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A SIMULATION MODEL FOR ESTIMATING HOSPITAL CAPACITY DURING EARTHQUAKE EMERGENCY

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Abstract

Many disastrous hazards (e.g. earthquakes, floods, tsunamis, storms or hurricanes, and terrorist attacks) can destroy buildings and infrastructures, causing massive economic loss and casualties within a short period. As important parts of communities, hospitals in earthquake-prone areas are required to ensure their functionality and receive the sudden surge of patients during emergency. However, most medical facilities are already saturated in normal conditions, and the gap between expanded demands and limited resources will affect the rescue and recovery following disasters. This may increase the number of casualties. For improving the performance of healthcare system, hospital resilience is getting attention. It is defined as hospitals' ability to withstand and absorb the shock of disasters, and it focuses on the functionality and recovery process of buildings and infrastructures. The first step in resilience assessment is to define and quantify the functionality or capacity of hospitals. The purpose of this paper is to propose a model for estimating the capacity of hospitals. Discrete event simulation method is developed here to model a case study hospital in China. Injury types, arriving rates, treatment rules, emergency plans and medical resource are included in the model. Patients that arriving at hospitals are classified as red, yellow, and green color codes, then they follow different treatment processes. The data of earthquake related patients collected during Wenchuan Earthquake is used as arrival rates. Hospital capacity is defined as the critical arrival rate that cannot accept. By sensitivity analysis, the importance of different medical rooms is identified and the suggested minimum number of rooms is given. The results indicate that the proposed model is able to simulate the medical process. Triage, DR, and operating rooms are the most essential medical parts for the treatment of the injured in earthquakes. The mode of arrive rate has a very large impact on the performance of hospitals. The estimation results of hospital capacity under different arrival modes differed by nearly ten times. It is recommended that the results of capacity estimation should give the total number of patients and detailed arrival rates at the same time. The presented model is able to provide policymakers with a tool to optimize patient routing and emergency plan.

Keywords: hospital, capacity estimation, earthquake, emergency, simulation model

1. Introduction

Earthquakes can demolish many buildings, kill and injure thousands of people in a few seconds. Hospitals are expected to offer medical services timely for patients in order to reduce the impact on human life. However, most medical facilities are already saturated in normal conditions, and the gap between expanded demands [1] and limited medical resources will affect the rescue of patients [2, 3]. This represents hospitals a vast medical challenge [4, 5]. Resilience of healthcare facilities is defined as the ability of hospitals to maintain pre-earthquake functionality and recover to a new level. Compared to performance-based earthquake engineering (PBEE), it focuses more on the functionality and recovery. The estimation of capacity is a key part of seismic urgent handling for hospitals in emergency plan. It is also the base of hospital seismic resilience assessment.

A hospital is a complex system which is composed of buildings, equipment, medical staff, patients and rules. Fault tree analysis [6, 7] can be used in the estimation of hospital capacity, but it is difficult to get quantitative results of functionality. A method that can simulate the patient process from arrival to departure and consider organizational factors in hospitals may be better. Discrete event simulation (DES) can simulate systems whose states are changed in discrete intervals [8], and it is able to track movement of patients in hospitals, model stochastic factors affecting systems and get responses over time. Yi et al [9] established a simulation model for hospitals based on DES and developed a parametric regression meta-model for real-time estimation. Cimellaro [10] developed a model for an emergency department and incorporated the influence of physical damage by penalty factors. They used the injury data in Northbridge Earthquake in DES and meta-models which have been used in the resilience framework for hospitals [11, 12].

DES shows great potential in the simulation of hospital operation after earthquakes. We should be cautious about the characteristic of patients (arrival rates, severity distribution, etc.) that varies with earthquake magnitude and location. The application of the meta-models should be limited in Northbridge or similar regions. As a country that is frequently hit by severe earthquakes, China urgently needs to accurately estimate the hospital capacity of treating patients after earthquakes. The data of patients collected during the Wenchuan Earthquake of 2008 provided an opportunity for this work. The direct use of DES, but not meta-model, is accept here for generality based on the experience in Chile [13].

