Organizational model of a hospital system

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ABSTRACT: The capacity and the dynamic response of a hospital network has been estimated using an organizational metamodel that is able to incorporate the influence of facility damage of structural and no-structural components on the organizational system. The waiting time of a patient before receiving treatment is selected as an aggregated function describing the global functionality of technical and organizational aspects and it is used to evaluate the seismic resilience of the hospital network. The metamodel of a single hospital has been used to evaluate the resilience of a hospital network of two hospitals in presence of an Operative Center, including the damage of the hospital buildings and the roadway system.

1 INTRODUCTION

Hospitals constitute an important part of the health-care system and during a disaster (e.g. earthquake, hurricane, etc.) play a critical role, because they need to provide timely treatment to patients injured in order to minimize the fatalities. Therefore, they need to be resilient (Cimellaro et al., 2010a) and functional in a short time. The disaster response of a community depends directly on the healthcare response, but also on the organization at the regional level. Transportation systems, including such facilities as highways, railroads, airports and harbours represent critical components of the societal infrastructure systems. In fact, if a natural disaster strikes, it is necessary to have the transportation system to remain operational in order to ensure its reliable and safe serviceability. The disaster mitigation efforts could be severely affected by the damage that a natural disaster could cause to the roads. Furthermore, the extent of these impacts will not only depend on the seismic response of the individual road components, but also on the characteristics of the roadway system, that contains these elements. These considerations lead to the conclusions that the road damage needs to be taken into account to obtain more accurate estimates of the time that the casualty would take to reach the hospital.

1.1 Resilience models

There is an extensive literature on the definition of disaster resilience (Bruneau et al., 2003; Bruneau & Reinhorn, 2007; Cimellaro et al., 2010a, Kafali et al., 2008) for health care systems and on the definition of the general framework. When considering a hospital network the different models available in literature can be grouped in *conceptual* and *simulation models*.

The *Conceptual models* provide a clear definition of the variables considered and the iterations among them, but no numerical model is proposed. For example, recently Mathew (2004) proposed a conceptual model for the Public Health Management of Disasters that visualizes the use of IT in the public health management of disasters by setting up the Health and Disaster Information Network and Internet Community Centers, which will facilitate cooperation among all those in the areas of disaster and emergency medicine.

Simulation models for complex integrated systems like hospital networks are very few because of the extensive data requirements that are needed to support such studies. In particular, Lowery (1993) describes the design and the validation of a general simulation model of a hospital's care unit that can be easily extended to a multiple hospital system. Each hospital has to provide data regarding the lognormal distribution of average patient interarrival times (IAT) and exponential length of stay (LOS), the variance of LOS, the number of beds and the unit configuration (organization of the emergency department). Fawcett & Oliveira (2000) present a simulation model, which describes a new approach based on a mathematical formulation of how a regional system of health care facilities responds to an earthquake event. The main purpose is to investigate planning and policies options applied on a regional system of hospitals through a model, which simulates the movement of casualties from the stricken area to the hospitals.

However, in such models there is no information regarding the evaluation of resilience of a hospital network where the roadway system and the consequences due to damage are included. This paper describes a model to quantify resilience of hospital networks that include both technical and organizational aspects as well as the impact of the damage of the roadway system. Each hospital in the network is modeled using a metamodel (Cimellaro et al. 2008) that is able to estimate the hospital resilience and incorporate the influence of the structural damage in the organizational model. The damage of the road network is evaluated in increments of the travel time (Werner et al., 2006).

2 RESILIENCE QUANTIFICATION

Resilience is defined in this paper as an index accounting for the capability to sustain a level of performance for a given building, bridge, lifeline networks, or community, over a period T_{LC} defined as the control time that is usually decided by owners, or society (usually is the life cycle, life span of the system etc.). This index is defined graphically as the normalized shaded area (Figure 1) underneath the functionality function $Q(t)$ of a system and is defined analytically as follows

$$R = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q(t)/T_{LC}\, dt \tag{1}$$

where the functionality $Q(t)$ is the measure of performance in time and ranges from 0 to 100%. 100% mean no reduction in performance, while 0% means total loss. In particular, if an earthquake occurs at time t_{0E} it could cause sufficient damage to the infrastructure such that the performance $Q(t)$, is immediately reduced (Figure 1). Then the functionality can be restored within a recovery period T_{RE}, when the system could return to an acceptable level of functionality.

