Research Paper

MODELING HOSPITAL RESOURCES BASED ON GLOBAL EPIDEMIOLOGY AFTER EARTHQUAKE-RELATED DISASTERS

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Abstract

In an earthquake emergency, injured people require hospital emergency services and timely medical treatment. Earthquake-related patients often have trauma injuries and stress-linked (ischemic) illnesses that require multiple healthcare procedures, such as minor orthopedic treatment, surgical treatment of fractures, and thrombolysis or thrombectomy. Hospital operation models have been proposed to examine these healthcare procedures; however, they exhibit two fundamental gaps that hinder their ability to assess critical service areas after earthquakes. First, these models rest heavily on emergency procedures based on injury severity rather than type. Second, healthcare demands and injury profiles are often modeled after moderate earthquakes in the United States without including mass casualty data after large earthquakes. This approach has led to an oversimplified representation of the utilization of hospital emergency services and resources, especially for the various profiles of trauma patients after earthquakes globally. This research presents a new hospital operations model based on patient injury type and worldwide earthquake epidemiology data to fill these two gaps. We built the model using discrete event simulations to capture patients' healthcare metrics that vary rapidly after the earthquake. We then used these metrics to study how healthcare outcomes vary with different levels of functional capacity in specific hospital service areas. Our case study showed that ED-level patients wait 40% longer to receive treatment when half of the examination rooms in the emergency department (ED) are lost and 35% less time if examination rooms increase by 50%. Also, the waiting time for hospital-level procedures reduces up to 65% if the bed occupancy rate drops by 15%, e.g., if reverse triage procedures are activated through a discharge of 15% of patients hospitalized before the earthquake. Our findings provide a valuable tool for decision-making in hospital preparedness as it links expected patient volumes to key healthcare metrics according to hospital functional capacity.

Keywords: hospital resources, hospital operations, earthquake casualties, earthquake injured, disaster medicine

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1 Introduction

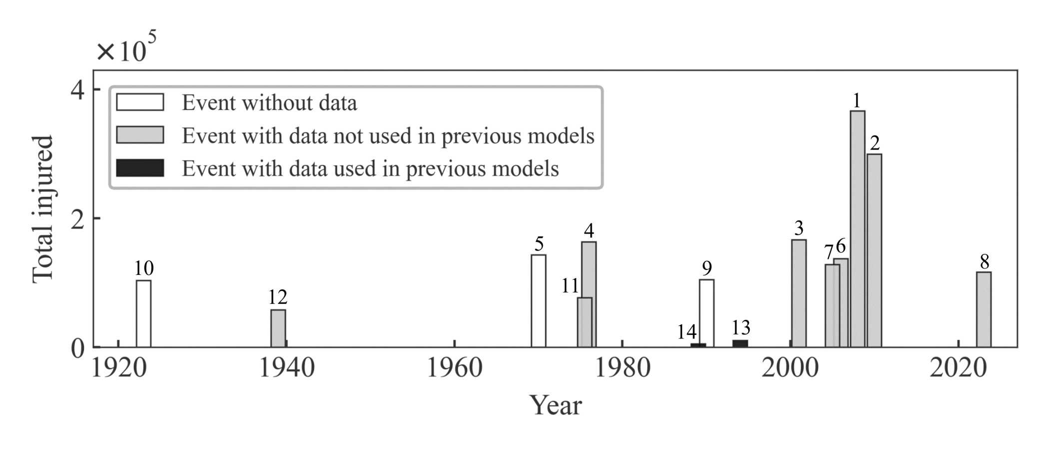
The continued operation of hospitals after earthquakes relies on the functional state of physical systems and the availability of human resources. The interruption of healthcare services after great disasters represents a significant public health concern. Earthquakes can reduce the capacity of hospital networks and hinder their ability to absorb acute care demands (Ceferino, Mitrani-Reiser, Kiremidjian, & Deierlein, 2018; Ceferino et al., 2020a, 2020b). For example, the effects of the 2008 Sichuan Earthquake in China on public health were notable. The injured toll reached 370000 people, and the healthcare infrastructure was severely damaged, including hospitals with modern buildings (Zhao et al., 2009). In Beichuan County (≈175000 inhabitants, PGA_{max}=1.40g, *MMI*: IX), the hospitals with tertiary services (i.e., highly specialized resources for hospitalization) experienced structural collapse, and no specialty services were available in the county for two months. Consequently, medical teams from other facilities had to transfer severely injured patients to hospitals in other counties (You et al., 2009).

Hospitals must enhance preparedness for earthquakes by providing safe and sufficient infrastructure to allow continued functionality of medical services, especially those critical during the emergency response (WHO-PAHO, 2015). Previous models on post-earthquake hospital performance have contributed to understanding the operations needed to treat earthquake-related patients. However, most existing models are based on historical data on hospital demand from injured patients recorded after a few moderate events in the United States (Figure 1), such as the 1994 M 6.7 Northridge Earthquake and the 1989 M 6.9 Loma Prieta Earthquake (Yi et al., 2010). Thus, they do not capture the epidemiological characteristics of large earthquakes (e.g., M $>$ 7.0) and other regions across the globe.

The current paradigm for modeling hospital operations assesses healthcare processes based on patients' injury and illness severity or triage categorization (Basaglia et al., 2022). This modeling criterion can help identify healthcare resource utilization under normal conditions when hospitals expect a regular flow of patients with a wide range of injury profiles. However, this paradigm lacks the granularity of more specific injury and illness types to assess complex emergencies that require the treatment of large fluxes of patients, such as those generated by earthquakes (Gautschi et al., 2008; Mackenzie et al., 2017).

Existing models focus on earthquake patients in emergency departments but neglect those requiring hospital-level services, such as hospitalization, intensive care, and dialysis. The latter patients represent an essential group of injured that accounts for most patients' profiles in several past earthquakes (Bar-On et al., 2013; CDC, 2011; Shi et al., 2010; Tanaka et al., 1997; Xie et al., 2008). Thus, neglecting these patients hinders part of our understanding of the relevance of the complex hospital resources needed to assist them, such as hospitalization beds, intensive care units, and dialysis units. Hence, a more comprehensive model for hospital operations is needed to capture key healthcare processes associated with the epidemiology of earthquake patients, aiming to examine better the hospital resources needed to treat patients, especially after large earthquakes.

