Disaster Resilience of hospitals considering emergency ambulance services

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ABSTRACT

The paper presents a new methodology to evaluate functionality and resilience of healthcare facilities considering the effect of the ambulance service during extreme events such as earthquakes. The main parameter considered to measure functionality is the waiting time of the injured person, before receiving assistance considered directly from its initial location after the extreme event. The damage of the road network and the distance of the injured person from the hospital is considered in the model, therefore interdependency between the hospital network and the road network is taken in account in the model. Finally the proposed methodology has been tested using different case studies to evaluate performances and weaknesses of the system and of the used dispatching policies.

INTRODUCTION

In the last decade, communities have proved to be vulnerable to extreme events, because they do not have sufficient experience on how to manage disasters. In fact, according to the Word Bank, the natural hazards, mostly earthquakes and storms, have caused 3.3 million deaths between 1970 and 2010 (i.e. about 82.500 a year with large year-to-year fluctuations) and have cost of $2,300 billion (in 2008 dollars) between 1970 and 2008. Often small damages can become catastrophes when the communities have no access to the emergency services to face them, so the concept of resilience – that is the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters, plan and enact an effective strategy to recover its activities so as to minimize social disruption – has gained attention. Indeed, the communities are accepting that they cannot prevent every risk, but rather must learn to adapt and manage risks in a fastest way that minimizes impact on human and other systems. To do this well, emergency managers must prepare plans in advance based on the resources available to them. The rapidly changing information during a disaster suggests developing models that can simulate the healthcare response to a disaster during the emergency. The PEOPLES framework has been used to investigate the emergency events evaluating the disaster community resilience. This framework (Renschler et al., 2011) is built on and expands on previous research at MCEER, linking several resilience dimensions (i.e., technical, organizational, societal, economic, etc.) and resilience properties (i.e., R^4: *robustness, redundancy, resourcefulness, and rapidity*) to model the overall behaviour of communities. The holistic framework provides the basis for development of quantitative models that measure continuously the functionality and resilience of communities against critical events. The seven dimensions have been identified with the acronym PEOPLES: *Population and demographics, Environmental/Ecosystem, Organized governmental services, Physical infrastructure, Lifestyle and community competence, Economic development, and Social-cultural capital.*

The interdependencies among the categories and the dimensions are the key to understand the performances of the community. For example, a damaged road might prevent access to some sub-areas or hospitals of the community thus excluding all services. An early alert for a monitored (with displacements, etc.) landslide - due to incipient rain - can save many citizens, enhancing the level of security in the area. The economic losses, during the recovery, may involve a slowdown of the recovery process. These examples show that the functionality of one sub-category is NOT only a function of the damage state of itself, but also depends on the boundary conditions provided by the other sub-categories. Hence, the community resilience is strongly influenced on the decision-making, i.e. the pre- and post- disaster decisions.

LITERATURE REVIEW

The emergency disaster management life cycle (Figure 1) can be divided in six phases: response, recovery, mitigation, risk reduction, prevention, and preparedness. The proposed research falls into the prevention, preparedness, and response analysing effects at the community level of dispatching policies, of resource levels, and of interdependences between ambulances, hospitals, damages of the road network, and clean up works of roads.

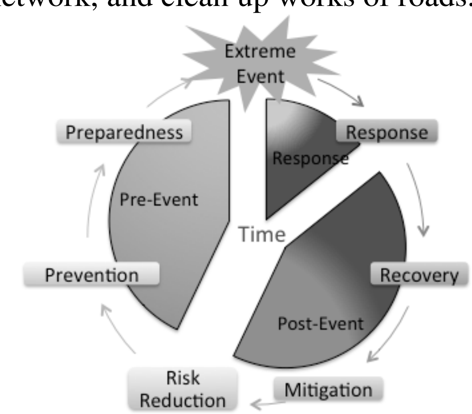

Figure 1 Emergency disaster management life cycle.

In general the models on emergency response are important because there is a relative scarcity experience of hospitals and of emergency managers in large-scale incidents compared to those daily. Moreover, the models can be used to identify weaknesses in response procedures (policies) for large-scale incidents that would not be apparent day-to-day practice.