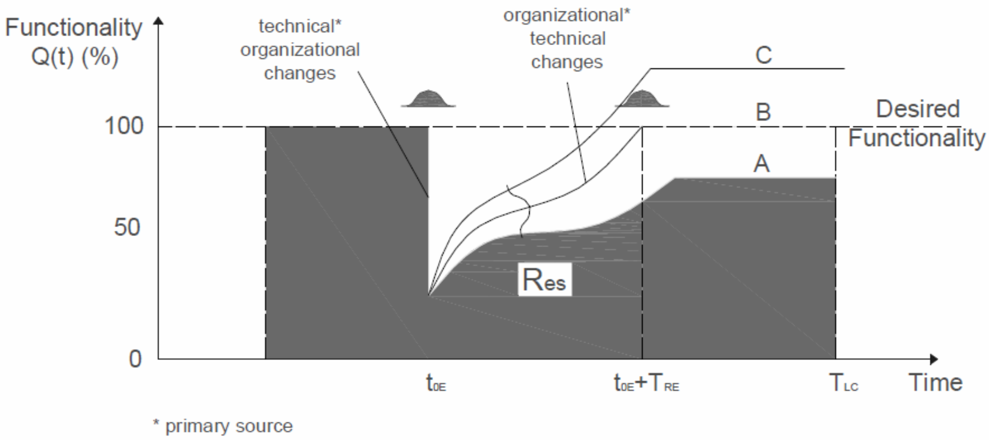

Figure 1 Schematic representation of seismic resilience

Both technical and organizational aspects control the functionality curve during the entire control period T_{LC}, however the immediate reduction of functionality at time t_{0E} can be controlled mainly by technical modifications, while the variation of functionality during the recovery time T_{RE} can be controlled by organizational modifications as shown in Figure 1.

2.1 **Functionality of a hospital**

The first issue to solve when approaching the problem of modelling of a health care system is defining the functionality of a hospital. Well acknowledged studies (McCarthy et al., 2000; Vieth & Rhodes, 2006) have demonstrated that the waiting time (*WT*) in an Emergency Department (ED) may be used as a key parameter in the quantification of the quality of service QS; therefore, it can be used as a measure of the accessibility, efficiency, and relevance of the outpatient service. *WT* is defined as the time elapsed between the received request of care by the hospital and the provision of the care to the patient. This parameter is related to the hospital resources, in particular to those of the ED, such as staff on duty, number of labs, beds (B) and operating rooms (OR), grade of utilization of the OR, but also to the degree of crowding of the ED. The functionality of the hospital is the main term to be defined in order to estimate resilience and it is the product of two components: (i) *qualitative functionality* Q_{QS} related to the quality of service (QS); (ii) *quantitative functionality* Q_{LS} related to the losses in healthy population. The first term has been defined as follow

$$Q_{QS}(t) = (1-\alpha) Q_{QS,1}(t) + \alpha Q_{QS,2}(t) \tag{2}$$

that is a linear combination of two functions, $Q_{QS,1}(t)$and $Q_{QS,2}(t)$, expressed in equation (3) and (4) respectively, while α is a weight factor that combine the two functions describing the behaviour in non saturated and saturated conditions. In particular, in non saturated condition, when the patient arrival rate is below the rate of treatment, $\lambda \leq \lambda_U$, where λ_U is the patient arrival rate in saturated conditions, the quality of care is expressed by the function $Q_{QS,1}(t)$:

$$Q_{QS,1}(t) = \frac{\max\left(\left(WT_{crit} - WT(t)\right),\ 0\right)}{WT_{crit}} \quad if \quad \lambda \leq \lambda_u \tag{3}$$