This paper first introduces the treatment process of patients, and proposes a method of establishing a DES model for hospitals. The arrival rates and distribution of injuries in Wenchuan Earthquake are analyzed, and West China Hospital is selected as a case study to establish the hospital simulation model. Finally, the performances of treating patients with two different patient arrival rates are compared, and the hospital capacity is estimated by increment arrival rate analysis. Considering that the hospital may be damaged after the earthquake, the minimum needs of medical departments are found for different treatment levels by sensitivity analysis.

2. Method

Falling objects or building collapse in large earthquakes can cause patients with multiple types of injuries such as fractures, soft tissue and crush injuries on extremities, head and neck [14]. According to guiding principles for emergency patient classification, emergency departments are divided into three areas corresponding to the three different color codes for patients: red, yellow and green. Red codes (emergency) are patients in immediate danger of life or severe disability who need to be rescued immediately. Yellow codes (urgency) are patients who will not in danger of life for a short time. Green codes (minor urgency) have no acute symptoms and need relatively few resources to complete treatments.

Patients will be first graded and assigned a color code based on their severity and required medical resources when they arrive at the hospital. Then they will go through different medical parts to complete their treatment according to the color codes after triage. Red codes are assumed correctly to skip the triage and directly go to rescue for vital emergency care. Then they undergo examination and enter operating rooms (OR). Yellow codes would enter the general ward after examinations and surgeries. Green codes can leave hospitals after triage and quick treatments in treatment rooms (TR) without examinations and surgeries. It should be noted that red and yellow codes may have different need of examinations and surgeries depending on their injuries. The waiting time (WT) of patients should not exceed the critical waiting time which is defined as the time that they can wait before a specific treatment. If not, patients' condition may worsen or even be life threatening and their severity will be changed. For example, yellow coeds will become red codes patient when the critical waiting time is reached. The treatment process for patients with different color codes is shown in Fig.1.

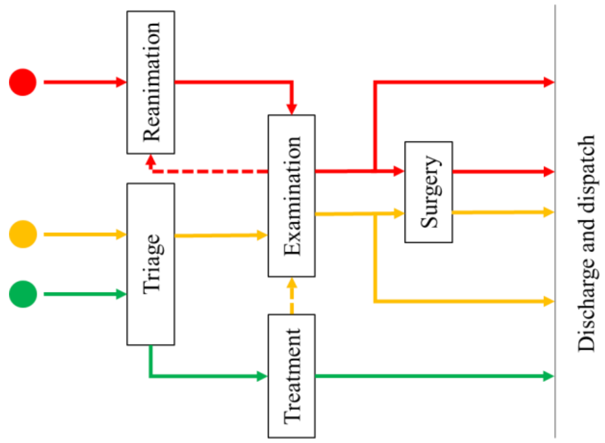


Fig. 1 - The treatment process for patients with different color codes. The dashed line indicates the deterioration of severity.

The process of patients receiving treatment is a kind of queuing behavior. DES can track the state changes of entities with discrete intervals in queueing structure systems. The first step in building the model is to establish the relationship between basic DES elements and medical parts in hospitals. A DES model is composed of entities, resources, processes and parameters, etc. Entities are the persons or items that flow through processes and their states may be changed and recorded. Resources are defined as a set of units that can be seized and released by events to change the state of entities. Processes give the relation between entities and resources. In the DES model, entities are the earthquake-related patients who need medical care, and resources correspond to the medical rooms. Meanwhile, hospitals may not accept, exam, and treat all patients at the same time due to the large number of patients and earthquake-induced damages. Queue rules need to be designed in the DES model where patients with less remaining survival time are assumed to have higher priority.

A method is then needed to estimate the hospital capability. Instead of the percentage of healthy population and the number of patients/day proposed by Bruneau et al [15], the number of patients that can be treated or cannot be treated in time (numOT) can be the indicator of hospital performance. As the magnitude of earthquakes increases, the increasing number of patients will make hospitals' ability reach the upper limit. A critical arrival rate is determined by increment simulation when a large number of earthquake patients get worse or die. Hospital capacity is defined by the critical arrival rate.

