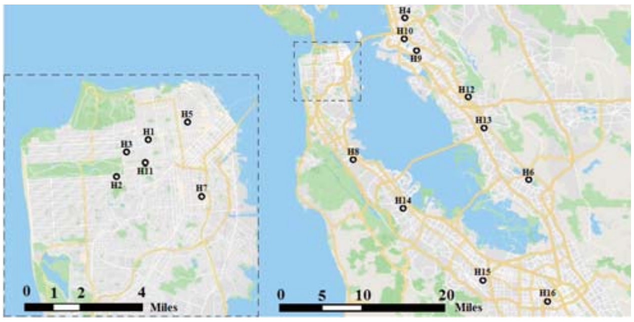

Fig. 3 Tertiary hospitals in the San Francisco's Bay Area

definition of maximum admissible WT. Thus, each of them is given an importance factor ranging from 0 to 1, where 0 means low importance and 1 means high importance. All the questions are in the format of multiple choices, in which the only two possible answers are "yes" or "no". To the option of "yes" has been assigned the score "1", to the option of "no" the score "0". "Yes" answer represents that the item related to the question is "highly" important to the definition of the maximum admissible WT, whereas the answer "no" is related to a "low" importance. The total score of each section has been evaluated by summing the score of each question. The collected questionnaires have been reviewed in order to check their completeness and consistency, then the factor analysis has been performed to build a valid framework and to measure the hospital disaster resilience. The basic idea of analyzing the survey's answers is to represent all the variables included in the hospital's resilience analysis with a smaller number of variables. Firstly, the presence of significant correlations between the items has been checked. Secondly, initial factor loadings have been calculated using principal component method. Once the initial factor loadings have been estimated, the factors have been rotated in order to find factors easier to interpret. Rotation goal was to ensure that all variables have high loadings only on one factor. Varimax rotation has been used to rotate the extracted principal components. Then, factors scores have been obtained and the number of factors have been chosen looking at the number of eigenvalues greater than 1. The values of maximum admissible WT have been obtained for each survey as linear combination of the extracted factors, taking into account the calculated weights. Finally, among the 16 obtained values, the average has been selected as representative maximum admissible WT in this study (Fig. 4).

The estimation of the number of injured for a given earthquake scenario is carried out based on the past earthquakes, considering the density of the population and the buildings' damage. The patient arrival rate for each hospital is assessed and is implemented as input for the meta-model in order to estimate the trend of patients' WT. The capability of a given hospital to respond to an emergency is assessed by comparing the estimated WTs through the proposed meta-model and the maximum acceptable WT.

In cases where one or more hospitals of a network are not capable to manage all the expected patients, different approaches may be considered to guarantee the emergency care within the maximum acceptable WT to all the patients. Two different approaches are discussed in this article. The first approach consists in redirecting all the patients who cannot be treated in the nearest hospital into the other healthcare facilities with higher capacity (resilience-based approach). An Operative Center that manages the patients' flow in the hospitals has to be provided. The second approach focuses on increasing the healthcare facilities number equipped with efficient Emergency Departments (mitigation action). Figure 5 summarizes the explained methodology for the general case of Emergency Department network.

3 Case study: San Francisco's healthcare emergency network

California is one of the world's most earthquake-prone regions. In the next few years, in the northern California Bay Area, a strong earthquake that could strike anytime on the San Andreas Fault is expected. The catastrophic earthquakes seem to strike along this area with an average return period of about 150 years. The San Andreas Fault has reached critical stress level for an earthquake of a large magnitude. This is inevitable and it would likely produce extreme and catastrophic consequences along the San Francisco's Bay Area (Poland, 2009). Thus, San Francisco's hospitals need to be prepared for a major earthquake. Even if it is almost impossible to predict exactly the location and the time of the seismic event, it is not equally impossible to estimate its consequences.

The final evaluation of the capacity of the healthcare system in San Francisco, for almost all seismic scenarios and due to several uncertainties involved,

