Framework for Recovery Assessment of Hospital Cluster Following a Scenario Earthquake Event

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ABSTRACT: Modeling the recovery process of a community's infrastructure after the occurrence of extreme events is now at the forefront of research. Estimating post-disaster recovery of either single or multiple infrastructure in a community requires proper flow and interaction of information of the physical, economic and social components of the involved sectors. Understanding this recovery process is essential, particularly for critical infrastructure, such as a hospital, which is vital for a community's well-being. In this study, a full seismic functionality and recovery process of a hospital cluster, located in Shelby County, Memphis, TN, is quantified and assessed using a comprehensive framework. The hospital functionality assessment encompasses both quantity and quality of the hospitalization service. The quantity of the hospitalization service is presented as a function of the number of staffed beds, which is expressed as a combination of the staff, space and supplies availability while the quality measured by the patient waiting time. The demand on the hospitals, estimated based on a newly developed patient-driven model, which considers patient constraints, patient-to-hospital connection, hospital availability in addition to hospital cluster interaction. The hospitals dependency on other infrastructure during the recovery process and the interaction between different hospitals is modeled. Socioeconomic data related to hospital operation and recovery after the earthquake are used for the assessment. The presented framework accounts for limitation in resources such as the repair crews within the community, expected economic return for each hospital, and interdependencies between the different lifelines including the investigated hospitals. The results are consequently used within a testbed to support assessment of community resilience in The Interdependent Networked Community Resilience Modeling Environment (NIST-CORE), which is a computational platform currently being developed to compute various resilience goals.

1. INTRODUCTION

Earthquake losses have concerned researchers and engineers over the years. The focus has primarily been placed on achieving certain performance objectives such as life safety and collapse preventions that are associated with certain drift limit states (ASCE/SEI 7-10, 2010). In other studies and guidelines the focus has been placed on maintaining a certain level of functionality for various infrastructures after the events (FEMA 577, 2007). The recommendations provided in these studies, however, are more or less qualitative. There is therefore a need for developing frameworks that can be used to quantify the extent of the service that can be offered by infrastructure, in relation to the time-varying demand, following an earthquake. Hospitals in particular are of great interest, as a critical infrastructure, since shortage of hospitalization service could have catastrophic short-term and long-term effects on the community including increase in morbidity and mortality due to either direct injuries or overcrowding in emergency departments as well as the potential for outmigration and social instability.

Unlike most of main community services that are not directly contacted to the service receptor, healthcare service has a direct impact on community members. Therefore, functionality of these services is not only measured in terms of the availability of service but also the level of consumer satisfaction. In the case of a hospital, functionality can be defined as the ratio between quantity (Q_V) and quality (Q_S) of the services offered before and after the hazard occurrence (Cimellaro, Reinhorn, & Bruneau, 2011). The quantity portion of the offered services is usually estimated based on hospital capacity or number of staffed beds offered for patients based on daily rate (N_t). According to (Jacques et al., 2014), for these beds to be available for service, three main components are required, namely 1) trained personnel such as physicians, nurses and supporting staff, 2) qualified space to offer an acceptable hospitalization service, and 3) sufficient supplies. The definition of the quality portion of the offered service, on the other hand, is complicated due to its qualitative nature. Previous studies identified several dimensions to define quality of the hospitalization service (Kalaja, Myshketa, & Scalera, 2016; Maxwell J. R., 1984). One way to do so is through defining it as a function of losses of different hospital departments, while considering the possibility of service redistribution among the departments as indicated by Jacques et al. (2014). The patient waiting time is also commonly used to represent the quality part of the functionality as per Mccarthy, Mcgee, & Boyle (2010). The losses, which caused the changed in functionality, can be recovered over time. Undoubtedly, different parameters play critical roles in the level of recovery that can be achieved following a major event. These include for example the type of damaged components, extent of damage, and available funding resources (e.g. insured losses or federal sources). The recovery process of infrastructure or its components is usually represented by plotting functionality over time. The area under the functionality curve is an indication of extend of losses and recovery endured by the infrastructure and is indicative of resilience.

The notion of resilience was first developed in 1940s in the area of psychology and psychiatry (Garmezy & Crose, 1948) and has been later recognized as a critical indicator of behavior in different fields, and more recently by community planners and decision makers in relation to natural and man-made disasters. The literal definition of resilience is the capacity to recover quickly from difficulties; it can be also defined as the ability to offer proper level of functionality for a lifeline. Therefore, the aim of this study is to devise a comprehensive model that can be used as a tool to investigate the functionality and recovery of hospitalization service and to use the model to estimate demand on hospitals, while accounting for their interaction, following a major earthquake.