To fill in this gap, we present a new operations model to overcome some existing limitations. The model is based on a proposed classification of expected patients from an extensive review of emergency medicine literature on earthquake injury patterns, validated through interviews



1	2008 M7.9 Sichuan, China	6	2006 M6.3 Yogyakarta , Indonesia	11	1976 M7.5 Guatemala City, Guatemala
2	2010 M7.0 Port-au-prince, Haití	7	2005 M7.7 Kashmir, Pakistan	12	1939 M7.9 Chillan, Chile
3	2001 M7.7 Gujarat, India	8	2023 M7.8 Kahramanmaras, Turkey	**13**	**1994 M6.7 Northridge, US**
4	1976 M7.4 Tangshan, China	9	1990 M7.4 Manjil-Rudbar, Iran	**14**	**1989 M6.9 Loma Prieta, US**
5	1970 M7.9 Ancash, Peru	10	1923 M8.0 Kanto, Japan		

Figure 1: Total injured for 11 worldwide earthquakes with the highest injured tolls reported (CRED, 2022). The historical events have been separated in two groups according to the availability of their associated epidemiological data. The 1989 Loma Prieta and 1994 Northridge earthquakes are additional to these 11 events.

with healthcare experts. As a result, we define seven patient types that represent common injuries and illnesses after major earthquakes and identify the resources needed to support the medical procedures to treat them. This model is designed to allow coupling with risk frameworks for estimating earthquake casualties (Ceferino, Kiremidjian, et al., 2018a, 2018b; Federal Emergency Management Agency (FEMA), 2020), aimed to identify hospital resources required to cope with surging healthcare demands in the aftermath of future major earthquakes. Thus, the proposed model's application offers decision criteria to develop hospital emergency plans based on medical resources relevant for earthquake-related patients.

This paper will proceed with section two, describing the literature review of existing models for hospital performance after large earthquakes and their main applications in disaster risk analysis. Then we describe in section three the methods employed to carry out our model and the details of its parameters. Section four presents the most relevant results of this research, and finally, in section five, we discuss these findings.

2 Review of post-earthquake hospital models

Simulation models are numerical tools that can be used in operations research to study complex systems that follow a queuing behavior (Aghapour et al., 2019). They are usually employed in the health sector to track stochastic metrics of patient queues and analyze strategies to enhance health outcomes from the design of service flows (Gupta, 2013). In the context of disasters, simulation models in healthcare systems have been increasingly developed in the literature.

Among the available types of simulation models, discrete event simulation (DES) has been a highly used technique to model emergency healthcare processes under disaster conditions (Gul & Guneri, 2015). DES models are computer-based techniques supporting the dynamic tracking of the state of entities or agents requesting services in a queuing system. For healthcare research purposes, the hospital system consists of sets of medical services supported by resources demanded by patients entering the system.

Few studies have been carried out to describe hospital operations under earthquake scenarios aimed at determining metrics to deliver healthcare services. Yi et al., 2010 described hospital operations in the context of earthquakes using DES to determine real-time hospital capacity to treat earthquake-related patients timely to maximize survivability. The proposed patient flows within the hospital were defined based on the main types of patients observed in the aftermath of California's 1989 and 1994 earthquakes. Their model was able to determine a hospital's capacity to treat patients from a relationship between the maximum waiting time and the corresponding arrival rates of patients.

More recently, Basaglia et al., 2022, proposed an updated hospital model to describe the healthcare response of an idealized hospital in routine conditions and after a major earthquake. Their model accounts for multiple services within the hospital and a detailed collection of the corresponding simulation parameters in both demand scenarios. With this model, they assessed the probability of mortality, identifying delayed treatment as the main factor contributing to fatalities.

Other studies in the literature employ DES models for hospital operations to determine hospital performance under the effects of physical damage or decreased functionality after earthquake scenarios. They integrate the seismic response of physical components (i.e., building and contents) and hospital operations due to a sudden increased demand for healthcare. Zhai et al., 2021, developed a post-earthquake hospital model and determined its functionality to assess the availability of physical resources to assist patients from a simplified DES model. Other simulation models have been used to determine the risk of exceeding patients' waiting times as a function of the earthquake hazard level (Favier et al., 2019). In such research, they assessed the functional state of service areas within the emergency department (ED).

This research closes existing gaps by developing a DES model at the entire hospital level instead of the emergency department level, as considered in previous research. In addition, this paper advances existing models by defining treatment processes according to injury type instead of severity to capture medical needs better and quantify medical resources after earthquakes. We also conduct a thorough review of earthquake epidemiology literature to define expected patient profiles generated by large earthquakes around the globe. Table 1 summarizes the contributions of this paper.

3 Methods

Our hospital model is based on discrete event simulations (DES) of hospital processes and was developed by integrating empirical data presented in the literature on disaster medicine, with expert elicitation of emergency healthcare staff. The DES model describes the flow of an increased volume of patients arriving at the emergency department (ED) and passing through

Features of previous hospital models	[1]	[2]	[3]	[4]	[5]	This study
Model scope for healthcare processes						
- ED-level	✓	✓	✓	✓	✓	✓
- Hospital-level		✓				✓
Earthquake-related epidemiology among arriving patients						
- US EQs	✓			✓		✓
- China EQs			✓			✓
- World EQs excluding China and US						✓
- Non EQs/not specified		✓				
Injury type-based approach for healthcare processes	✓	✓	✓			✓

Table 1: Overview of the proposed model characteristics relative to previous studies: which are advanced in our model; [1]: Yi et al., 2010; [2]: Basaglia et al., 2022; [3]: Zhai et al., 2021; [4]: Favier et al., 2019; [5]: Romani et al., 2022.

different healthcare processes. Sequential combinations of healthcare processes define different paths associated with different types of patients. For example, the healthcare path for a trauma patient with crush syndrome includes the following healthcare processes and resources: triage, examination, laboratory, surgery, intensive care, dialysis, and hospitalization.

Arriving patients were studied as an inflow of injured and ill agents divided into seven groups denoted as patient types. The relationships between patient types and the healthcare paths within the hospital were identified by coupling documented medical processes from past earthquakes with specialized knowledge from emergency physicians. Such relationships were validated by interviewing eight experts on emergency hospital operations from different disciplines. Initially, our target experts were ED physicians; however, additional healthcare professionals contributed significantly to this part of the research. Table 2 summarizes the disciplines and places of elicitation experts who contributed in the validation of this model.

Experts consulted	Institution	Discipline
Leader emergency physician	SAMU	Medicine
Operations coordinator	LFH	Engineering
Emergency coordinator	SSMSO	Nursing
Disaster advisor	INEE	Engineering/Hospital Disaster Risk
Regional disaster advisor	PAHO	Medicine/Hospital Disaster Risk
Safe Hospital Program members (6)	IMSS	Medicine

Table 2: Interviewed experts for the model setup: **SAMU**: Servicio de Atención Médica de Urgencia/Metropolitan Urgent Medical Aid Service (Chile); **LFH**: La Florida Hospital (Chile); **SSMSO**: Servicio de Salud Metropolitano Sur-Oriente/South-East Metropolitan Healthcare Service (Chile); **PAHO**: Pan American Health Organization; **IMSS**: Instituto Mexicano del Seguro Social/Mexican Institute for Social Insurance (Mexico).