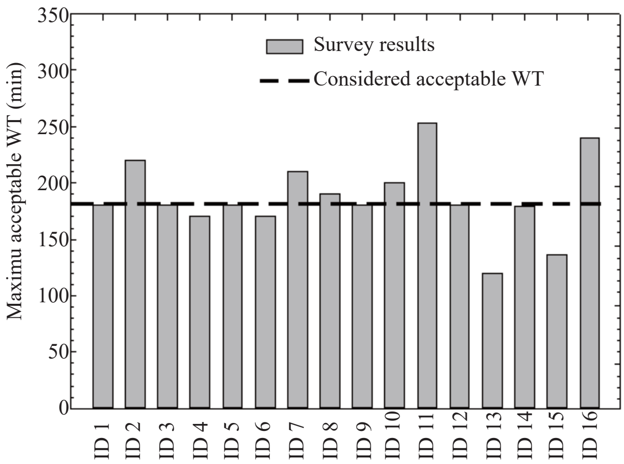

Fig. 4 Results of the surveys and considered maximum acceptable WT

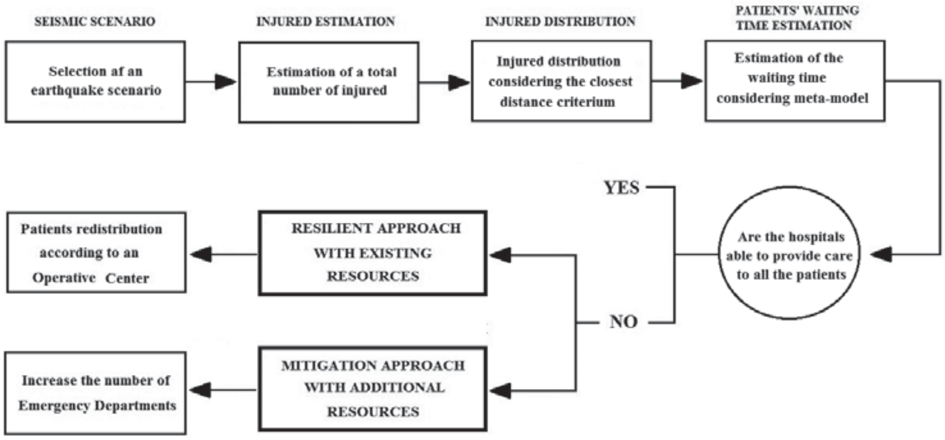

Fig. 5 Flowchart of the methodology applied to San Francisco's Emergency Department network

may be complex. It is almost impossible to predict exactly the characteristics of next large earthquake will strike the city such as location, size, and many other seismic parameters. Different parts of the city will be affected by earthquake depending on the distance to earthquake epicenter, soil condition, and buildings type. In addition, depending on when the earthquake happens, the number of injured and the severity of the injuries, can vary considerably. For example, during the night, most people are at home in small wood frame buildings, whereas in the day-time, people are mostly at work or school in buildings with different structural characteristics. Instead, if the earthquake occurs during the day, the older concrete buildings, which are located mostly in the business areas, will be responsible for the largest share of casualties. Similarly, if it occurs at night, the soft-story residential buildings will cause the most casualties. Since the buildings density, their type, and their occupancy vary by neighborhood in the city of San Francisco, thus the time occurrence of the earthquake might affect considerably the number of injured and its distribution across the city.

This research aims to provide a valid first-order methodology for assessing whether the network of hospitals in San Francisco will be able to deal with such a seismic event. The case study emergency network includes the six most important San Francisco's hospitals, equipped with a functional Emergency Department. As the first step, a 7.2 M_w magnitude earthquake along the Peninsula section of the San Andreas fault has been assumed to evaluate the performance of San Francisco's hospital network. This seismic scenario is used for seismic improvement by the San Francisco CAPSS committee (Community Action Plan for Seismic Safety) (Tobin and Samant, 2009). This earthquake is representative of the level of shaking that the building code requires to design new structures. The consequences of the next large earthquake are likely to be similar in nature to the consequences of the considered scenario (Tobin and Samant, 2009). Therefore, the estimated capacity of the healthcare system in San Francisco could be considered as a feasible first order evaluation.

According to the Public Works Department, the city of San Francisco has been classified into fourteen large neighborhoods, including Western Addition, Twin Peaks, Sunset, Richmond, Pacific Heights, North Beach, Mission Bay, Mission, Merced, Marina, Ingleside, Excelsior, Downtown, and Bayview (Tobin and Samant, 2009). In this case study, only six San Francisco's general hospitals equipped with functional Emergency Department have been considered, leaving aside all the other healthcare facilities. Figure 6 shows the San Francisco neighborhoods and the distribution of the six considered hospitals.