3. Model

According to the proposed method, a hospital DES model can be established. The arrival rate and type of the injured in earthquakes are affected by many factors such as earthquake magnitude, distance, and communication, etc. Two types of patients' data in Wenchuan Earthquake are used in this model: (1) literature and reports [16-18]; and (2) field data of West China Hospital of Sichuan University (WCH) in Wenchuan Earthquake. The closest hospital to epicenter is People's Hospital of Deyang City (PHDC), and WCH mainly treated patients that are transferred from other hospitals. The dynamic variations in PHDC and WCH represent two kinds of typical situations. Both of them are Level 3 and Grade1. The dynamic variations of earthquake-related admissions in PHDC and WCH are illustrated in Fig.2 (the day of earthquake occurred is set as the 0th day). After the earthquake, PHDC admitted over 800 patients at the first day, then the number dropped rapidly and decreased slowly after the 2nd day which was similar to the report about the Northbridge Earthquake [19]. The number of admissions in WCH increased gradually and stayed stable for a long time, and the peaks appeared at the second and eighth day. The data will be used here as the input of DES model and patient arrivals are assumed to follow non-homogeneous Poisson process. The dynamic variations of admissions of PHDC and WCH will be referred to as PHDC mode and WCH mode afterwards.

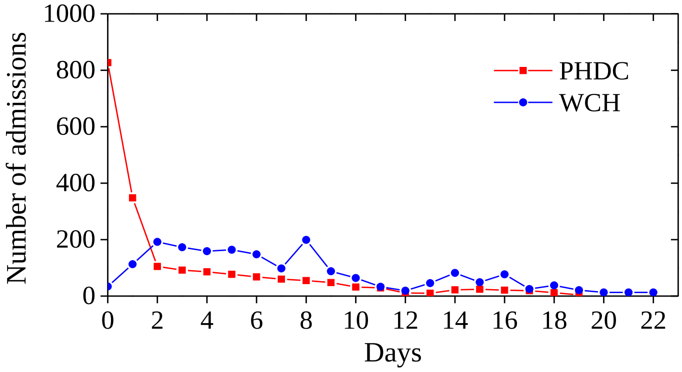


Fig. 2 - Dynamic variations of admissions following the Wenchuan earthquake

The injuries are usually various and need different treatment processes. In Wenchuan Earthquake, patients were first diagnosed based on the International Classification of Disease and given a 6-point Abbreviated Injury Scale (AIS) where 1 means minor and 6 means maximal. Then the patients would be graded and classified with a color code by severity. Patients with unknown injury region and diagnoses are excluded, and the distribution of injuries and color codes collected by WCH [20] are listed in Table 1 and Table 2.

Table 1 - The distribution of injuries in WCH and PHDC

Type	Region	Diagnose	PHDC	WCH
1	Head and face	Fracture	20	10
2		Wound and brain injury	256	182
3	Trunk	Fracture	163	326
4		Wound and organ injury	198	140
5	Extremities	Fracture	415	658
6		Others	159	204

Table 2 - The distribution of color codes of injury types

Type	Green (%)	Yellow (%)	Red (%)
1	83.4	15.1	1.4
2			
3	0.3	92.9	6.8
4	53.1	45.6	0.9
5	31.5	67.2	1.2
6	80	20	0

For red codes, they need rescue and surgery as soon as possible. Yellow codes and green codes only need surgery and simple treatment before the critical waiting time respectively. The critical waiting time (WTcrit) for three color codes is assumed in Table 3. It should be noted that the time spent before hospitals is not included in the WTcrit. For patients, they need a period of time to accept treatment in one medical part, and related resources would be occupied for a certain time. The stay time of patients in triage and treatment room are set to 5 min. The stay time in CT, DR, and ultrasound are set to 15 min, 10 min, and 10 min respectively. The rescue for the red codes would takes 20 min. Meanwhile, the need of examinations and surgeries may vary according to the severity and injury type of a patient. The probability and time of examination and surgery are given in the Table 4 based on the records of earthquake patients.