The loss of healthy population is related to the patients that are not treated, so in saturated condition when $\lambda > \lambda_U$, the function $Q_{QS,2}(t)$ can be written as

$$Q_{QS,2}(t) = \frac{WT_{crit}}{\max\left(WT_{crit}, WT(t)\right)} \quad \lambda > \lambda_u \tag{4}$$

where WT_{crit} is the critical waiting time of the hospital in saturated conditions, when = $_U$; WT_0 is the waiting time in normal operative conditions when = $_0$; and $WT(t)$ is the waiting time when = (t). When the hospital operates in saturated condition, it is not able to guarantee the normal level of QS, because the main goal now is to provide treatment to the most number of patients. Therefore, in this case the number of patients treated N_{TR} is a good indicator of functionality Q. The quantitative functionality $Q_{LS}(t)$ is then defined as a function of the losses $L(t)$, which are defined as the total number of patients not treated N_{NTR} versus the total number of patients requiring treatment N_{tot}. In this case, the functionality is defined as follows

$$Q_{LS}(t) = 1 - L(t) = 1 - \frac{N_{NTR}(t)}{N_{tot}(t)} = \frac{N_{TR}(t)}{N_{tot}(t)} \tag{5}$$

where the total number of patients requiring care N_{tot} and the total number of patients that do not receive treatment N_{NTR} are given by the following formulas

$$N_{tot}(t) = \int_{t_0}^{t_0+t} \lambda(\tau) \cdot d\tau ; \qquad N_{NTR}(t) = 1 - N_{TR}(t) = 1 - \int_{t_0}^{t_0+t} \min\left(\lambda(\tau), \lambda_u\right) \cdot d\tau \tag{6}$$

Finally, the total functionality $Q(t)$ of the hospital can be formulated as:

$$Q(t) = Q_{QS}(t) \cdot Q_{LS}(t) \tag{8}$$

2.2 Measuring waiting time

Health care systems are inherently complicated, in terms of details, dynamic and organizational aspects, because of the existence of multiple variables, which potentially can produce an enormous number of connections and effects. Furthermore, in a disaster, the emergency adds more complexity to the health care system. Several modelling methods are available in literature to represent these complex hospital operations; however, in this research we focus on *discrete events simulation models* (DES) and *metamodels*. Further details can be found in Cimellaro et al. (2009).

DES models are valuable tools for modeling the dynamic operation of a complex system, and in particular the emergency nature of a disaster can be easily incorporated in discrete event simulation, for different types of hospitals (Lowery, 1993). However, although DES models are valuable tools for hospital modelling, they are time consuming because they require multiple simulation runs for the results to be acceptable statistically due to the random nature of simulation experiments.

On the other hand, *metamodels* are easier to manage and provides more insights than DES models. A metamodel is simple set of equations that does not require a long execution time, as in the case of DES models, therefore it becomes a good candidate for modelling operations for any general hospital in disaster condition. The patient WT is the output variable of the simulation with the metamodel that is a double exponential function defined in Cimellaro et al. (2008). The metamodel needs to be calibrated, and the first problem to handle when dealing with disaster is the lack of data. This deficiency (Stratton et al., 1996) is related to the difficulties in collecting data during a disaster, because the emergency activity is the first aim, and the registration of the patient is, of course, not done with the usual procedure. Because of the above reasons, all parameters of the metamodel are regressed using outputs from DES model. An example of the shape of the *metamodel function* is given in Figure 2, where the dots are the patient waiting time obtained from simulations with DES model.

The metamodel is able to consider uncertainties within the parameters, because it provides one approach to statistical summarization of simulation results, obtained with a DES model, therefore is a generalized statistical model for a set of similar hospitals. In this particular case, the physical model describing the hospital is the result of a statistical analysis of Californian hospitals. Sensitivity analysis on the parameters estimation is given elsewhere (Cimellaro et al., 2009).