The buildings density and their occupancy vary

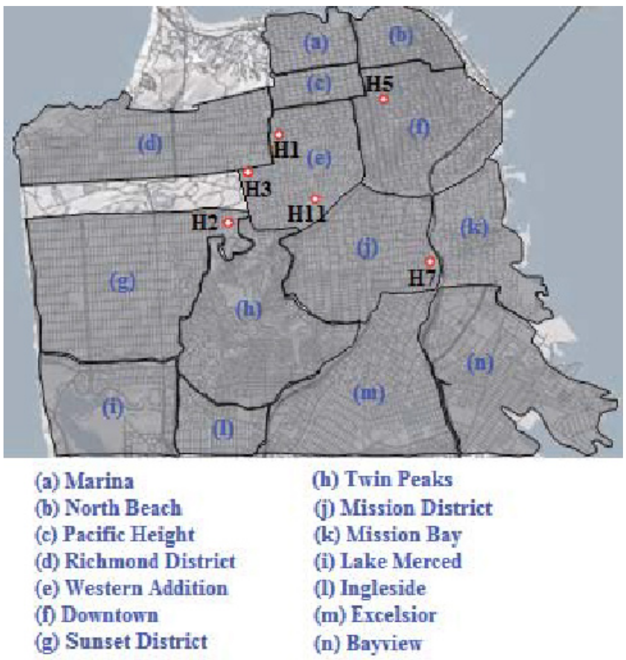

Fig. 6 San Francisco's neighborhoods and hospitals distribution

by neighborhood. Only the privately owned buildings regulated by the Department of Building Inspection have been considered in order to estimate their amount of damage. Post-earthquake damage to roads and infrastructures serving the healthcare system can affect both the number of injured and the patient's flow to hospitals. Studying the interdependencies between the infrastructures and the healthcare system is beyond the goal of this paper. Therefore, the post-earthquake infrastructural damage and their cascading effects on the healthcare facilities have not been taken into account in this study. However, the consequences of infrastructure post-earthquake damage will be added to those described in the proposed methodology in the near future. The Hazard US methodology (FEMA, 2011) has been used to estimate the amount of damage in the buildings for the selected earthquake scenario.

Figure 7(a) presents the damage estimates, summarizing each neighborhood's share of total residential building damage in the City, compared with each neighborhood's share of the total households in the City for the considered scenario (Cimellaro *et al*., 2014; Cimellaro *et al*., 2014; Tobin and Samant, 2009). In particular, Figure 7(a) illustrates that the level of estimated damage in Mission, Sunset, Richmond, and Western Addition neighborhoods is very high, while Mission Bay, Merced, and Bayview suffer the lowest damage level. It has been assumed that the number of injured could be distributed proportionally to the damage in the residential buildings. This assumption is reasonable because the main causes of injuries during earthquakes are the damaged or the collapsed buildings. This assumption is valid if the population is uniformly distributed across the city. However, the number of injured could vary considerably depending on the time occurrence of the earthquake, affecting the population distribution in the city's neighborhoods. The number of injured people can be estimated as a percentage of the building physical damage (D) and the population percentage (P) (Fig. 7(a)) for each neighborhood at the time of the earthquake (Eq. (4)).

$$n_{i_{\mathrm{Inj}}} = N_{\mathrm{Inj}} \cdot \left[D_i + \frac{P_i}{n} - \frac{1}{n^2} \right] \tag{4}$$

where $n_{i,\mathrm{Inj}}$ is the estimated number of injured people within the ith neighborhood, N_{Inj} is the total number of estimated injured people across the city, D_i is the damage percentage within the ith neighborhood. P_i is the population percentage for the ith neighborhood at the time of earthquake strikes, and n is the total number of city's neighborhoods. In this study, the casualties from other sources have not been considered. Patients are grouped into four different severity levels based on the acuity of their health care problems and the time they can wait safely (Tobin and Samant, 2009). Severity 1 includes patients who are stable and they can be treated by a general doctor. This severity level is indicated with white or green triage codes. Severity 2 is associated with yellow triage code representing the patients who have partial-risk of deterioration or some time-critical problems. This group of patients is needed to be treated in the Emergency Department. Severity 3 is related to patients with critical life-threatening injuries needed to be treated immediately. This severity is indicated with yellow or red triage codes. Finally, severity 4 associated with red triage code referring to patients who mortally injured and they need prompt life-saving intervention. Based on the past earthquakes, the results of the estimation of the number of injured for each severity level and for a 7.2 M_w magnitude earthquake scenario, are reported in Table 3 (Tobin and Samant, 2009). The estimated casualties are caused by damage to *privately-owned buildings* and assuming that the earthquake