Once the healthcare paths within the hospital for every patient type were defined, we assumed a patient arrival function describing the rate of patients coming into the ED during the first week after the earthquake. According to this function, the simulator stochastically generates arriving patients and randomly assigns the patient a healthcare condition from the previously defined group of patient types. Then, the patient is associated with the corresponding path and starts requesting hospital services, i.e., the healthcare processes required to treat every patient type. Each service is developed in a physical space and uses different types of resources. Figure 2 summarizes the steps to perform the model simulations. The following subsections describe the patient profiles considered in the model and the details of the different resources involved in treating them.

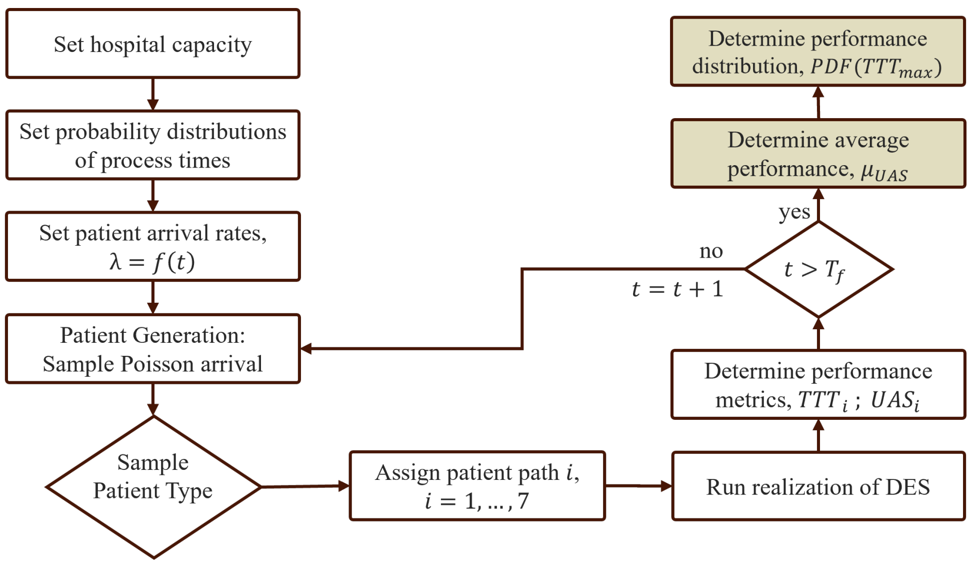


Figure 2: Flow chart of the pseudo-code for the hospital DES model.

3.1 Demand

The proposed model was developed with particular emphasis on the expected profile of the patients that reach large urban hospitals in the aftermath of a destructive earthquake. To do so, we conducted an extensive literature review to identify the most frequent patient profiles and defined seven patient types that account for most earthquake-related injuries and illnesses. They range from frequent trauma conditions to stress-related ischemic conditions. The most common healthcare conditions found in the literature for patients from earthquakes worldwide are the following:

- **Path 1/Minor injuries**: include contusions, lacerations, cuts, among others, which only need basic first aid and ambulatory procedures in the ED, covered by the medical assessment performed by an emergency physician in the examination room (Tanaka et al., 1997).

- **Path 2/Non-surgical injuries**: include injuries that can be treated without a surgical procedure (e.g., dislocations, fractures). They can be treated in a trauma room or examination room, i.e., those where medical staff mobilizes equipment for orthopedic procedures. This patient type usually requires X-ray imaging to support the medical diagnosis.

- **Path 3/Surgical injuries (extremities)**: include soft-tissue injuries or upper and lower limb fractures needing a surgical procedure under general anesthesia in an operating room (e.g., internal fixation, debridement, skin grafting) and a recovery process in a hospitalization bed. This group of patients represents most earthquake-related injured, ranging from 36 to 60% (CDC, 2011; Zhang et al., 2009; Zhang et al., 2014; Xie et al., 2008; Bertol et al., 2014).

- **Path 4/Surgical injuries (non-extremities)**: include injuries or fractures in the head, neck, thorax, and pelvis for which major surgery in an operating room is needed. Additionally, intensive care is carried out after such procedure in most cases, especially for patients with spinal cord injury (Gautschi et al., 2008). These fractures represented more than 20% of total fractures observed after the 1995 Kobe earthquake. For this earthquake, 11% of trauma patients required intensive care units (ICU) as a resource (Tanaka et al., 1997). Evidence from past disasters suggests that older people are more likely to suffer these type of trauma condition (Zhang et al., 2014).

- **Path 5/Crush syndrome**: represents a critical condition developed by most patients who have suffered crush injuries during earthquakes and did not reach medical facilities promptly. This condition requires intensive care in most cases. Also, subsequent hemodialysis procedures are often needed for patients with renal failure, a common complication after prolonged muscle compressions (Xie et al., 2008; Yang et al., 2009). (Tanaka et al., 1997) showed that for 70% of patients who developed crush syndrome, their injuries were caused by house collapse, requiring ICU resources, and hemodialysis in 33% of the cases.

- **Path 6/Amputation**: is required when patients experience a severe musculoskeletal trauma. Amputation rates in past large earthquakes have reached up to 16% (CDC, 2011; PAHO, 2011; Xie et al., 2008; Yang et al., 2009). Trauma patients needing amputation procedures usually access the hospital's ED through resuscitation processes, thus using the shock room (Wolfson, 2012). The amputation procedure requires major surgery and subsequent intensive care.

- **Path 7/Ischemic disease**: includes myocardial infarction. This is the most frequent stress-related disease in the aftermath of earthquakes, e.g., 1995 Kobe Earthquake in Japan (Tanaka et al., 1997), 2010 Maule Earthquake in Chile (P. Molina, personal communication, October 2021). In most cases, this condition is treated in a catheterization laboratory, performing a hemodynamics surgery (i.e. thrombectomy). When the catheterization laboratory is unavailable, the thrombolysis treatment is performed in a conventional examination room by providing a clot-busting drug.

Table 3 presents a distribution of injuries/illnesses-related patient types, following the average patterns documented from past events. As seen in the proposed distribution, the leading medical specialty is trauma, and most injuries require surgical treatments (75%). Other milder trauma conditions represent 15%, and less cases (5%) account for myocardial infarction. To account for crush injuries, the renal specialty has been included for 5% of patients, according to the data available in the literature.

Patient type	Injury/Illness	Medical Specialty	Distribution (%)
1 [MI]	Minor injury	Trauma	10
2 [NS]	Non-surgical injury	Trauma	5
3 [SE]	Surgical injury (extremities)	Trauma	55
4 [SN]	Surgical injury (non-extremities)	Trauma	15
5 [CS]	Crush syndrome	Trauma/renal	5
6 [AM]	Amputation	Trauma	5
7 [ID]	Ischemic disease	Medicine	5

Table 3: Earthquake-related patient types proposed for the assessment of healthcare demand in the hospital. Specialties for every type are included as well as the respective percentage relative to the total patient volume.