2. RECOVERY FRAMEWORKS

2.1. Hospital functionality Framework

Reduction in hospital functionality can be defined as the ratio between the amount of services offered after the hazard to the amount of services offered before the hazard. The functionality itself can be categorized into quality, measured by the patient waiting time (Peek-asa et al., 1998) and quantity, measured by the number of beds available for the patient (Lupoi, Cavalieri, & Franchin, 2013). The quality of the hospitalization service is function of the hospital demand and therefore is expected to reduce with increase in the number of casualties (Lupoi et al., 2013; Peek-asa et al., 1998). Usually capacity of hospitals is represented as the number of beds offered. For effective operation of these beds, they need to be supported by physical components such as electric and water systems, medical equipment and supplies, and qualified physicians and nurses as well as supporting staff (Jacques et al., 2014). The functionality of each hospital used in this study, is based on fault tree analysis and is outlined in detail in (Hassan & Mahmoud, 2018b).

The framework is presented in terms of quantity of the offered hospitalization service, which includes the effect of functionality of other lifelines or infrastructure as well as their interdependence. The fault tree presented here extends the work by Jacques et al. (2014), where functionality of an emergency department was estimated, so that it 1) applies to a complete hospital building and 2) accounts for interdependence between other relevant infrastructure. Estimating hospital functionality using the fault tree analysis is conducted by assigning functionality levels for different basic events. These basic events not only depend on the hospital building itself but are also highly related to the surrounding community's physical, economic and social infrastructure. Therefore, mathematical functions are introduced to represent the availability of each basic event. These functions are considering the components affect the availability of each basic event.

The quality component of the hospital functionality represents patient's satisfaction of the offered hospitalization service. Maxwell (1984) listed six different dimensions of healthcare quality service: relevance, accessibility, effectiveness, fairness, acceptability and efficiency, and economy. For immediate functionality drop after the earthquake, accessibility is the main dimension controlling hospitalization quality. The waiting time *W(t)* can be used to express service accessibility as per (McCarthy, McGee, & O'Boyle, 2000) and is calculated in this study as a function of the patient travel time to the hospital and the patient waiting time in hospital before getting the hospitalization service. Quality functionality is estimated as shown in Equation (1).

$$Q_S = [W_{max} - W(t))]/[W_{max} - W(0)] \geq 0.0 \qquad (1)$$

Where, W_{max} is the maximum waiting time when the hospital reaches its capacity; the waiting time, *W(t)*, is the waiting time during recovery of the hospital; and *W(0)* is the waiting time at normal operating conditions. The total functionality is estimated by combining both the quantity and quality functionalities as shown in Equation (2). Where, α_V and α_S are weighting factors.

$$Q = Q_V^{\alpha_V} * Q_S^{\alpha_S} \qquad (2)$$

The reason for multiplying the two measures of functionalities is because they are calculated in a probabilistic sense and as such their multiplication indicates the joint functionality of two independent events.

2.2. Hospital Demand Estimation

The demand on hospitals is controlled by patients and expected to increase after earthquakes due to the injures resulting from the earthquake damage. The total number of patients in each severity level is estimated as a function of the buildings damage level based on (FEMA/NIBS, 2003). The severity levels after the earthquake is classified into four categories based on the injury level and the patient need for hospitalization service: a) severity 1 where no medical care needed, b) severity 2 where some medical care needed; c) severity 3 where immediate medical care is needed, and d) severity 4 which is ultimately death. On other hand, the day-to-day demand on a hospital under normal operation can be estimated using each hospital's service area, which is well defined before the earthquake hazard and is expected to change after earthquake occurrence. Both regular and earthquake-related injuries have to be assigned to hospitals to avoid complications from injuries. The demand on hospitals is usually estimated based on either data collection or predictive methods (Barros, Weber, Reveco, Ferro, & Julio, 2010; Boyle, Ireland, Webster, & Sullivan, 2016). However, these methods are applicable during normal operation of the healthcare network and are not very relevant after earthquake disruption.

To estimate the demand on hospitals after earthquake occurrence, a patient-driven model is introduced in this study, which can be used to distribute patients to the surrounding hospitals. The presented model gives the probability each patient will go to a hospital within the healthcare network. The probability of a patient going to a specific hospital is function of patient constraints, availability of the connection between the patient and the hospital and capability of the hospital to treat that patient.

2.3. Hospital Interaction Framework

The interaction between hospitals can take place in different forms. Closure or partial closure of any hospital is expected to affect the demand on other surrounding hospitals. Transferring the patients, staff, resources, etc. can significantly change the functionality and the recovery of hospitals. However, in general, the ability to perform the transfer process is function of the existence of agreement between hospitals. The hospitals with the same management or the same brand have the higher willingness to transfer.