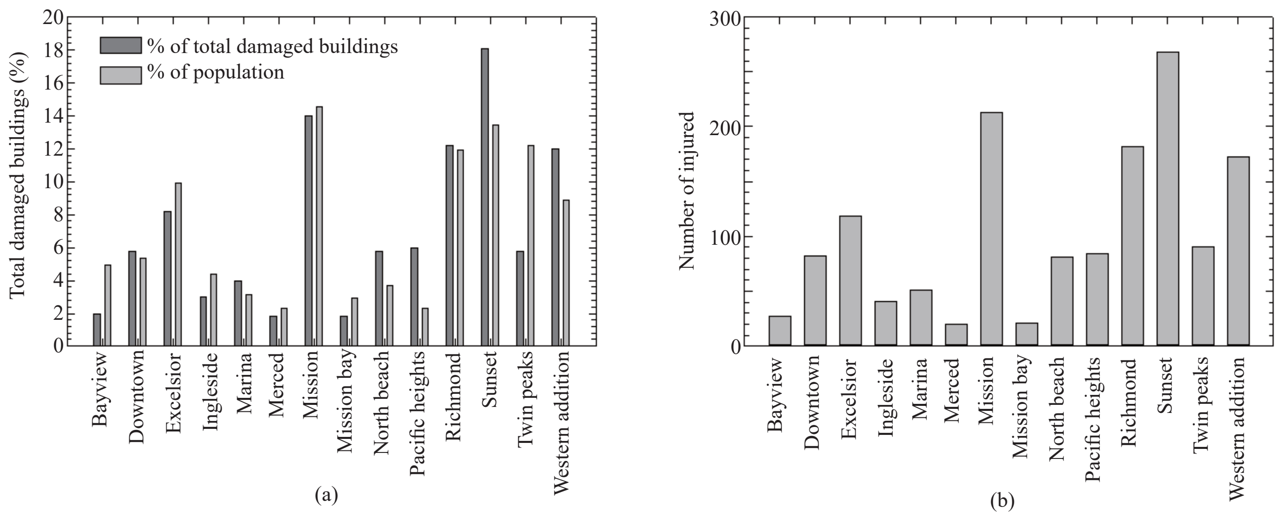

Fig. 7 Percentage of damaged buildings and population for each San Francisco's neighborhood (a) and number of injured per neighborhood (b) for *M* 7.2 earthquake scenario

Table 3 Estimated number of injured for different levels of severity (Toblin *et al*., 2009)

Levels of severity	Casualties
Severity 1	3200 to 5600
Severity 2	760 to 1300
Severity 3	90 to 150
Severity 4	170 to 300

happens during night-time when they are crowded.

In this research, only patients with yellow code have been considered; thus, severity 1 and 4 are not taken into account. Furthermore, the maximum number of injured for both severity 2 and severity 3 has been considered to evaluate the worst case scenario. Thus, San Francisco's hospitals have to treat 1450 patients with yellow triage code distributed among different neighborhoods. According to the building damage distribution and population density, the number of injured for each neighborhood has been obtained (Eq. (4)) and the results are illustrated in Fig. 7(b).

After a disastrous event, all the injured have to reach one of the Emergency Departments among the city. The patients practically are distributed to the closest Emergency Department to shorten the average travel time, because a long travel time may threaten the condition of the patients. Therefore, in this study, all the estimated injured have been distributed considering the distance between the position of the injured and the nearest hospital. To do that, a uniform injured distribution for each neighborhood has been assumed. Table 4 reports the percentage of the patients arriving at each hospital and the number of injured per each hospital accordingly. Patients WT has been selected as a criterion to measure the hospital resilience after the earthquake. As illustrated in Fig. 4, the survey has shown that the WT more than 3 hours may threaten the conditions of the patients and thus the hospital is considered not resilient.

In this study, the estimation of the patient's WT in each hospital has been estimated through the meta-model developed by Cimellaro *et al*. (2017). The number of functional emergency rooms treating patients with yellow codes (m) for each hospital has been obtained through the questionnaire and reported in Table 4. According to the regulation SB1953 (Alesch *et al*., 2012), all acute-care hospitals must be retrofitted or replaced to meet current seismic safety standards, in order to ensure that the hospital buildings can withstand a major earthquake and remain operational after that. Therefore it is assumed that the healthcare facilities remain fully functional after a seismic event.

In this case study, the patient arrival rate collected in a Californian hospital during 1994 Northridge earthquake (Cimellaro *et al*., 2011) has been assumed as seismic input parameter for the meta-model. Sensitivity analysis has been performed in the Emergency Departments and the patients' arrival rate has been proportionally amplified using a scaling procedure based on the MMI. First, the seismic intensity level of the considered scenario (7.2 M_W) has been converted in MMI. This value has been used as intensity scale factor (α_I) compared to the 1994 Northridge earthquake that is considered the reference scenario. The patients' arrival rate requires a further scaling procedure to take into account the total number of patients for the case study in comparison to the 1994 Northridge earthquake. The reported total number of patients who have received care in the Californian hospital during the 1994 Northridge earthquake is 559 (Cimellaro *et al*., 2011). According to Yi (2005), 40.1% of the total patients are treated with yellow code in emergency operating conditions (Table 1). Hence, the total number of patients with yellow code in emergency operating conditions has been assumed equal to 223.