The increased demand for healthcare services in the initial phases of the response to the aftermaths of the earthquake was assumed as a time-dependent distribution of patient arrivals at the hospital. The model follows the time scales proposed in previous research frameworks for emergency medical teams deployed to support the healthcare response after earthquakes (Lind et al., 2012). The first two phases are defined in days and weeks; phase 1 has been proposed as the first 72 hours, and phase 2 as the range between days 4 to 21 (<3 weeks). The arrivals of injured patients were simulated over the first seven days after the earthquake, with most of them arriving during the first stage (<72 hours), according to the arrivals data reported by hospitals in past earthquakes (Bulut et al., 2005; Ganjouei et al., 2008; Yang et al., 2009).

The patient arrivals obey to a non-homogeneous Poisson process. The Poisson distribution of arrivals accounts for uncertainties of inter-arrival times of injured people. An arrivals pattern was defined on a basis of the average daily patient volume recorded in past earthquakes (Bulut et al., 2005; Chen et al., 2001; Ganjouei et al., 2008; McArthur et al., 2000; Nie et al., 2011; Uz et al., 2022). The arrival rate, λ, decreases over time, with a maximum value equivalent to 50% of the total patient volume within the first 24 hours. In the subsequent days, λ tends to zero, as shown in Figure 3. Besides, simulations were performed for two weeks after the earthquake to capture the healthcare response during the second phase of the emergency (<3 weeks). Finally, we assumed a random selection of patient types entering the ED to include the variability of patient profiles according to the injury/illness distribution data presented in Table 3.

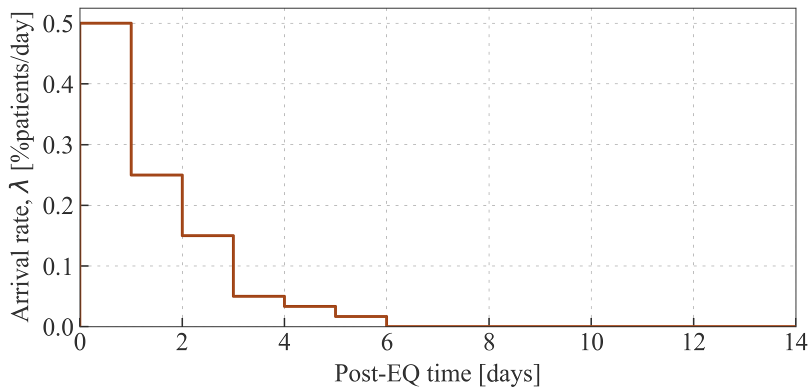


Figure 3: Assumed daily variation of patient arrival rates considered to perform simulations of injured/ill people demanding hospital services after the earthquake. λ is presented in terms of the proportion of the total patients.

3.2 Processes

Healthcare processes were defined based on the medical resources needed to treat the arriving patient types. In the proposed model, every process requires a list of resources that include the physical area (or equipment, when corresponding) where the service is performed. Human resources are assumed to be available if the service is available. Figure 4 shows the simulated processes (dark boxes) and the corresponding resources (light boxes) associated with every patient type arriving to the hospital. Numbers define patient types according to Table 3, indicating the different paths they go through.

Unlike existing models, the services considered herein cover specialized medical processes at tertiary hospitals, including but not limited to the ED. Hospital services can be understood in two components: ED-level treatment and hospital-level treatment. ED-level patients (minor injury, non-surgical injury) access medical services through the ED (triage, examination, diagnosis support, minor trauma treatment). As they require minor treatment, they can be discharged safely after receiving such treatment. In contrast, hospital-level patients (i.e., patient types 3 to 7) are expected to undergo surgery, subsequent hospitalization, or intensive care for recovery. This group of patients experiences longer waiting times for hospital-level services, as bed and ICU occupation times are significantly higher than those at the ED. In past earthquakes, hospital-level services such as surgery and subsequent procedures represented a high percentage of orthopedic treatment for trauma patients (Bortolin et al., 2017).

For the sake of completeness, we describe next the healthcare processes in our simulation and the associated resources:

- **Resuscitation** refers to the process in which specialized medical staff assists critically injured/ill patients under life-threatening conditions. It occurs in a resuscitation room, RR (also known as a shock room), equipped with high-complexity medical resources like those found within an operating room. Resuscitation procedures can be initiated as a pre-hospital assistance process within an ambulance for severely injured patients that

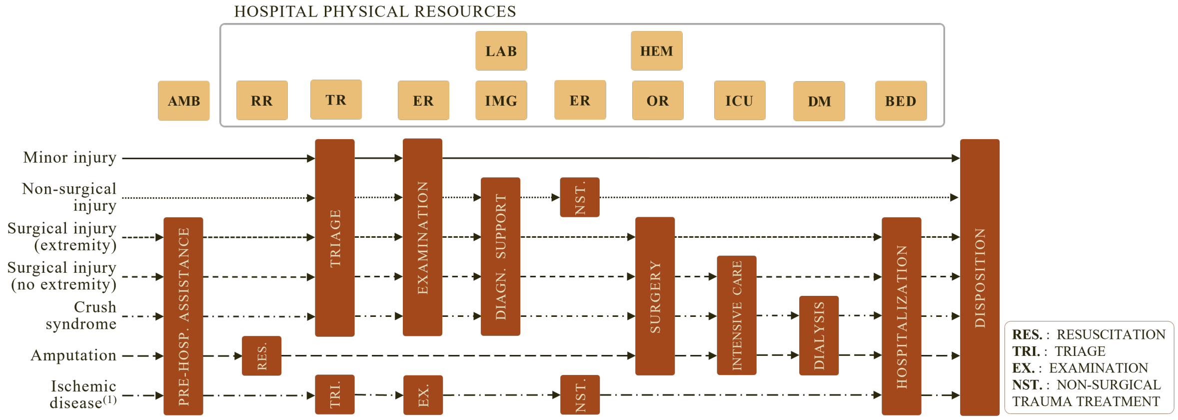


Figure 4: Emergency healthcare flows for expected patient types. The processes in dark boxes are associated with the light boxes showing the corresponding required resources (AMB: ambulance; RR: resuscitation room; TR: triage room; ER: examination room; IMG: imaging room [X-rays/CT/ultrasound(US)]; LAB: laboratory; OR: operating room; HEM: hemodynamics room/catheterization laboratory; ICU: intensive care unit; BED: general hospitalization bed; DM: dialysis machine).$^{(1)}$This flow shows a non-surgical treatment approach for patients with ischemic conditions. However, surgical treatment is an alternative when the catheterization laboratory (HEM) is available for ischemic surgery

can not reach the hospital autonomously.