The resilience index is also affected by uncertainties because the entire process is a combination of stochastic variables that are taken in account in a more complex formulation described in the MCEER report of Cimellaro et al. (2009). However, in the paper for lack of space only a deterministic approach is described.

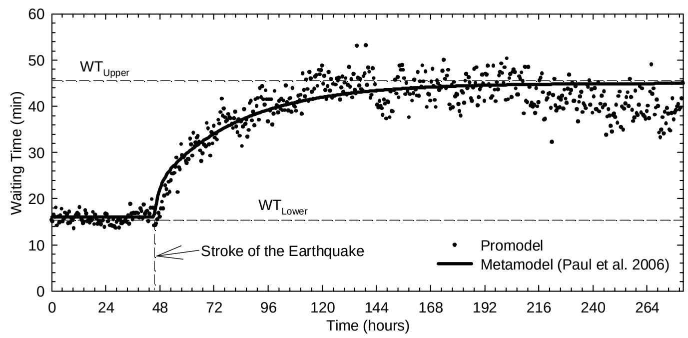

Figure 2 Metamodel (Paul et al. 2006)

2.3 Modelling damage in the organizational system of a hospital

Structural and nonstructural damage cause reduction of functionality of the hospital at the organizational level. The hospital however is more affected by nonstructural damage than structural damage, because if power water and medical resources are damaged, they can make the hospital useless. The metamodel described earlier is able to incorporate the effect of structural and nonstructural damage on the organizational model by incorporating a penalty factor that is used to update the available emergency rooms, operating rooms and bed capacity of the hospital (Figure 3).

Its value is determined by the fragility curves of each structural and nonstructural component inside the hospital. Fragility curves are functions that represent the conditional probability that a given structure's response to various seismic excitations exceeds given performance limit state (Cimellaro and Reinhorn, 2010b). From fragility functions is possible to evaluate penalty factors that are applied to all the internal parameters of the hospital (i.e. *B, OR, E*), where *E* is the efficiency measured as the number of operations per operating room per year.

The penalty factors PF_i for each structural or non-structural component are given by the linear combination of the conditional probabilities of having certain levels of damage. Four levels of damage are traditionally considered: P_1 slight, P_2 moderate, P_3 extensive and P_4 complete. These probabilities can be read on the fragility curves provided for each structural and nonstructural component. The total penalty factor affecting each component analyzed is given by

$$PF_i = a\cdot\left(P_1 - P_2\right) + b\cdot\left(P_2 - P_3\right) + c\cdot\left(P_3 - P_4\right) + P_4 \tag{11}$$

where the coefficients *a, b, and c* are obtained by normalized response parameters (e.g. drifts, accelerations, etc.) that define the thresholds of Slight, Moderate, Extensive and Complete damage states. For example, if a drift sensitive nonstructural component is considered, the coefficient *a* is defined as $a = drift_{slight}/drift_{complete}$. A complete list of damage states drift ratios for all building types and heights are provided in HAZUS (FEMA, 2005).