Dynamic systems

The Dynamics System simulation technique are used to model larger systems in a simplest way and focuses on flows around networks than on the individual behaviour of entities, considering three main objects: stocks (e.g. number of patients in a hospital department), flows (i.e. the movement of items between different stocks), and delays. Mathematical programming is generally used to find solutions to the optimization problems, such as maximal zone coverage or minimizing response time. Dynamic systems have been developed for Emergency, Preparedness and Response (Wright et al. 2006) for applications such as vehicle dispatching and routing (Haghani et al. 2004), logistics coordination (Barboso & Arda 2004, Yi & Özdamar 2007) evacuation planning (Chien & Korikanthimath 2007), etc. The Hypercube Model (Larson 1974) was an early model for emergency medical service, where the whole response system is modelled as an expanded, spatially distributed, multi-server queuing system.

Discrete-event simulation systems (DES)

Discrete-Event Simulation (DES) is probably the most widely used simulation technique, which is often used to model complex systems with interacting entities, which would include emergency response systems. As the name suggests it models a process as a series of discrete events defined in advance.

In the 1980 has been developed a DES (RURALISM, Shuman et al. 1992) to design and evaluate rural emergency medical service systems, generating multi-type and multi-severity distributed emergency incidents, which are solved according to a set of pre-defined operational rules. Goldberg et al. (1990) built another comprehensive DES model to evaluate the emergency system performances simulating the response to emergency calls with a multi-server queuing system. This model has not a flexible application because was extensively validated with the data of Tucson, AZ. Moreover, DES models have been used to simulate operations in hospitals, such as: the process of patient flow through the hospital system (Boginski et al. 2007), or to establish a quantitative relationship between emergency department performances and upper limits of patient length of stay (Kolker 2008).

Agent-based simulation (ABS)

The final simulation method that will be looked at in this paper is Agent Based Simulation (ABS) technique. These models contain a collection of autonomous (self-directed) agents, which follow a series of predefined rules to achieve their objectives whilst interacting with each other and their environment. In ABS an “agent” could be a multitude of different things, from people in a crowd to cells in a body and because of this versatility it has been used to model a wide range of situations from flocking behaviour in birds to modelling the emergence and spread of cancer cells throughout a body.

Because of this, ABS models have been developed to model emergency responses. For example, Carley et al. (2004) developed a multi-agent simulation model (BioWar) to simulate biological and chemical attacks. Narzisi et al. (2007) developed PLAN-C to study the performance of populations under catastrophe scenarios. Daknou et al. (2008) studied applications of multi-agent systems for modelling emergency departments and proposed a tool to assist decision-making process for the care of patients at the emergency department. Wang et al. (2012) built a model of emergency response that includes pre-hospital care and transportation as well as emergency rooms.

PERFORMANCE OF HEALTH CARE SYSTEM

A large-scale disaster involves a large number of victims (affected people) with injuries at different severity levels. In particular, the entities (Figure 2) that work in synergy to face up and compose the emergency response are: casualties, medical technicians, policemen, fire fighters, and emergency vehicles.

Figure 2 Emergency response components

Therefore emergency managers, when the incident has been notified, have to assess the situation and the location of victims and then have to plan how to dispatch resources to deal with the disaster scenario during the emergency – i.e. to perform pre-triage, stabilization, evacuation, triage, and treatment of injured people. The pre-triage is usually performed at the scene by the first arriving medical technicians, while the standard triage is performed at hospital. It consists to screen and classify injured victims into several categories (i.e. Black, Red, Yellow, and Green) in away to assign lifetime and appropriate medical resources for treatment. For critical patients (Black, Red, and/or Yellow) who suffer severe injury, the medical emergency responders have to treat, stabilize, and evacuate them using ambulance service to an appropriate hospital for more definitive treatment. An ambulance may travel back and forth between the scene and various hospitals multiple times, depending on the damage and the recover (performed by the fire-fighters) of the road network. Moreover, when a patient arrives in the hospital has a queue time that is the amount of time that a person spends before being treated. This is function of the number of beds in intensive care unit or in general ward, of medical technicians, of patients into the hospital, and of medics.