In the considered seismic scenario, the minimum value of the number of patients equal to 223 has been obtained for the fourth hospital (H4). The scaling procedure based on the total number of patients has been carried out and the related scale factor (α_{II}) are reported in Table 4. The total scale factor for each hospital has

Table 4 Estimated percentage of total injured for each analyzed hospital and related meta-model parameters

Hospital	Hospital Name	% of Injured	No. of Patients	α_I	α_{II}	α	m	a	b	c
H1	Kaiser Geary	15.45%	224	1.12	1.01	1.13	2	1882598.37	4432.32	0.23
H2	California Pacific Medical Center	15.95%	231	1.12	1.04	1.16	3	233329.44	3480.62	0.2
H3	Saint Francis Memorial Hospital	15.55%	225	1.12	1.02	1.14	2	1962825.45	4464.31	0.23
H4	St.Mary's Medical Center	15.35%	223	1.12	1.00	1.12	2	1804744.89	4400.25	0.22
H5	UCSF	16.35%	237	1.12	1.08	1.21	3	296294.03	3545.11	0.21
H6	Zuckerberg San Francisco General Hospital	21.35%	310	1.12	1.39	1.56	5	406977.84	3459.13	0.38

been obtained by multiplying the intensity scale factor (α_I) and scale factor based on the total number of patients in the Emergency Department (Table 4).

The trend of patients' WT for each assumed hospital has been obtained setting m and α parameters. Table 4 shows also the values of a, b, and c derived for each hospital. A comparison among the estimated WT and the maximum acceptable WT (180 minutes) for each hospital has been carried out and the results are shown in Fig. 8.

Figure 8 illustrates that hospitals 1, 3, and 4 cannot provide a secure care to the injured within the maximum acceptable WT. In particular, the peak value of patients' WT reaches about 436 min, 450 min, and 420 min for hospitals 1, 3, and 4, respectively. The results depend on the capability of the hospital that is determined by the number of available emergency rooms. According to the obtained results, the emergency framework of San Francisco has shown the inability to respond to an emergency situation caused by a 7.2 M_w earthquake. In this study, two different methodologies have been proposed to improve the functionality of San Francisco's healthcare network. The first methodology assumes a resilient perspective using available resources by redistribution of patients who cannot receive the care to the other hospitals with greater capacity (hospital 2, 5, and 6). This necessitates the presence of an Operative Center that manages the patients' flow in the hospitals. The second action considers the possibility of constructing a new hospital equipped with an efficient Emergency Department (mitigation action).

4 Improvement of resilience of the emergency network

4.1 Approach 1: emergency management with an operative center

For the considered case study, the distribution of the patients according to the closest distance criterion does