Table 3 - WTcrit for red, yellow and green codes

Color codes	**Red**		**Yellow**	**Green**
	Rescue	**Surgery**		
WTcrit (min)	40	80	120	180

Table 4 - The settings about examinations and surgeries in the model

Type	**Examination**			**Surgery**	
	DR	**CT**	**Ultrasound**	**Prob.**	**Time (min)**
1	-	100%	-	15%	150
2	-	100%	-	15%	200
3	85%	15%	-	20%	130
4	25%	-	50%	30%	230
5	90%	-	-	45%	90
6	-	-	-	30%	20

After earthquakes, a large number of patients would arrive at hospitals and enhance the risk of aggravating conditions. So emergency plans are required to be prepared and implemented after earthquakes. Once emergency plans are activated, the rules on medical staff and the use of equipment will be changed to help hospitals respond efficaciously to emergency situations. Structural, non-structural components, and equipment may be damaged by earthquakes. Considering the role of the emergency plan, hospitals would stop receiving normal patients temporarily, and all medical resources are prioritized for earthquake patients. The number of available medical rooms and staff is assumed to be equal to that in normal. The number of medical rooms available for earthquake patients is listed in Table 5.

Table 5 - The number of medical rooms

Triage	**Rescue**	**CT**	**DR**	**Ultrasound**	**OR**	**TR**
4	4	14	32	40	81	4

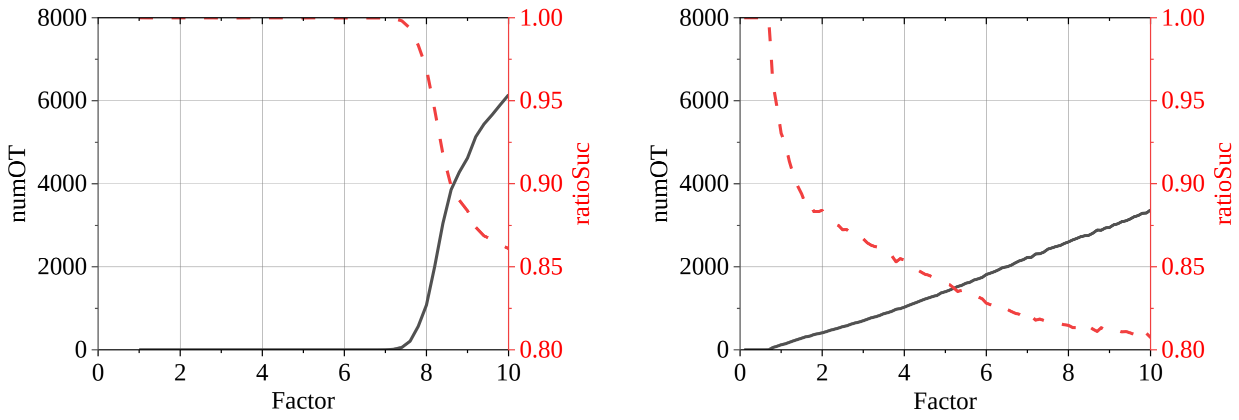
4. Result and Discussion

A DES model was developed using AnyLogic [21]. The uncertainty of the model is included by Monte Carlo simulation. The Simulation results in WCH and PHDC mode are shown in Table 6. Under WCH mode, the case study hospital can successfully treat all patients. However, only 84.4% of patients are able to get timely medical treatment under PHDC mode, and the waiting time of patients is too long. This shows that the arrival rate of patients has a significant impact on the performance of the hospital. The situation where patients arrive in a short time is likely to bring severe challenges to hospitals.