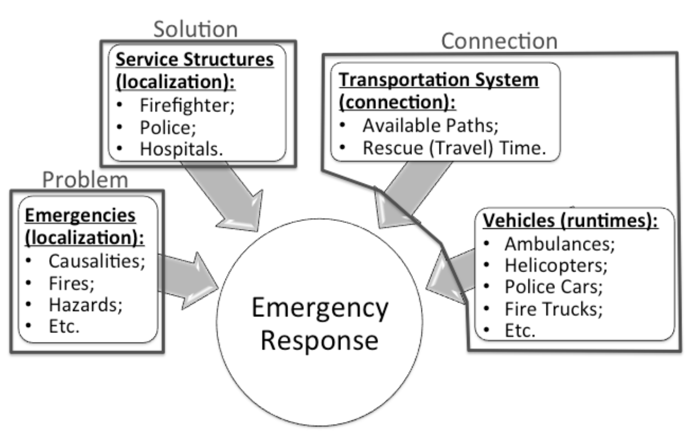

Figure 3 Problems, solutions, and connections of emergency response

Figure 3 shows that the problems to be solved are victims, hazards, fires, etc., while the solutions that minimize the social impact are the services structures – i.e. fire fighters, police, and hospitals. The connection between them are the transportation system – which depends on its damage status in terms of available paths and rescue (travel) time – and the available vehicles – e.g. ambulances, helicopters, police cars, fire trucks, etc.

The key role of interdependencies

The phenomenon of medical emergency response is strongly related to the interdependences between each entity of the system. Generally, the healthcare response to a mass casualty incident (0) – i.e. the road network and hospitals are free of damages – depends on:

- Localization of victims into the region;
- Severity levels of injured people (Black, Red, Yellow, and Green);
- Amount of available ambulances;
- Localization and treatment capacity of hospitals.

Therefore, the objective of ambulance services is to bring injured people to hospitals, according to: their severity levels, treatment capacity of hospitals, and minimum travel path.

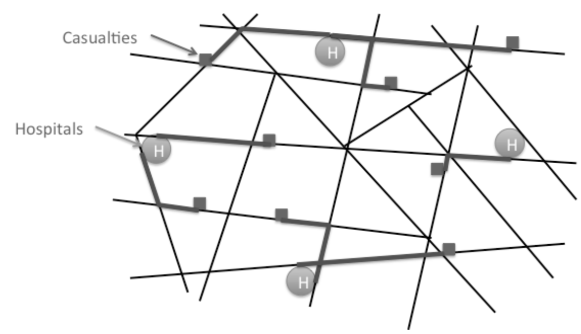

Figure 4 Ordinary transportation network

When a natural disaster has been occurred, it involved a large number of victims but also it damaged bridges, tunnels, roads (with realised debris), and strategic buildings (e.g. hospitals, operative centre, etc.), affecting the overall functionality of the healthcare system. In fact, treatment capacity of damaged hospitals is reduced and debris or obstacles on roads can affect the normal routing of ambulances making unreachable casualties and/or hospitals (Figure 5).

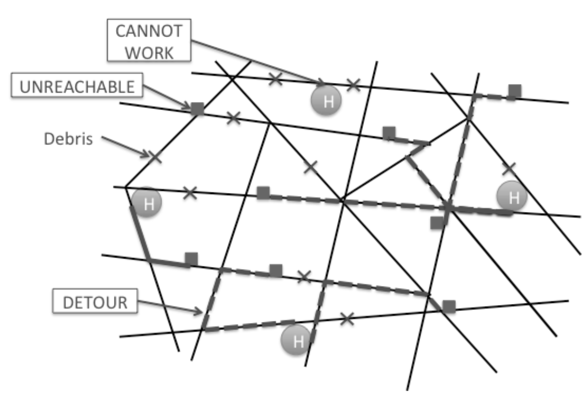

Figure 5 Damaged transportation network

If we not consider the fire-fighters service, the medical emergency response is strongly related to the localization of debris and/or obstacles on the road network (this is not acceptable), while considering the fire-fighters service (Figure 6), the healthcare response depends on:

- Localization of victims into the region;

- Severity levels of injured people (Black, Red, Yellow, and Green);
- Amount of available ambulances;
- Localization of debris and obstacles on the road network;
- Routing (dispatching policies) of ambulances and fire trucks;
- Localization and treatment capacity of hospitals.