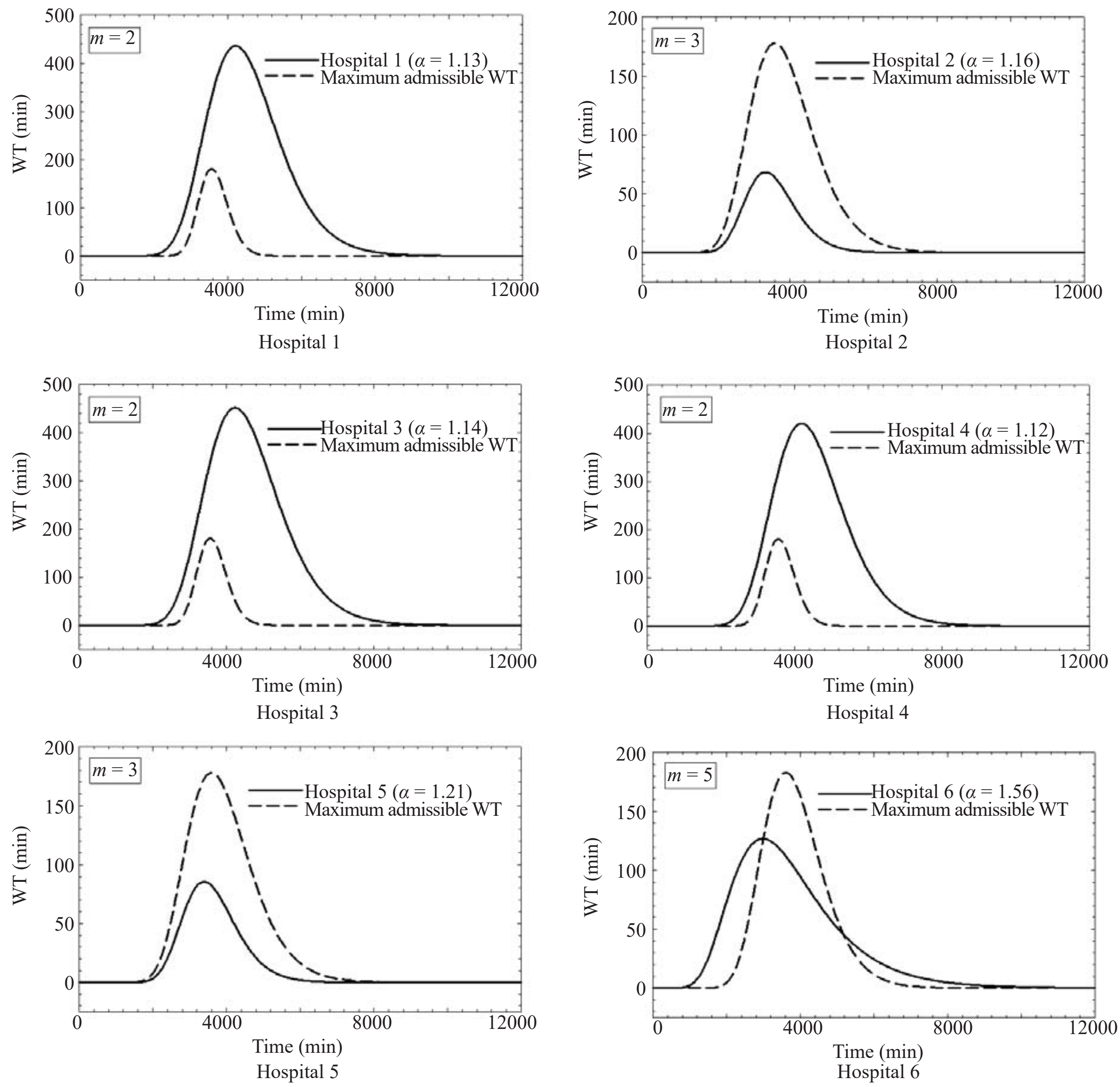

Fig. 8 Patient's estimated WT vs. maximum acceptable WT (3 hours)

not meet the emergency needs. Patient's redistribution approach has been proposed to secure all the injured will receive emergency care in the San Francisco's area under 7.2 M_w seismic event. The presence of an Operative Center has been assumed in order to manage the flow of patients in the hospitals. The predicted WTs for the hospitals 1, 3, and 4 exceed the maximum acceptable WT. Setting the maximum acceptable WT, the maximum capacity of these hospitals has been calculated and then the rest of injured has been redistributed among the other hospitals with higher capacity. The minimum travel distance has been considered as a criterion to redistribute the patient. Table 5 resumes the new calculated α, and the parameters a, b, and c values considering the redistribution of the patients.

The trend of Patients' WT considering the new α values after the redistribution has been evaluated for each hospital. A comparison between the estimated WTs and the maximum acceptable WT value has been carried out for each hospital (Fig. 9).

As shown in Fig. 9, the patients' WT after redistribution is always less than the maximum acceptable limit (180 minutes) for all the considered hospitals. On the contrary, the travel time to reach hospital 2, hospital 5, and hospital 6 increases. To assess the efficiency of the proposed approach, the difference between the travel time before and after patient redistribution has been evaluated. To do that, the normal traffic condition for San Francisco at night-time has been considered and accordingly the maximum travel time to reach each hospital is calculated. The results are listed in Table 6.

Table 6 shows that the maximum increasing rate is about 7 minutes for the hospital 2. Thus, the proposed approach is a good option to manage the injured care in the San Francisco's emergency network. In order to manage the patients' flow in the hospitals, the presence of an Operative Center has to be considered.

4.2 Approach 2: increase the emergency network capacity

The second methodology is conceptually a mitigation action by constructing a new hospital to fulfill the emergency needs. The first step is to identify the new hospital location. As previously illustrated, hospital 1, 3, and 4 cannot provide emergency care to the estimated patients of their service area within the maximum accepted WT. These three hospitals serve emergency care to San Francisco's neighborhoods including Downtown, Marina, Western Addition, North Beach, Pacific Heights, and Richmond district. The center of gravity for each neighborhood has been calculated taking into account the uniform distribution of injured in each area. The Cartesian reference system has been used and the total estimated injured for each neighborhood has been used as weighting factors. Then, the center of mass has been obtained as the appropriate location of the new hospital. Figure 10 depicts the new hospital location, the center of gravity for each neighborhood, and the number of injured per each district.