Table 6 - The Simulation results under WCH and PHDC mode

Arrival rate	**WT_Red (min)**		**WT_Yellow (min)**	**WT_Green (min)**	**numOT**	**ratioSuc**
	Rescue	**Surgery**				
WCH	0	19	36	7	0	100%
PHDC	3	1515	1940	1491	274	84.4%

The simulation results reproduce the treatment of patients arriving at hospitals after earthquakes. By increasing arrival rates linearly, the relationship between the number of patients cannot be treated in time, the success rate, and arrival rates is shown in Fig.3. The arrival rate is obtained by multiplying a factor to recorded arrival rates. Under WCH mode, all patients can be treated when the factor is less than 7.2, and then the number of patients cannot be treated will increase rapidly. Under PHDC mode, the success rate started to decline when the factor is greater than 0.8. The number of patients cannot be treated has a slower increase. With the same medical resources and the total number of patients, the capacity of hospitals under WCH mode is nearly 9 times that under PHDC mode. The mode of arrive rate has a very large impact on the capacity of hospitals.



(a) WCH mode (b) PHDC mode

Fig 3 - Sensitivity of arrival rates on the performance of the case study hospital.

Current seismic design codes can ensure that the structures of hospitals are not severely damaged in earthquakes. However, the damage of non-structural components and medical equipment is common and it would cause the closure of partial area. This requires emergency plan to reach a balance between the assignment of resources for normal and earthquake patients. Sensitivity analysis is used to study the impact of the number of medical rooms on hospital capacity. When the number of other rooms remains the same as Table 5, the number of OR has a greater impact on the results than the number of DR rooms (see Figure 3.a). Under PHDC mode, the numOT is related to multiple kinds of medical rooms (see Figure 3.b to d). There are 81 operating rooms in the case study hospital, but a large number of patients still cannot be treated. According to the results, increasing the number of triage and DR may be a good choice. If there are six triage and DR rooms, all patients can be treated.