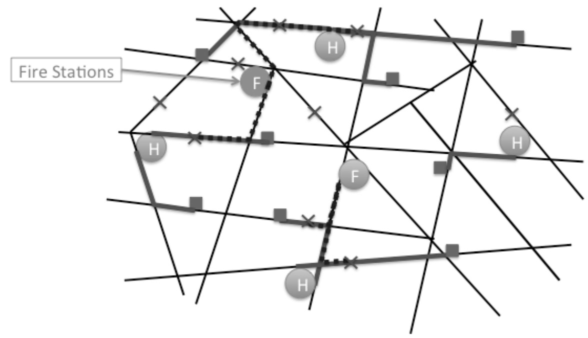

Figure 6 Recovered transportation network

Therefore, the objectives of emergency services (ambulances and fire-fighters) are to clean up debris and obstacles, and to bring injured people to hospitals according to: their severity levels, treatment capacity of hospitals, and the minimum travel path (considering detours due to debris or obstacles on roads). The basic emergency response objectives for maximizing the healthcare response are: for the ambulance system, to stabilize casualties at the scene and transport them to medical facilities as soon as possible with a priority based on their severity levels; for police and fire vehicles, to help and assist people during the emergency considering multiple and consequentially paths according to the runtimes of vehicles; and for hospital system, to accommodate and treat the largest number of victims as soon as possible.
Therefore, a model that simulates the emergency medical response requires to integrates the evaluation of: incident scene and/or patients localization, triage of causalities, ambulances and fire trucks routing for evacuation of causalities, hospital flow to provide definitive care, and a decision tool to decide the response activities according to information available.

PROPOSED AGENT-BASED SIMULATION METHODOLOGY

The objective of this research is to develop a new agent based simulation model to evaluate functionality and resilience of health care services during a natural disaster such as earthquakes – considering the interdependences between the ambulance services, the hospitals network, the damage of the road network, and the clean up works of roads – in order to demonstrate the effects of different policy options or available resources and to respond and minimize the disaster effects.

The methodology divides the problem in two blocks: risk and resilience assessments. The first block evaluates: the damage states of the buildings and of the road network (Arcidiacono et al. 2011, Arcidiacono & Cimellaro 2012), the distribution and severity levels (colour designation Red/Yellow/Green) of causalities according to the scenario time, the population distribution data, and damage state probabilities (FEMA 2005), and the residual functionality of hospitals (Cimellaro et al. 2010). The second block evaluates the disaster healthcare resilience according to the proposed agent based simulation model.

In this paper we will focus on the agent based simulation model that is characterized by the use of agents as entities in the system (i.e. casualties, ambulances, hospitals, obstacles, fire fighters, operative centre). According to Mical & North (2010), agents are identifiable as discrete individuals who are autonomous and self-directed. They can interact with each other and explore their environment based on pre-defined protocols that depend on their characteristics and rules. In an emergency response, responders and emergency managers (agents) begin with limited information about the disaster and make decisions according to information collects through communicating with other agents. For example, in a disaster, there is an initial notice (e.g. call from citizen, instrumental warning, etc.) that warns the operative centre, which sends first units of rescuers on the scene that report the situational gravity and give the first aid. When the situation is well defined, the emergency managers will adapt the response to the size, location, and type of disaster according to the available resources.