The proposed methodology might identify the place of the new hospital in an unfeasible region. In this case, the decision maker may choose another feasible location nearby the determined location. In fact, this calculation

Table 5 Number of patients and related meta-model parameters after redistribution

Hospital	No. of Patients	α	a	b	c
Hospital 1	174	0.88	648330.09	3602.29	0.11
Hospital 2	281	1.27	397904.32	3628.72	0.22
Hospital 3	172	0.88	648330.09	3602.29	0.11
Hospital 4	176	0.88	648330.09	3602.29	0.11
Hospital 5	284	1.40	715560.44	3833.12	0.24
Hospital 6	363	1.81	675336.73	3777.74	0.22

Table 6 Maximum travel time between hospitals and their service areas calculated considering normal San Francisco traffic conditions in the rush hour

Hospital	Travel time before redistribution	Travel time after redistribution	Increase in patients travel time
Hospital 1	21-29 min	21-29 min	0 min
Hospital 2	10-17 min	17-24 min	7 min
Hospital 3	20-28 min	20-28 min	0 min
Hospital 4	17-26 min	17-26 min	0 min
Hospital 5	19-25 min	24-30 min	5 min
Hospital 6	24-30 min	29-38 min	5 min

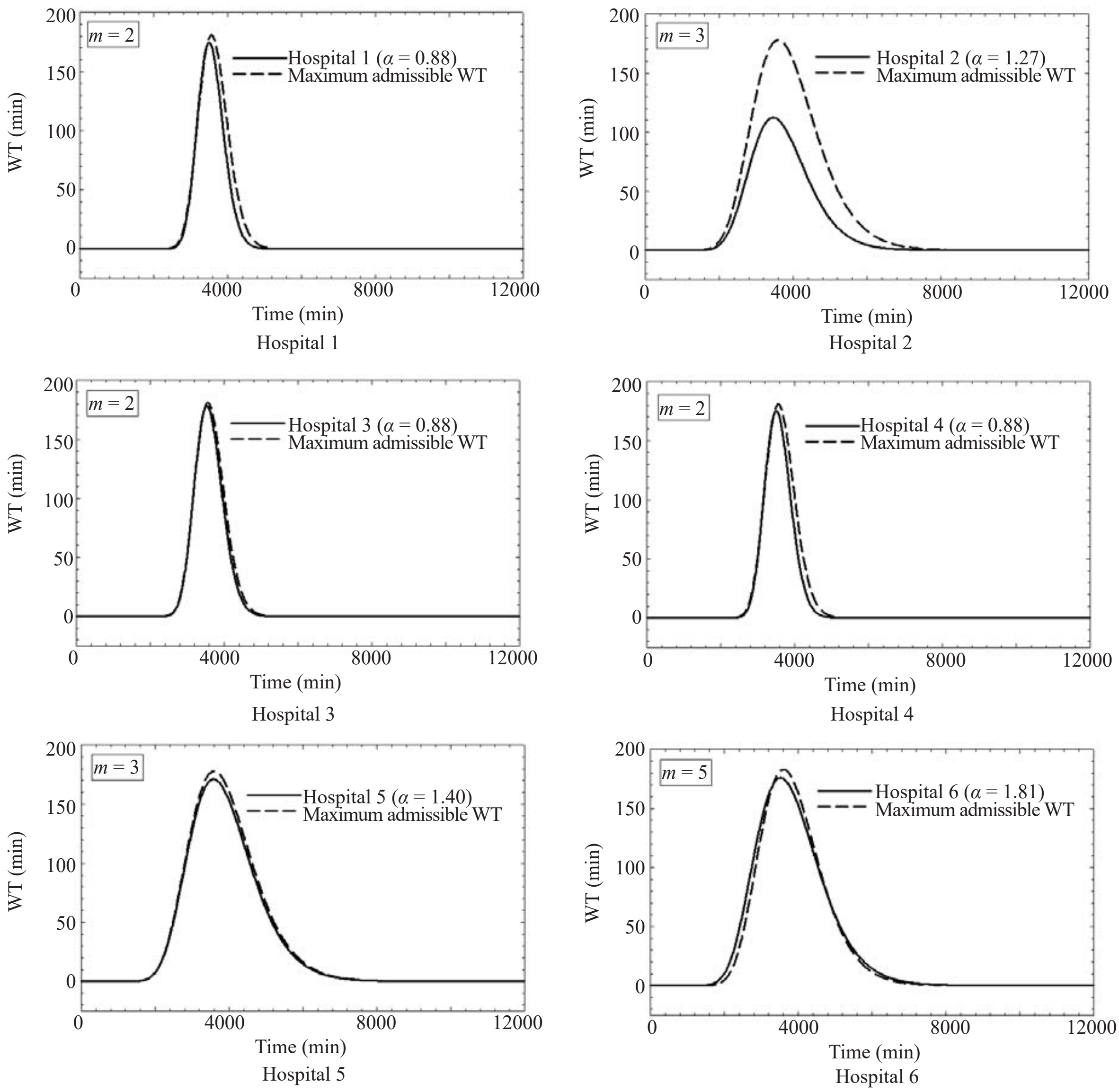

Fig. 9 Patient's estimated WT with Operative Center vs. maximum acceptable WT (3 hours)