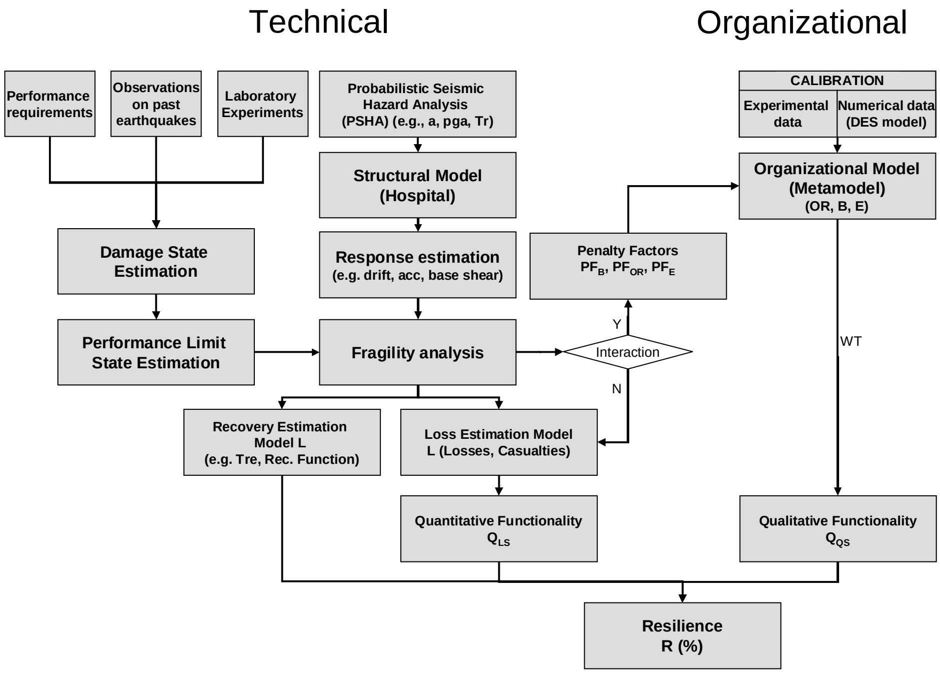

Figure 3 Flow chart to evaluate resilience of a hospital

The total penalty factor PF_{tot} affecting all the organizational parameters of the hospital is given by linear combination of the individual penalty factors using weight factors obtained as ratio between the cost of each component and the overall cost of the building

$$PF_{tot} = w_1 PF_{str} + \sum_{i=2}^{n} \frac{\left(1-w_1\right)}{n} PF_i \le 1 \tag{12}$$

where w_1 is the weighting factor of the structural component of the building; PF_{str} is the penalty factor of the structural component of the hospital; PF_i is the penalty factors of the nonstructural components considered; n is the number of non structural components. The proposed model incorporating facility damage can be used to identify the critical facilities, which would need increased capacities.

2.4 **Resilience of a roadway system**

In order to include the roadway system in the hospital network it is necessary first to evaluate the disaster resilience of the road network, which can be defined as the ability of the system to recover rapidly from an earthquake event. Let us define the recovery time T_{re} of a roadway system, as the "*time after the earthquake that would be required for the system wide travel times to attain their pre-earthquake levels*". The recovery time will vary over the range of earthquake events that could occur within the surrounding region. The recovery time T_{re} can be computed as function of the return period using programs as REDARS (Welner et al., 2006). Therefore, resilience and recovery time are directly related in a roadway system. An acceptable level of resilience should be determined by balancing the costs that would be required to upgrade the system to achieve a given recovery time against the socioeconomic impacts to society that would result if that recovery time is not achieved. The resilience of the roadway system depends on such factors as:

1. Seismic performance characteristics of the individual components within the system;
2. Rate at which damage to the components can be repaired;
3. Roadway links along which the damaged components are located;
4. Redundancy and traffic carrying capacity of the roadway links;
5. Trip demands on these system which will vary according to the post-earthquake traffic carrying capacity of the system's roadway links;

All these factors are considered in REDARS and therefore the program can be used to evaluate the disaster resilience of the *roadway system*. Then the disaster resilience of the *hospital network* can be valuated by adding at the waiting time *WT* of each single hospital the travel time to reach the hospital through the damaged roadway system. The total time is then compared with the critical waiting time of each single patient. The more you are far from the WT_{crit} the better is the functionality of the hospital network and the higher are the values of resilience.