- **Triage** refers to the initial examination of the patient's vital signs performed by a nurse or a physician (depending on the hospital protocols for disaster conditions) in the triage room (TR). In a disaster setup, the triage process is intended to categorize the patient as a function of the risk of death, the chance of survival, expected resource requirements, and expected duration of treatment, among other variables (Merin et al., 2011). Hospital triage can also occur after an initial triage performed as a part of a pre-hospital assistance process within the ambulance for non autonomous patients.

- **Examination** refers to the initial patient assessment performed by a physician and supported by nursing staff in the examination room (ER) that requires basic equipment, so human resources are imperative.

- **Diagnosis support** refers to the healthcare processes needed to deliver a diagnosis by the physician when the initial assessment has not been enough to decide the necessary treatment. Essential diagnosis support services generally include imaging (e.g., X-ray, CT scan, US) and laboratory. They operate in imaging rooms (IMG) and laboratories (LAB), respectively. For earthquake-related injuries, imaging services have been highly demanded in past disasters to support decisions for treating trauma patients. Our model considers that the imaging resource includes both X-ray and the CT scan. X-ray resource can be a mobile machine or in a fixed room. They are expected to be used for ED-level patients with minor injuries, and CT scan for those patients with more complex trauma conditions.

- **Non-surgical trauma treatment** refers to the treatment for ED-level patients, for which the required trauma equipment can be moved to any examination room to perform procedures for minor trauma injuries.

- **Surgery** refers to the medical process in which teams perform trauma treatment under general anesthesia. Surgery is performed in operating rooms (OR). Several publications have described the multiple emergency procedures developed for trauma patients in ORs after great earthquakes (Gerdin et al., 2012; Herard & Boillot, 2016; Mohebbi et al., 2008).

- **Intensive care** refers to the process in which critical patients stay in the hospital under specialized medical treatment and monitoring after surgery. The process requires an intensive care unit (ICU) with high-complexity resources to support the patient's life. References from past earthquakes show the critical role of ICUs in the hospital response to the emergency, such as medical care of severely injured patients and dialysis therapy for those with crush syndrome (Gautschi et al., 2008; Shimada et al., 2015; Tanaka et al., 1997).

- **Dialysis** refers to the specialized process in which patients receive hemodialysis through a dialysis machine (DM) that is moved to the ICU. The proposed model incorporates the dialysis process for those patients with crush syndrome who develop renal failure and need hemodialysis, as it has occurred in past disasters (Better, 1997; Jiang et al., 2012; Tanaka et al., 1997).

- **Hospitalization** refers to the specialized process in which patients stay in the hospital for recovery under medical treatment and observation after undergoing surgery or intensive care. It occurs in a hospital BED, a resource assumed to include all the equipment to support the patient care.

- **Disposition** indicates to the process in which the patients are referred to a different facility with available bed capacity or they are dispatched home.

Some processes can be linked to more than one service area. For example, diagnosis support (DS) can be performed either in the imaging room (IMG) for most trauma injuries or at the laboratory (LAB) for specific patients with crush injuries, as described above. The same logic applies to the case of surgery (SG); it can be performed in the operating room (OR) for trauma patients or in a hemodynamics room (HEM)/catheterization laboratory for ischemic patients (Figure 4).

We simulated all these processes as described above. Our model considers the strategies employed in the Chilean Public Healthcare Network to conduct surgery, since our case-study hospital to apply the simulation model belongs to such network. Local protocols establish that a bed or ICU must be secured before the surgery process for hospital-level patients to ensure the patient's recovery after the intervention, based on their healthcare condition. Thus, the model includes a restriction of having a guaranteed available bed/ICU before requesting an OR to receive surgical treatment. Hence, we simulate a double resource request (bed and OR) for accessing surgery, which often leads to higher waiting times.

As shown in Figure 4, some processes are common to multiple patient types and, thus, associated resources (TR, ER, IMG). Patient queues are expected to happen for such services when the demand for resources exceeds the available capacity, like the resources to treat the most expected patient type. Also, long queues are expected in resources with long usage time (e.g., hospitalization beds/ICU). The examination room resource (ER) is duplicated for patients with a non-surgical injury (i.e., patient type 2) as they return to the examination room (ER) for minor trauma treatment after passing through imaging.

The model requires two input types: the physical capacity in terms of the number of resources for every healthcare process (i.e., services areas), and the duration of each process. The amount of resources was based on the installed capacity of the case-study hospital described next, which is La Florida Hospital. The duration of processes was modeled as random variables with exponential distributions. Mean values for every distribution were collected from the literature on emergency medicine. Table 4 provides the parameters used for the hospital model.

PROCEDURE	DURATION: Mean value (SD), units	SOURCE
Resuscitation	29.30 ($\pm$9.00), minutes	Albinali et al., 2022
Triage	**1.23** minutes	Dursun et al., 2012
Examination	17.20 minutes	Cho et al., 2020
Imaging	10.50 minutes	Cho et al., 2020
Laboratory	10.50 minutes	Cho et al., 2020
ED Treatment (trauma)	27.20 minutes	Cho et al., 2020
ED Treatment (ischemic)	60.00 minutes	Cho et al., 2020
Surgery	**22.40** minutes	Mulvey et al., 2006
Hemodynamics Surgery	30.00 minutes	Cleveland Clinic Website
Dialysis	**3.00** hours	Tani et al., 2014
Hospitalization	**8.80** ($\pm$9.60), days	Hatamizadeh et al., 2006
Intensive care	**9.13** days	Demirkiran et al., 2003

Table 4: Simulation parameters used for every process, adopted from healthcare procedures recorded in previous research; average values were collected from more than 50 papers on emergency medicine. Mean values in bold letters represent control measures from earthquakes, disasters, or drills, while the rest indicate procedure times in normal baseline conditions.

3.3 Hospital performance metrics

We defined two performance metrics for our hospital simulation model: *patient's time-to-treatment* (TTT) and *unassisted-patients ratio* (UAS). Existing queuing models for hospitals often employ performance metrics such as queue size for resources, waiting times, length of stay, patients exceeding a waiting time threshold, and decreased life-saving rates (Gul & Guneri, 2015). We defined the TTT metric because it explicitly captures the total time since the patient arrives until it receives treatment. In general, a longer TTT is expected to worsen the patient's health condition and outcome. The UAS metric was also selected to analyze the quality loss in the healthcare service for patients exceeding target thresholds of waiting time adopted from international standards, as described below.

The *time-to-treatment* variable (TTT) was defined as the time for the patient to receive meaningful assistance for the corresponding diagnosis (also known in the literature as *time to first treatment, TTFT*). Thus, for ED-level patients, the TTT includes all the waiting times before a diagnosis is given. For minor injury patients, TTT is measured from the moment the patient starts waiting for triage until it has left the examination room with a medication recipe and leaves. For patients with a non-surgical injury, TTT is measured from the moment the patient starts waiting for triage until it leaves the imaging room to receive non-surgical trauma treatment. For hospital-level patients, TTT includes all waiting times from the triage until any OR is available to enter surgery (including waiting times for hospital beds or ICUs). Figure 5 conceptually depicts the definition of maximum TTT values for the $i-th$ single Discrete Event (DE) realization.