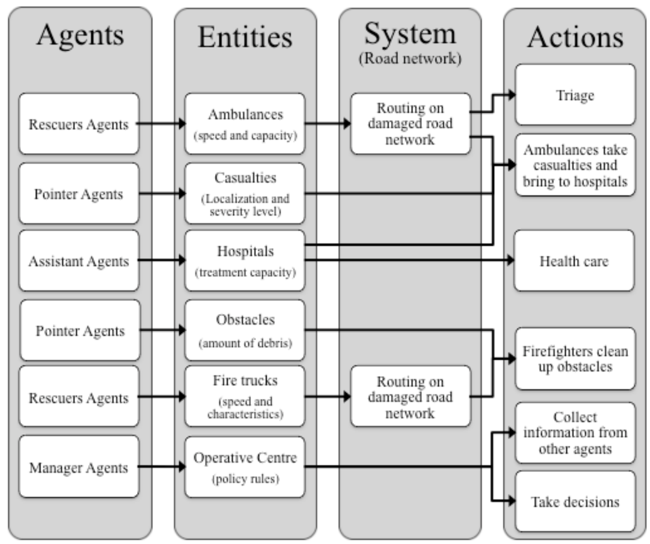

Figure 7 Agent Based Simulation model

Therefore, the agent based simulation model is great to model the emergence response system, because it models the interdependences between and among entities and the problem of information gathering during the response. In the proposed model (Figure 7) we defined four types of agents: Pointers, Rescuers, Assistants, and Managers.

Pointer agents are agents with abilities of information sending, but without those of decision-making or of information gathering. They cannot move through the system by themselves, but they can be moved or removed through or from the system (i.e. the road network) by the other agents such as rescuers and assistants. Pointer agents model casualties and obstacles that are characterized by localization, severity level, and amount of debris. Rescuer agents move through the system according to their internal rules or instruction from manager agents, can send information (such as localization, travel time, etc.) to other agents, and can bring or remove pointer agents. The ambulances and fire-fighters trucks are modelled as rescuer agents. Assistant agents cannot be moved, but they can send information and can accommodate and/or discharge from the system other agents (i.e. casualties) according to their internal rules (Figure 8). In this system, the hospitals are modelled with assistant agents that are characterized by localization and treatment capacity. Manager agents are full agents that collect information from other agents and use this information to direct rescuer agents according to their protocols to minimize the social impact of the disaster, i.e. the time from the disaster spent by the causalities to receive a definitive care. The operative centre is modelled as manager agent.

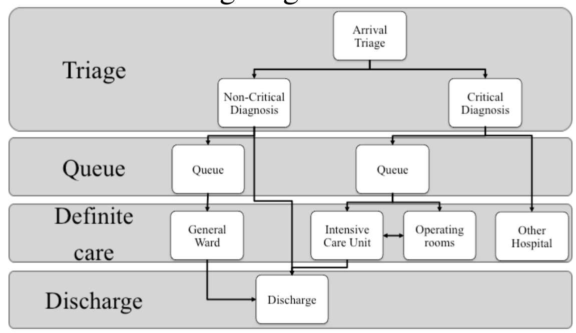

Figure 8 Hospital flow to treat a patient

The proposed model will be used to evaluate two potential dispatching policies of ambulances to face up the emergency response.

Performance of the medical emergency response

The main parameters that define the performances of the healthcare response are: the time of medical response T_{EM} (i.e. when all causalities receive a definitive medical care) and resilience index RI_M^{Ph} of medical system that is function of the resilience indices of medical entities $RI_h^{Ph,M}$.

$$RI_M^{Ph} = \frac{\sum_h w_h^{Ph,M} \cdot RI_h^{Ph,M}}{\sum_h w_h^{Ph,M}} \tag{1}$$

where: h is the medical entity index (i.e. F:Fire fighters, A:Ambulances, and H:Hospitals), $w_h^{Ph,M}$ are the weight coefficients for each medical category (for the case studies we adopted F:20, A:30, and H:50). The *accessibility* of the hospitals from the causalities – i.e. the possibility to reach a hospital from the causality place –, which is strongly influenced by the clean up works of fire fighters, has been identified with the medical resilience index of fire fighter services $RI_F^{Ph,M}$. This is analytically defined in the following equation.