3 **EXAMPLE**

The example describes a network of two hospitals modelled using the metamodel. It is assumed that they are 40 km away each other and they are located in urban area. The example models the damages of the two hospitals and of the network connecting the two facilities. The importance of the Operative Center (OC), keeping the contacts between the two hospitals and delivering the patients according to the real time capacity of the emergency departments has been investigated. The OC has the function to decide the best delivery of the patients, taking into account the real time waiting time and capacity of the facility, the distance from the place of injury, the damage of the network and the travel time to reach the facility. Different options are considered with and without OC. The scheme of the two hospitals model is illustrated in Figure 4.

where t_{oi} is the travel time necessary to reach an hospital i from the position 0 of the injury; t_{ij} is the travel time on the link $i-j$ (t_{12} in Figure 4) that is obtained by dividing the length of the link by its travel speed; t_{inf1} t_{inf2} are the time delay to collect and update the data of the hospital connected to the system to the OC; t_{el} is the time delay necessary to elaborate the data provided by the hospitals and make decision on the emergency policy to adopt.

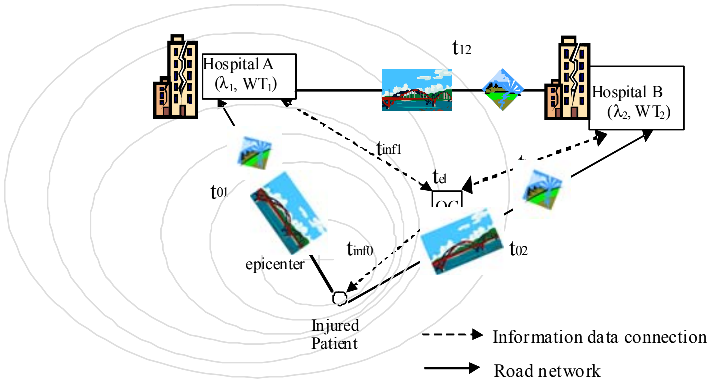

Figure 4 Scheme of the model of two hospitals with Operative Center (OC)

Therefore, the total time necessary to update the information related to the hospital network at the OC is

$$t_{st} = t_{\inf 1} + t_{\inf 2} + t_{el} \tag{13}$$

Travel time for a given link changes as the travel speed fluctuates, because of the damage condition of the network for example. For estimating the travel time between the position of the injured people and the nearest hospital, the speed – volume relationship developed by the U.S. Department of Transportation is used. The travel time on a given link is given by

$$t_i = t_{a0}\left[1+\alpha\left(\frac{x_a}{C_a}\right)^{\beta}\right] \tag{14}$$

where α=0.15, β=4.0, t_{a0} is the travel time at zero flow on the link *a*, given by the length of the link, divided by the free flow speed (FFS); x_a is the flow (or volume) on the link *a* (expressed in Passenger Car Unit per day); C_a is the "practical capacity" of the link a (expressed in Passenger Car Unit per day). The free flow speed (FFS) of a link can be defined as the average speed of a vehicle on that link, measured under low-volume conditions when drivers tend to drive at their desired speed and are not constrained by control delay. The FFS is the mean speed of passengers cars measured when the equivalent hourly flow rate is no greater than 1300 pc/h/ln (passengers car / hour / line). If speed studies are not available, the FFS can be determined on the basis of specific characteristics of the freeway section including:

1. The lane width;
2. The number of lanes;
3. The right shoulder lateral clearance;
4. The interchange density.

The mathematical formulation is given by

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \quad \text{[mi/h]} \tag{15}$$

where BFFS is the base free flow speed, that is 112 km/h in urban region and 121 km/h in rural region; f_{LW} is the adjustment for line width; f_{LC} is the adjustment for right shoulder lateral clearance; f_N is the adjustment for number of lines; f_{ID} is the adjustment for interchange density. Values of these parameters can be found in the tables shown in Cimellaro et al. (2009). This detailed procedure can be used when the roadway system is very simple, like in the example shown in Figure 4. Alternatively, for more realistic and complex roadway systems the program REDARS can be used to evaluate the travel times.

3.1 *Hospital network with and without operating system,*

The OC plays a key role in a hospital network, because it has the function to decide the best delivery of the patients, and it takes into account the real-time waiting time and capacity of the facility, the distance from the place of injury, the damage of the network and the travel time to reach the facility. For these reasons, two hospitals networks described in the following paragraphs have been considered with and without the Operative Center (OC).