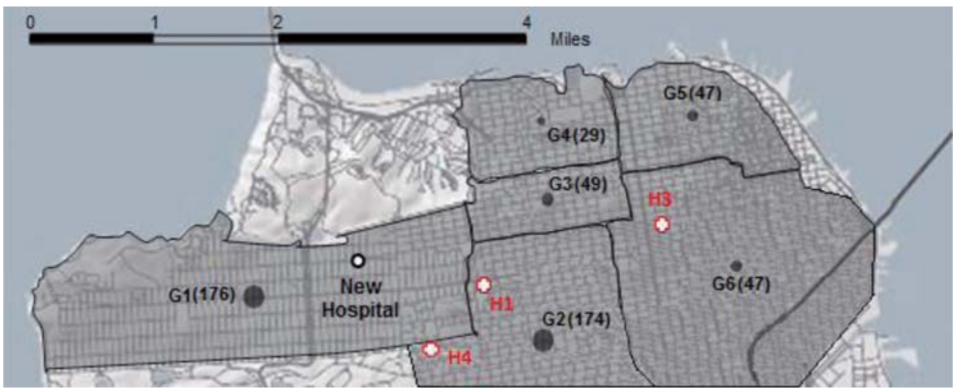

Fig. 10 New hospital location

tackles to only distribute the estimated injured to the most possible closest place regardless the effective road paths. However, this first order method provides important information that can support decision-makers during the design process. Table 7 reports the estimated number of injured arriving at each Emergency Department considering the construction of the new hospital.

In order to define the size of the new hospital, the

Table 7 Estimated number of injured, α and WT for each analyzed hospital

Hospital	No. of patients	α	Average WT peak
Hospital 1	174	0.88	175 min
Hospital 2	231	1.21	85 min
Hospital 3	172	0.88	173 min
Hospital 4	176	0.88	164 min
Hospital 5	237	1.16	68 min
Hospital 6	310	1.56	127 min
New Hospital	150	0.67	180 min

expected number of patients has been used as input parameter. Setting the number of injured arriving at each Emergency Departments, the seismic input parameter (α) can be obtained (Table 7). The minimum number of emergency rooms (m) for the new hospital has been determined through an iterative procedure by fixing the seismic input corresponding to the number of expected patients (α equals to 0.67), and the maximum allowable WT (180 min). The result shows that a minimum number of three emergency rooms is essential for the new hospital. In order to evaluate the response of the new emergency network, the peak value of patients WT for each considered hospital has been assessed (Table 7) (Zhong *et al*., 2014).

Comparing the estimated WTs and the maximum acceptable WT value (180 minutes), each hospital is able to treat all the injured arriving at Emergency Department within an acceptable WT. Therefore, the proposed solutions appear to be a preliminary efficient guess to increase the resilience (Cimellaro *et al*., 2016) of the San Francisco's emergency network.

4.3 Comparison between the two proposed approaches

Both proposed approaches improve the resilience of the San Francisco’s emergency network after the earthquake event. Approach 1 includes patients’ redistribution among the healthcare facilities having higher capacity and allows optimizing San Francisco’s resources. Exploiting the existing resources leads saving the time required to build a new hospital and to avoid the construction costs. Moreover, the presence of an Operative Center could manage patients’ flow in real time ensuring an acceptable WT. Nevertheless, the behavior of people during and after disasters strongly influences the management of the patients. Therefore, the Operative Center may not be able to manage the emergency. In addition, roads could be negatively affected by the earthquake causing unacceptable travel times to reach the healthcare facilities. Approach 2 is based on mitigation by using additional resources. This approach focuses on finding the appropriate location of a new hospital. The total construction cost is an important parameter in estimating the benefits of this action. Thus, a benefits-costs analysis has to be performed in order to evaluate the validity of the proposed approach.

5 Concluding remarks

Recent seismic events have shown how moderate and severe damages can lead to catastrophic effects if the communities are not prepared to face them. The concept of resilience, that is defined as the ability of a community to respond a disaster and bounce back from stress, has gained more attention in the last few years. In this paper, a methodology to assess the resilience of San Francisco’s hospital network for the next large earthquake has been developed. A magnitude 7.2 M_w earthquake scenario has been assumed and the six most important hospitals of San Francisco equipped with Emergency Department have been considered. The capability of the hospital network to provide emergency care to the injured after the earthquake has been studied. The result shows that three hospitals are failed to treat injured within the maximum acceptable WT. Two different methodologies evaluating the optimal recovery plans have been proposed to improve the functionality of healthcare network and to make the city able to manage the post-earthquake consequences. The proposed methodology helps to estimate the capacity of San Francisco’s emergency network and provides an efficient and a simple tool for evaluating the first order response of the healthcare facilities of the city, therefore the post-earthquake infrastructural damage and their cascading effects on the healthcare facilities (such as transportation network, hospitals structures, etc.) as well as the financial aspects have not been taken into account.

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