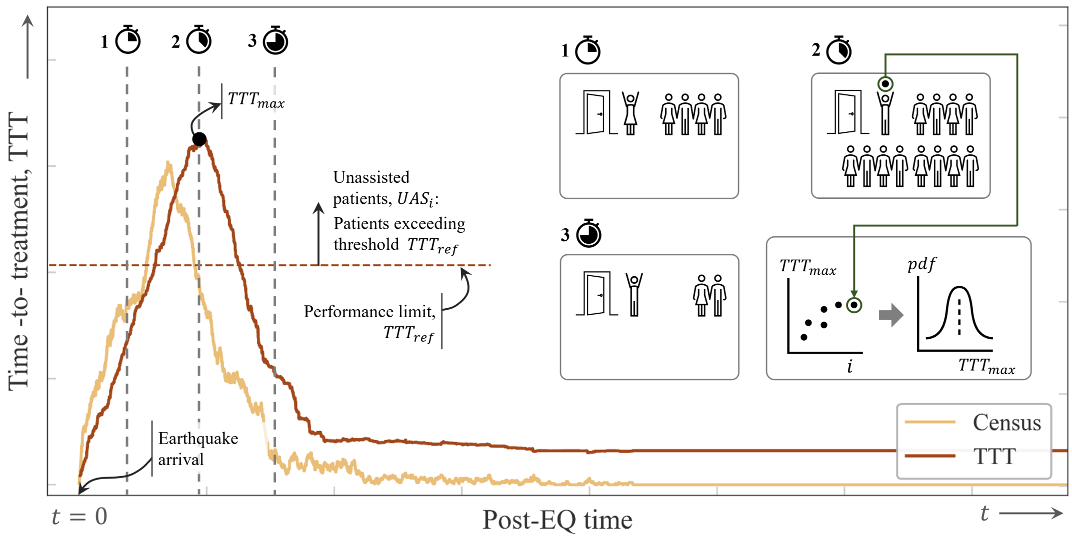


Figure 5: Definition of the two performance metrics studied. An example for the $i-th$ DE realization, is used to show the TTT_{max} point and the criteria to determine the UAS, the right side of the plot illustrates how Monte Carlo simulations are used to define the probability distribution of TTT_{max}.

UAS ratio was determined as the ratio between the number of unassisted patients and the number of arriving patients for every patient type. Unassisted patients value is the number of patients experiencing an excess of waiting time to receive treatment (Figure 5). Such excess was defined based on a waiting time limit of 4 hours for ED-level patients, following a standard limit used in several hospitals as a target quality indicator (Paling et al., 2020, Gul and Guneri, 2015). Although waiting times will probably increase under disaster conditions, there is still no consensus about a target waiting time in case of an earthquake. Using a non-earthquake threshold represents a reasonable measure of loss for urban hospitals, as it can be compared to those patients waiting more than 4 hours in normal conditions, so that actions can be designed to be prepared to manage a greater demand.

We accounted for a boarding time in addition to the 4-hour limit, to assess the $UASratio$ for hospital-level patients. The boarding time is the waiting time for an available bed after patients are dispatched from ED to hospitalization. We adopted a maximum boarding time of 80 min using as a reference the average time recorded in US hospitals (Pitts et al., 2014). The UAS ratio was used to study the decreased hospital performance that can lead to the need for patient transfers to other facilities as a result of long waiting times, or the leave of patients without medical assistance. Indeed, increased waiting times can become unmanageable for the hospital staff; they also lead to undesirable healthcare outcomes when non-critical patients leave without seeing a physician or critical patients are not treated promptly.

4 Results and discussion

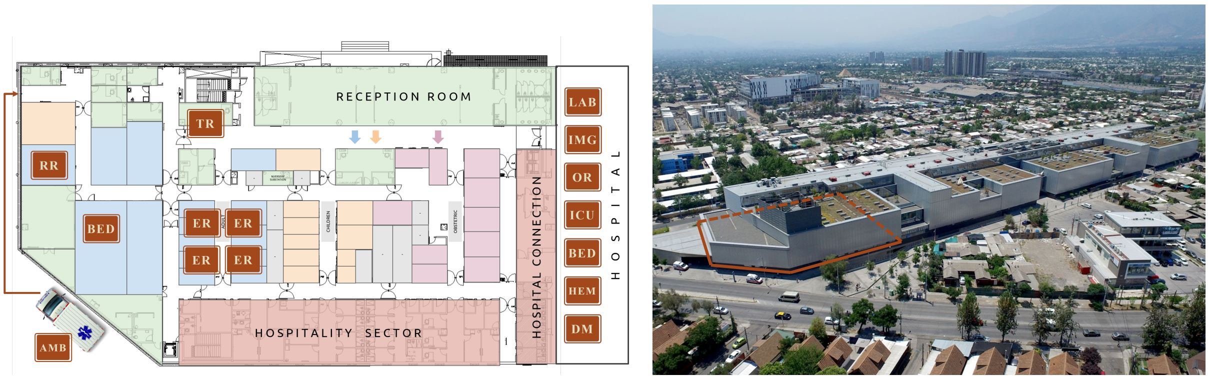
This section presents the results of the proposed post-earthquake hospital performance model based on Discrete Event Simulations (DES) for the emergency treatment of earthquake-related patients. We determined the maximum values of TTT for different patient types and studied their probability distribution from 100 Monte Carlo simulations of complex and dynamic hospital operations for a time window of 14 days after the earthquake. We also studied the sensitivity of such distributions to changes in the number of available service areas. With this approach, we identified essential resources to offer timely assistance after earthquakes and the consequences of losing resource capacity or enhancing performance by enabling additional resources. The unassisted-patients ratio was also monitored from the same perspective throughout the entire 14 days of simulations.

4.1 Application to the Metropolitan Region of Santiago

We applied our model to study La Florida Hospital in the Metropolitan Region of Santiago, Chile (Figure 6b). La Florida hospital is a tertiary-level public facility, and the second in size of a four-hospital sub-network in the corresponding urban area of Santiago. With more than 70000 m^2 of built area and 391 beds, this facility receives more than 85000 emergency patients annually (MINSAL, 2022). The hospital is located 8 km from the San Ramón Fault, a crustal fault, which has a high potential to generate damaging earthquakes (Yañez et al., 2020). Thus, the studied hospital is of interest to stakeholders in public health sector.