$$RI_F^{Ph,M} = \frac{\int_{T_{Dis}}^{T_{Dis}+T_{EW}} Q_F^{Ph,M}(t) \cdot dt}{T_{EW}} \quad \text{with: } Q_F^{Ph,M}(t) = \frac{\sum_c w_{\tau(c)}^{Ph,M,F} \cdot NH(t, P_c)}{N_H \cdot \sum_c w_{\tau(c)}^{Ph,M,F}} \tag{2}$$

where: T_{Dis} is the disaster time (i.e. when the disaster occurred), T_{EW} is the recovery time (i.e. when the community functionality reaches 100%), τ is the severity level index of casualties (i.e. W:White, G:Green, Y:Yellow, R:Red, and B:Black), c is the casualty index, $w_{\tau(c)}^{Ph,M,F}$ are the weight coefficients for each casualty, N_H is the total number of hospitals, $NH(t, P_c)$ is the number of hospitals reachable from the initial position P_c of cth casualty at time t.

Other parameters that can describe the performances of the emergency medical response are: the average waiting time when an ambulance receives the command to keep a casualty and the average time to treat a patient in a hospital. These two parameters are analytically described by the medical resilience indices of ambulance $RI_A^{Ph,M}$ and of hospital $RI_H^{Ph,M}$ services.

$$RI_A^{Ph,M} = 1 - \frac{\sum_c w_{\tau(c)}^{Ph,M,A} \cdot TC_c}{T_{EW} \cdot \sum_c w_{\tau(c)}^{Ph,M,A}} \quad RI_H^{Ph,M} = 1 - \frac{\sum_c w_{\tau(c)}^{Ph,M,H} \cdot \left(TD_c - TE_c\right)}{T_{EW} \cdot \sum_c w_{\tau(c)}^{Ph,M,H}} \tag{3}$$

where: $w_{\tau(c)}^{Ph,M,A}$ and $w_{\tau(c)}^{Ph,M,H}$ are the weight coefficients for each casualty, TC_c is the time when an ambulance receives the command to keep the cth casualty, TD_c is the time when the cth casualty is discharged from the hospital or receive a definitive care, TE_c is the time when the cth casualty enter to the hospital.

CASE STUDIES

In this paper, we use the proposed methodology, which implement the PEOPLES framework, to evaluate the effects on the system of a set of alternative assumptions. These differ in the routing policies of ambulances, the available vehicle resources (i.e. ambulances and fire trucks), and the damages of the road network. The times of medical response and the resilience indices have been used as measurements to compare the set of alternative assumptions.

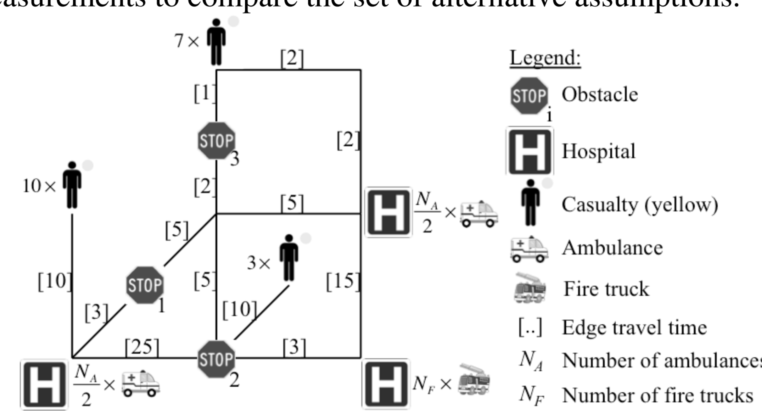

Figure 9 System analyzed

Figure 9 shows the configuration of the studied system. There are twenty casualties with yellow severity level that require medical care. For each of the three hospitals, we assumed that there is just one operating room and that on average a patient spends: five minutes for the arrival triage, twenty-five minutes to receive a definitive care or to be discharged, and a variable time due to queuing inside the chosen hospital. We introduced also three obstacles that fire fighters have to clean up during the emergency phase. Moreover, we assumed that the available ambulances are distributed in two of the three hospitals, while the fire trucks are in the third one. Furthermore, we adopt two dispatching policies of ambulances that minimise: (*i*) the time TE_c when an ambulance arrives to the chosen hospital and (*ii*) the time TD_c when the casualty is discharged from the hospital or receive a definitive care. The first policy considers as main parameter the travel time to the hospital, while the second considers also that the treatment of casualty can be delayed due to queuing inside the chosen hospital.