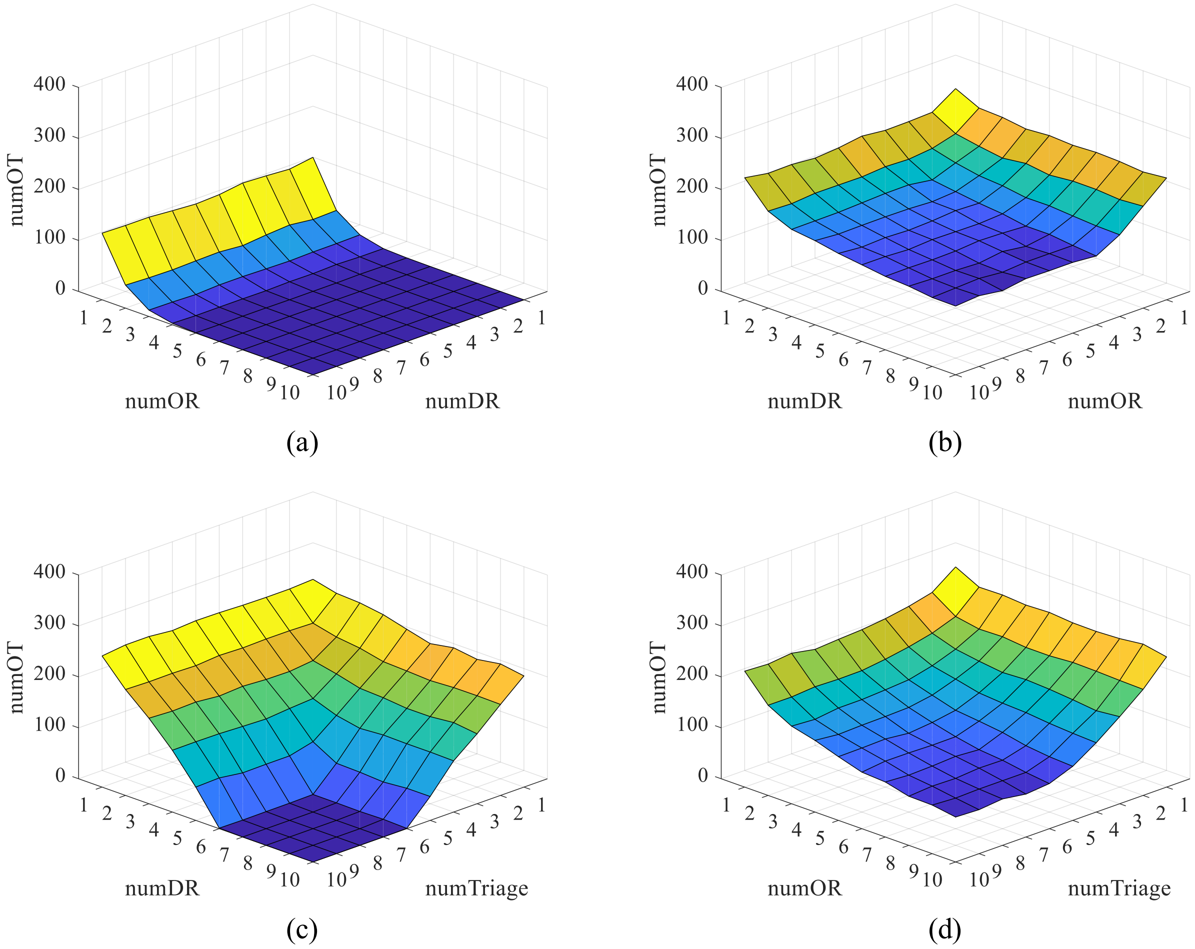


Figure 4 - Sensitivity of the number of different medical rooms on numOT. (a) is under WCH mode, and (b)-(d) are under PHDC mode.

Minimum number of rooms is a very important part of emergency plans. By sensitivity analysis, the minimum number of medical rooms under multiple performance level for two arrival modes are found and listed in Table 7 and Table 8. Under WCH mode, as long as other kinds of rooms are available, two operating rooms can ensure that the numOT does not exceed 50. When three more operating rooms are added, all patients would be treated. Under PHDC mode, more triage, DR, and operating rooms are needed. In hospitals, few special equipment is required in triage. Compared to other options, the addition of triage rooms or teams is more feasible and recommended. Based on the minimum resource requirements, to achieve the same level of performance, the total number of medical rooms required under PHDC mode is about three to 4 times that under WCH mode.

Table 7 - Minimum resource requirements under WCH mode

numOT	**Triage**	**Rescue**	**CT**	**DR**	**US**	**OR**	**TR**	**Sum**
0	1	1	1	1	1	5	1	11
10	1	1	1	1	1	3	1	9
20								
50	1	1	1	1	1	2	1	8
100								

Table 8 - Minimum resource requirements under PHDC mode

numOT	Triage	Rescue	CT	DR	US	OR	TR	Sum
0	7	1	2	6	1	23	3	43
10	7	1	2	6	1	20	3	40
20	7	1	1	6	1	16	2	34
50	6	1	1	6	1	13	2	30
100	5	1	1	5	1	10	2	25

5. Conclusion

Hospitals play a key role in community especially when earthquakes occur. It is essential for hospitals to ensure their functionality during emergencies. Discrete event simulation is a powerful method to model the treatment process in hospitals. The capacity of a case study hospital is estimated by increment arrival rates. Sensitive analysis is performed to get the key medical rooms and minimum number.

This paper draws the following conclusions:

1. The proposed model is able to simulate the medical process and estimate hospital capacity. It takes account in the arrival rates of patients, emergency plan, and medical resources.

2. The mode of arrive rate has a large impact on the capacity of hospitals. It is recommended that the results of capacity estimation should include the total number and corresponding arrival rates at the same time.

3. Triage, DR, and operating rooms are the most essential medical parts for the treatment of patients after earthquakes. The minimum number of medical rooms under multiple performance level are given by sensitive analysis.

The proposed model can be further developed for estimating the earthquake resilience of hospitals. It can also be used by decision makers for pre-earthquake preparation and emergency management after earthquakes.

6. Acknowledgements

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