La Florida Hospital has a base-isolated structure and construction finished in 2012. It is expected to withstand large shaking without disrupting its functionality, and serve as the main assistance center in case of functionality disruptions in the surrounding hospitals after a major earthquake. The building has seven stories, and all the service areas of the ED are located on the first level (first story above the isolated base), as shown in Figure 6a.

The hospital drawings in Figure 6a highlight different types of service areas in the ED (blue, yellow, and pink colors indicate adult, pediatric, and maternity sectors, respectively) and point out the resources considered in our model and described in section 3.2 (Figure 4). Figure 6a shows physical spaces of the ED and the entrance door to the hospital in case of disasters. Table



(a) Distribution of ED service areas

(b) La Florida Hospital

Figure 6: Distribution of healthcare ED service areas at the case study hospital.

5 shows the installed capacity in baseline conditions. The resource indicated at the right side of the plan are distributed within different building stories, as they are considered as hospital-level services. In this case study, diagnosis support services are located outside the ED, unlike other complex hospitals serving the same healthcare network.

Resource	Symbol	Capacity
Resuscitation room/station	RR	2
Triage room/station	TR	1
Examination room/station	ER	15
X-ray/CT room	XR/CT	1
Mobile X-ray/US	XR/US	1
Laboratory	LAB	1
Operating room	OR	17
Hospitalization bed	BED	391
Intensive care unit	ICU	60
Dialysis unit/machine	DM	1

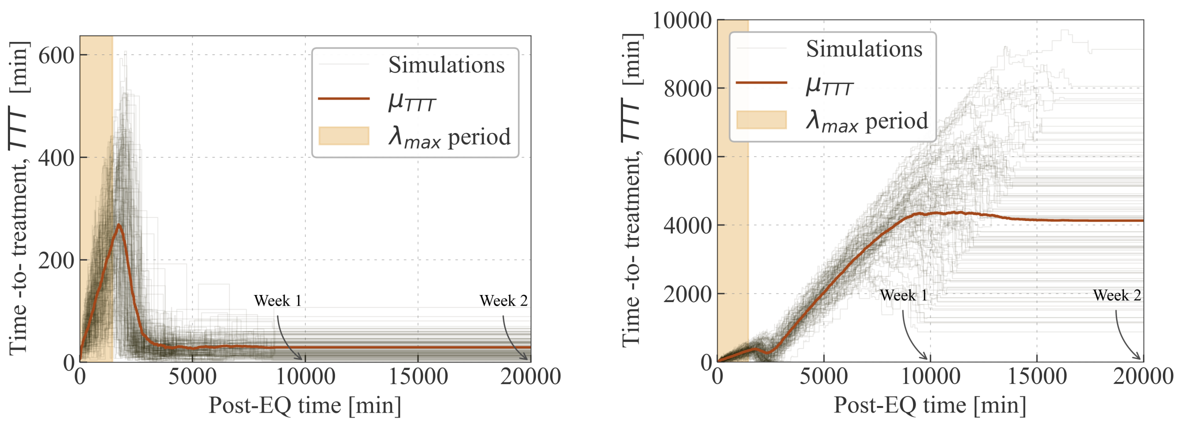
Table 5: Physical capacity of healthcare resources in La Florida Hospital.

4.2 Post-earthquake hospital performance

Hospital performance metrics were studied using 100 Monte Carlo simulations to account for the uncertainties in the arrival of patients, patient types, and duration of medical processes. Every simulation was run for a time window of 14 days, and mean curves were computed. We set a total volume for incoming patients to ED equivalent to twice the daily average of patient demand in non-earthquake conditions in La Florida Hospital. Records from regional hospitals after damaging earthquakes show increased arriving injured from 1,8 to 2,8 fold the average inflow before such emergencies (Chen et al., 2001; Pointer et al., 1992; Salinas et al., 1998).

Thus, a total of 500 patients was distributed during the first seven days after the earthquake according to the arrival function in Figure 3.

Figure 7 shows TTT example curves for two different types of patients, one passing through the ED (non-surgical injury) and the other one needing hospital-level healthcare services (surgical injury). The mean TTT for hospital-level patients follows a similar trend and scale as those for ED-level patients during the first 40 hours while pre-earthquake available beds get occupied (Figure 7b). Unlike the ED case, the mean TTT stabilizes after the first week of arrivals, but it does not recover to the initial values even during the second week due to the long patient queues.



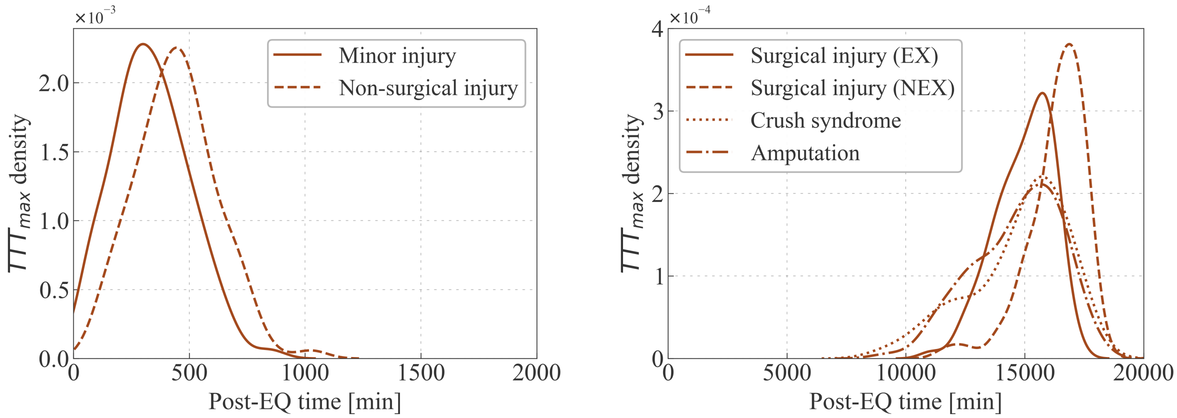
(a) ED-level patients

(b) Hospitalization-level patients

Figure 7: TTT results from Monte Carlo simulations over 14 days after the earthquake for two different patient types. Mean curves are presented in bold lines, and the light strip indicates the period when λ_{max} occurs (<24 hours).

In addition to the demand level, performance metrics are found to be highly dependent on the specific processes and resources for different patient types. Figure 8 shows the probability distribution of maximum TTT values, PDF(TTT_{max}), as defined in section 3.3 and Figure 5, from Monte Carlo simulations. For ED-level patients, mean values of TTT_{max} are smaller than those of hospital-level patient (Figure 8). ED-level patients require healthcare procedures only within the ED, without the need of hospital-level resources, such as hospitalization beds. In our model, ED-level services (i.e., resuscitation, triage, examination, diagnosis support, and minor trauma treatment) are characterized by distributions of process durations with mean values below 30 min (Table 4). In contrast, TTT_{max} distributions for hospital-level patients show larger values (Figure 8b), as they require beds and ICUs, which have long occupation times (Table 4). Thus, waiting times for hospital-level services increase significantly if high percentage of beds and ICUs are busy, as usually happening in tertiary hospitals.