To ensure that the patient will receive the required medical care, the hospital might offer to transfer the patient to other hospital specially when it reaches the capacity or when it cannot treat the patient (Kulshrestha & Singh, 2016). The patient transfer process is function of the patient case criticality. For instance, some patients can only be transferred using air ambulance while others can use the regular ambulance. Equation (3) is used to calculate the number of the distributed patients (N_{dist}). Where, $\varepsilon(t)$ is the maximum capacity of the hospital, which varies by time based on the available number of staffed beds, $I(t)$ is the interaction matrix. The interaction matrix, shown in Equation (4), represents the probabilities (P) that hospital i will transfer a patient to one of the other hospitals within the healthcare system, where, n is the total number of the hospitals. The diagonal entries of the matrix denote the probability of a patient transferring to a hospital in which he/she already reside and as such they are zero. In addition, Equation (5) shows the demand on hospitals after transferring the patient.

$$N_{dist}(t) = \big(N(t) - \varepsilon(t)\big) * I(t) \tag{3}$$

$$I(\mathrm{t}) = \begin{bmatrix} 0 & P_{i,j+1} & \cdots & P_{i,n} \\ P_{i+1,j} & 0 & & P_{i+1,n} \\ \vdots & & \ddots & \vdots \\ P_{n,j} & P_{n,j+1} & \cdots & 0 \end{bmatrix} \tag{4}$$

$$N_{mod}(t) = N(t) - N_{dist}(t) \tag{5}$$

It worth noting that the patient transfer process is complicated and not all cases can be transferred. Fault tree analysis used to estimate the probability of patient transfer, which will be utilized in the calculations of the intreaction matrix *I(t)*. Different factors control the patient transfer decision: 1) patient constraint, 2) hospital-to-hospital connection and 3) receiver hospital availability. The main constraints that might control the patient transfer are either case criticality or insurance coverage. On the other hand, the presence of a smooth transfer and the availability of connections between hospitals is expected to encourage both the patient and the hospital to make the transfer decision. In addition, capability of the receiver hospital to safely transfer and treat the patient have major effect on this transfer decision.

2.4. Hospital Cluster Recovery Framework

A discrete Markov chain process is utilized in this study to estimate recovery for the various hospitals components such as corridors, elevators, stairs, and structural and non-structural components, through discretizing the functionality to different independent sub-levels. Since there are typical limitations in available resources following an extreme event, the resources are distributed to different lifelines based on their importance and significance in community recovery. Previous studies by Hassan & Mahmoud (2018a, 2018b) showed that water, power, transportation, telecommunication, wastewater and the drinking water, in addition to different supplies, are important factors affecting hospital functionality. Moreover, in the work by Cimellaro (2016), leadership indices were assigned to the various lifelines to represent the importance of the lifeline and its effect on other lifelines. The highest leadership indices were assigned for the government, electricity, emergency department, transportation, food supply and water. In addition, Ramachandran et. al. (2015) developed a priority matrix for estimating recovery of different lifelines and showed that transportation has the highest priority since roads are essential for any repair crews to reach the damaged building or infrastructure. In addition, electric power network was shown to be the second lifeline to be restored followed by communication, water, and sewer water.

Equation (6) shows the Markov chain process, which includes the interaction matrix, E, that dictates the effect of functionality of each lifeline on the repair process of the other considered lifelines. This equation can provide an estimate of lifeline, n, functionality, Q_n, based on the assigned repair resources, x_n, for damaged components as function of time accumulation after earthquake occurrence, $k\Delta t$. Where, k is a counter and Δt is the time increment from the onset of earthquake occurrence to total recovery. The functionality at time, $k\Delta t$, is calculated using the initial functionality, $Q_n(0)$. The transition probability matrix, P_n, is used to introduce the probability that lifeline, n, will successfully transfer to the next state of functionality. The adjustment factor, A_n, is used here to adjust the transition probability matrix, P_n, to consider the effect of lifelines interaction. This adjustment factor depends on the interaction matrix, E, as a multiplication of the α_j factor for each lifeline from lifeline one to lifeline N as shown in Equation (7). The factor α_j can be set equal to one if the interaction factor, e_{nj}, equals to zero or Q_j/α_{nj} if e_{nj} is more than zero. Each interdependency factor is an element of the interaction matrix as shown in Equation (8). The factors, e_{ij}, represent the effect of lifeline j on lifeline i. Therefore, the interaction matrix is utilized to simulate the relationship between the different lifelines and their effect on each other and on the hospital repair process.

$$Q_n(x_n, k \Delta t) = Q_n(0) * \prod_{j=0}^{k-1} A_n P_n(x_n, j \Delta t) \quad (6)$$

$$A_n = \prod_{j=1}^{N} \alpha_j \quad (7)$$

$$E = \begin{pmatrix} e_{11} & \cdots & e_{1n} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nn} \end{pmatrix} = e_{ij} \quad (8)$$

3. CASE STUDY

Shelby County, Tennessee is used as a testbed to demonstrate and evaluate the previously introduced frameworks. Shelby County has 21 hospitals that provide medical care for a population of 936,961. These hospitals have a total of 4730 staffed beds, which have average ER visits of 432 per each 1000 population a year. Most of these ER visits are not major and only lead to 4 inpatients per each 1000 population a year. In addition, some hospitals in Shelby County have the same brand name and/or the same managements, therefore the probability of patients and resources transfer between these hospitals is higher.