Without OC, it is assumed that the two hospitals do not know the real time condition of the components of the system. The overflow is completely absorbed by the facility, which has the highest attractiveness, i.e. the shortest distance from the epicenter of the earthquake, while the second hospital works in normal operative condition. In this case, without loosing generality, we assume that *hospital A* is closer to the injured patient ($t_{01}<t_{02}$) and that there is no damage to the road network. Therefore, the arrival rates at the two hospitals defined respectively with subscript 1 and 2 before hospital A reaches its critical condition are defined as follows

$$\begin{aligned} \lambda_1(t) &= \lambda(t) \\ \lambda_2(t) &= \lambda_{20}(t) \end{aligned} \qquad if\ \lambda(t) < \lambda_{1U}(t) \tag{16}$$

Hospital A is able to provide the requested care until it reaches the saturated condition (λ1 = λ1U), then it starts to deliver the overflow to the next health care system. *Hospital A* can sustain the critical condition without any external help until all the resources (drugs and medical equipment) are sufficient to satisfy the demand ($t \le t_{sub}$), while *hospital B* has an increase in the normal flow.

In the case of saturated condition of *hospital A*, the arrival rates at the two hospitals are defined respectively as follow

$$\begin{aligned} \lambda_1(t) &= \lambda_{1U} \\ \lambda_2(t) &= \lambda_{20}(t) + \lambda(t) - \lambda_{1U} \end{aligned} \qquad if\ \lambda(t) \ge \lambda_{1U} \tag{17}$$

Therefore, the waiting time at both hospitals is given by the following expression

$$\begin{aligned} WT_1(t) &= WT_{1crit} \\ WT_2(t) &= WT_2(\lambda_2(t)) \end{aligned} \qquad if\ \lambda(t) \ge \lambda_{1U}\ \text{and}\ t \le t_{sub} \tag{18}$$

where λ_2 is given in equation (16). If $t \ge t_{sub}$ then *Hospital A* collapses because of lack of resources and it cannot handle anymore the critical arrival rate. In this case, the entire patient flow will be send to *Hospital B*.

In the presence of an Operative Center (OC) the patient will call the OC to have information about the status of the two hospitals that is described by the real time waiting time (*WT*). In this case, the OC can decide the optimal distribution of the number of patients per unit of time (arrival rate λ) between the two hospitals according to the following rule, for example

$$\begin{aligned} \lambda_1(t) &= \lambda(t) \\ \lambda_2(t) &= \lambda_{20}(t) \end{aligned} \tag{19}$$

if $WT_1(t)+t_{01}< WT_2(t)+t_{02}+t_{st}$ with $t_{01}<t_{02}$. In this case, it is more convenient for the injured patient going to *hospital A* that is also closer to him because it will be served in a shorter time. On the other hand, the arrival rates can be redistributed according to the following rule

$$\begin{aligned} \lambda_1(t) &= \left(\frac{WT_2(t) + t_{02} + t_{st}}{WT_1(t) + t_{01}} \right) \lambda(t) \\ \lambda_2(t) &= \left(1 - \frac{WT_2(t) + t_{02} + t_{st}}{WT_1(t) + t_{01}} \right) \lambda(t) + \lambda_{20}(t) \end{aligned} \tag{20}$$

if $WT_1(t)+t_{01} \geq WT_2(t)+t_{02}+t_{st}$ with $t_{01}<t_{02}$. In this case, if the total waiting time at hospital A exceeds the waiting time at *hospital B* increased by the transportation time t_{st}, the OC starts to redistribute the patients between the two facilities increasing the total resilience of the system, as shown in the results.