Therefore, eight case studies (Table 1) have been developed modifying available resources – i.e. the rescue vehicles such as fire trucks and ambulances – and obstacles on the road network.

Table 1 Assumptions of the case studies

Case	Policy	Ambulances		Fire trucks	Hospitals			Time to clean up the i^{th} obstacle		
		N_A	Pre-triage	N_F	Triage	Operating room		1	2	3
		[-]	min	[-]	min	[-]	min	min	min	min
1	*i*	4	10	3	5	1	25	70	60	60
2		4	10	3	5	1	25	70	60	60
3	*i*	4	10	0	5	1	25	70	60	60
4		4	10	0	5	1	25	70	60	60
5	*i*	4	10	-	5	1	25	-	-	-
6		4	10	-	5	1	25	-	-	-
7	*i*	20	10	-	5	1	25	-	-	-
8		20	10	-	5	1	25	-	-	-

The first policy has been assumed in the even cases, while the second policy was assumed in the odd cases. Moreover, in the first four cases, we assumed that there are three obstacles on the road network; while in the other cases the road network is free of obstacles, which means that fire fighters are not required. Therefore, the intervention of the firemen – thus the interaction between the ambulance services and fire-fighter services – has been modelled in the first two cases considering three fire trucks available to clean up the damaged roads. Furthermore, we considered that there are four ambulances available for the first six cases, while for case 7 and case 8 we assumed twenty ambulances. The eight cases were simulated using the proposed methodology that models the medical emergency response.

Table 2 Comparison of the obtained results

Case	T_{EM} min	$RI_F^{Ph,M}$	$RI_A^{Ph,M}$	$RI_H^{Ph,M}$	$RI^{Ph,M}$
1	240	90%	83%	88%	87%
2	330	90%	87%	75%	81%
3	inf	40%	74%	67%	64%
4	inf	40%	75%	62%	61%
5	235	100%	84%	88%	89%
6	368	100%	85%	70%	80%
7	235	100%	100%	72%	86%
8	330	100%	100%	64%	82%

Table 2 shows obtained results, i.e. the times of medical response and the medical resilience indices – evaluated with T_{EW} equal to 368 minutes. From the table we can observe the following phenomena.

The second dispatching policy is more powerful than the first, because it always obtains lower times of medical response. The resilience indices tell how much well the rescue resources were designed. Cases 7 and 8 – although they have the highest number of ambulances and have not any obstacles on the road network – were not well designed, because the ambulance system has overloaded the hospital system reducing its performances. Indeed, the case 5 – which has the same conditions of cases 7 and 8, except that has four ambulances instead twenty – has obtained the same time of medical response of case 7, but it has higher medical resilience indices, because the rescue resources are well balanced.

Cases 3 and 4 have the lower resilience indices, because an obstacle blocks three of casualties that could not receive any medical care. Indeed, the time of medical response tends to infinite. Moreover, the medical fire fighter resilience index is the lower; this means that the weakness of this system is that there are not fire trucks that could clean up the obstacles, which impede the normal traffic flow of the road network. Therefore, the cases 1 and 2 – that have available three fire trucks to face up the emergency – have obtained times of medical response and resilience indices similar to those of cases 5 and 6. This means that the weakness of the system – with fire fighters, or without obstacles – is the treatment capacity of the hospitals that reduce the overall performance of the medical response.

REMARKS AND CONCLUSIONS

The methodology proposed in this paper is developed to assist decision-makers in the emergency management of the health care system after critical events. The methodology evaluates the damage states, recovery time, and resilience index of the health care system analyzed. Interdependencies among the road network, the ambulances, the fire fighters, and the hospital services are considered in the model. An agent based simulation model which is able to find the best dispatching policy is used. The model maximizes the resilience index of the health care system RI_M^{Ph} and minimizes the recovery time T_{EM}, with respect to physical and social constraints. The proposed methodology was applied to eight case studies that show the importance of the accessibility of casualties after the disaster to the hospital, the dispatching policy of ambulances, and the interdependences between the components of the system.

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