A scenario earthquake with magnitude 7.7 and origin located at 35.3N and 90.3W is selected. This earthquake is expected to impact various lifelines and buildings within Shelby County and result in a number of deaths and severities as shown in Fig. 1(a) and (b) for severity level 2 and 3, respectively. Moreover, people with severity level 2 require immediate medical care; therefore, they have priority to receive healthcare and are expected to stay longer in a hospital. Demand on each hospital is classified into a regular demand, which refers to injuries that is not related to earthquake and additional demand caused by the earthquake. The patient-driven model with hospital interaction model are applied in a preliminary analysis to obtain the demand on each hospital and estimate the total number of patients that will be transferred. Fig. 1(c) shows the selected hospital by each patient at day 1 after the earthquake in each census tract within Shelby County. It also displays total number of available staffed beds, average waiting time and average hospitalization service functionality at this day in Shelby County.

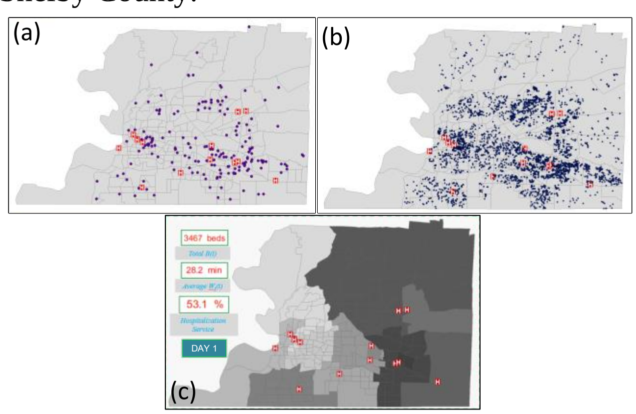

Fig. 1. (a) Severity level 2 (immediate medical care needed), (b) severity level 3 (some medical care needed) and (c) patients distribution per hospitals

Earthquake damage at hospitals is mainly function of both the earthquake intensity and buildings' earthquake damage resistance. It can also result to damage to transportation, power, telecommunication, water and wastewater systems, which have a direct effect on hospitals that depend on these systems. The previously-mentioned frameworks have been applied to Shelby County to estimate the effect of earthquake damage on hospitals, direct social and economic losses resulting from this earthquake and immediate functionality drop for these two systems. Recovery model, which is function of repair resources and allocation of these resources to achieve specific targets, is utilized. Dynamic optimization with different objective functions has been used to distribute repair resources to all hospitals in Shelby County. Fig. 2(a) and (b) show quality and quantity portion of the hospitalization service for each hospital, respectively. Fig. 2(c) shows the total functionality after the selected earthquake scenario.

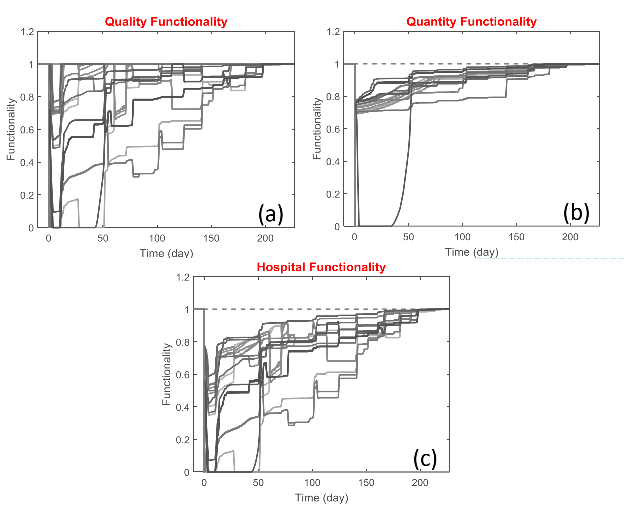

Fig. 2. (a) quality functionality, (b) quantity functionality and (c) total functionality of the hospitals in Shelby County

4. CONCLUSIONS

In this study, a framework for estimating hospital cluster functionality and recovery after occurrence of a scenario earthquake are introduced. Followings are the major findings form this study:

- Considering the quality of the service as a part of the functionality is essential for fully quantifying functionality term.
- Hospital and transportation network functionality are the most significant component in estimating the patient demand immediately after the earthquake.
- Including hospital interaction is critical for reduce the patient waiting time.

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