3.2 *Results of the analysis*

The results of a hospital network model (with and without Operative Center) are presented for different configurations of the system. It is assumed that:

- The first hospital (hospital A) is damaged;
- The distance of the two facilities is 40 km and the damage of the road network is moderate, according to REDARS classification (Werner et al. 2006);
- Initially only the first hospital absorbs the sudden increase of patient flow, while the second one works in normal operative conditions;
- The weighting factor considered for the qualitative functionality is equal to 0.8.

Four types of hospital networks configurations are considered:

1. Small size hospital (100 beds) with small surgical capacity (OR = 5) and low efficiency (E=600 operation per operating room per year) cooperating with a small size facility with medium surgical capacity (10 OR) and medium efficiency (E= 900 operation per operating room per year);
2. Small size hospital of configuration 1 cooperating with a medium size facility (300 beds), medium surgical capacity (10 OR) and medium efficiency (E= 900 operation per operating room per year);
3. Small size hospital of configuration 1 cooperating with a large size facility (500 beds) with high surgical capacity (15 OR) and highest efficiency (E= 1200 operation per operating room per year);
4. Two medium size hospitals (100 beds) with medium surgical capacity (OR = 5) and medium efficiency (E = 900 operation per operating room per year) cooperating each other.

Table 1. Configuration 1 and 2 of the hospital network

	Configuration 1							Configuration 2						
Operative Center	**Hosp. N.**	**B**	**OR**	**E**	**R Hosp**	**N p_{inj}**	**R network**	**Hosp. N.**	**B**	**OR**	**E**	**R Hosp**	**N p_{inj}**	**R network**
Without OC	**A**	100	5	600	51.18	603	40.83	A	100	5	600	51.18	603	49.35
	B	100	10	900	100.00	0		B	300	10	900	100.00	0	
With OC	**A**	100	5	600	98.69	4	87.01	A	A	100	5	600	98.69	91.19
	B	100	10	900	93.47	111		B	B	300	10	900	96.03	

Table 2. Configuration 3 and 4 of the hospital network

	Configuration 3							Configuration 4						
Operative Center	**Hosp. N.**	**B**	**OR**	**E**	**R Hosp**	**N p_{inj}**	**R network**	**Hosp. N.**	**B**	**OR**	**E**	**R Hosp**	**N p_{inj}**	**R network**
Without OC	**A**	100	5	600	51.18	603	55.73	A	300	10	900	94.80	115	90.34
	B	500	15	900	100.00	0		B	300	10	900	100.00	0	

Number of injured persons

With OC	**A**	100	5	600	98.69	4	98.23	A	300	10	900	97.66	53	93.65
	B	500	15	900	99.54	12		B	300	10	900	99.13	1	

Results show that the presence of the OC improve resilience of about 50% for the first three configurations (Table 1, 2) when the two hospitals have different capacities. On the other hand, the presence of the OC (configuration 4) is not that effective for two medium size hospitals of the same capacity (Table 2). The reason of this result is because the mid size hospitals A and B are already capable to absorb the patient arrival rate by themselves, as proved by the high values of Resilience index, therefore the improvement of the OC is less evident (around 3%).

4 CONCLUDING REMARKS

The resilience of a hospital network has been estimated including the influence of the facility damage on the organizational system and the roadway system. Each hospital in the network has been modeled using the metamodel that describes the hospital dynamic response in term of waiting time defined as the time a patient has to wait before receiving treatment. The impact of an Operative Center in the global resilience of a hospital network has been investigated. Results shows that the Operative Center improves the disaster resilience of the hospital network, although this improvement may not be so evident when medium size hospitals of the same capacity are included in the network. The results of the proposed model can be used to evaluate the optimal allocation of resources, the transport vulnerability and capacity, the structural vulnerability of the building and the hospital stock. A regional planner could make use of the proposed model in various ways. It could be used to perform a clean-slate design for an earthquake prone region. In such a design it is assumed that no hospitals have been built and the design tells us where to build hospitals and what capacity each hospital should be. However, a more likely situation is one in which hospitals already have been built in an earthquake prone region and a decision has to be made on capacity reallocation between these sites so as to best prepare for an earthquake.

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