For every patient type, mean curves of the *UAS* ratio were determined from the Monte Carlo simulations. As mentioned in section 3.3, the *UAS* ratio metric was defined to quantify the percentage of patients waiting for treatment for more than a critical threshold of four hours, plus an additional boarding time for hospital-level patients (Figure 5). For ED-level patients,



(a) ED-level patients.

(b) Hospital-level patients.

Figure 8: Distribution of maximum values for time-to-treatment of all patient types studied.

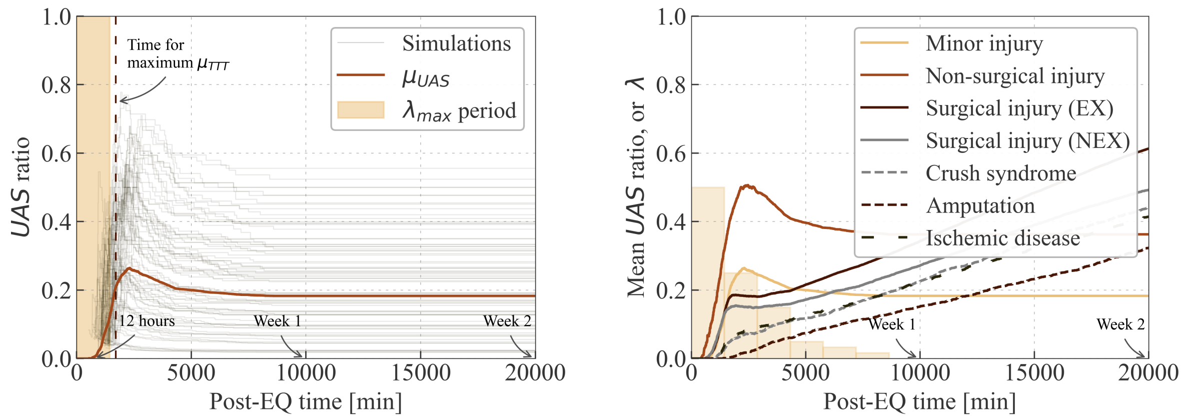
we observed that the UAS ratio is zero during the first 12 hours when TTT values have not exceeded the time threshold (Figure 9a). It increases with time as TTT increases, and gets its maximum value near two hours after TTT reaches its maximum mean. After the peak, mean *UAS* ratio decreases following the reduced patient arrival rates and the TTT values. Finally, the ratio stabilizes after the seventh day, following the end of patient arrivals to the hospital. The curve keeps a constant ratio when new patients stop arriving.

For those patients requiring hospital-level services (patients on paths 3 to 7), the *UAS* ratio values keep increasing beyond the end of arrivals on day seven (Figure 9b). We observe that the increasing needs for hospitalization generate higher values of the *UAS* ratio due to the long duration of the hospitalization process of surgical patients. *UAS* ratio values for hospital-level patients resemble a bi-linear behavior for which the change in the increasing rates follows the variations of the patient arrival rates. In contrast, the *UAS* ratio for ED-level patients stops increasing past the maximum patient volume that arrives at the hospital (Figure 9b).

4.3 Enhanced performance by increased capacity

We also evaluated how an increase in capacity enhances hospital performance. To synthesize our findings, the results are presented again in terms of **ED-level** and **hospital-level** patients rather than the specific patient types studied (3). We selected patient types 2 (non-surgical injury) and 3 (surgical injury/extremity) as proxies for ED-level and hospital-level patients, respectively. Such patient types were found to experience the highest μ_{TTTmax} among their respective group, given their significant need for shared resources (e.g., ERs, imaging resources, ORs, beds), or the increased percentage of arrivals among all patient types (Table 3). In case-studies with expected high ratios of patients with non-extremity surgical injuries, crush injuries, and amputees, other resources are of primary interest (e.g., ICUs, hemodialysis equipment).

For every patient type, we computed performance metrics considering different capacity scenarios (e.,g., the number of available resources in different service areas). The simulated scenarios are intended to represent both, the need for increased capacity as a crisis response



(a) Patient with minor injury.

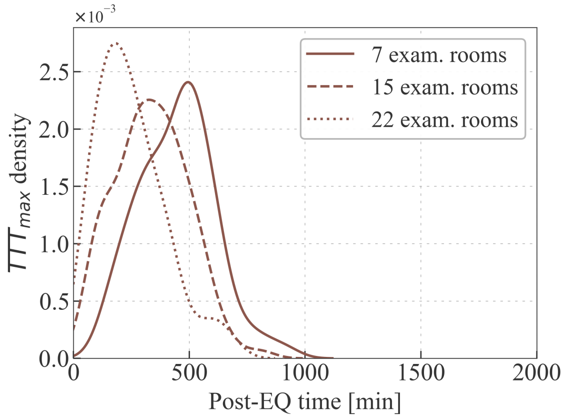
(b) All patient types studied.

Figure 9: Fourteen-days UAS ratio results: Figure (a) shows the mean curve in dark brown and the responses for all simulations. The shaded region indicates the period of maximum arrival rates (i.e. the first 24 hours), and the dashed line denotes the time when TTT_{max} occurs. Figure (b) presents mean curves for all patient types (MI: minor injury; NS; non-surgical injury; SE: surgical injury/extremity; SN: surgical injury/non-extremity; CS: crush syndrome; AM: amputation; SD: ischemic disease).

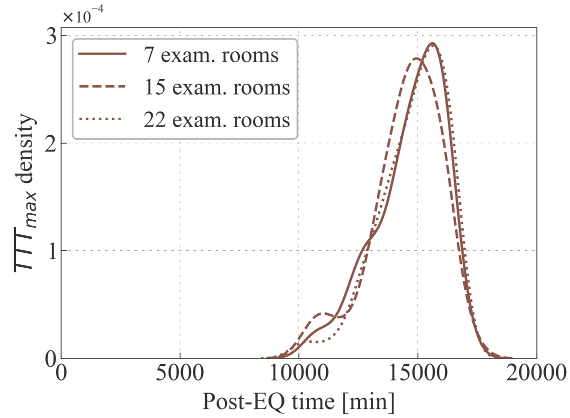
measure when additional service areas are enabled, and the impact of a possible reduced capacity due to loss of functionality in critical services caused by the earthquake disruption. Past evidence suggests that hospitals' performance is highly related to the functionality in service areas and that increased capacity enhances health outcomes of earthquake-related patients (Achour & Miyajima, 2020). This study shows how hospital performance metrics such as TTT and UAS ratio vary when there is a change in the number of highly shared resources in the case of earthquake-related patient types.

We calculated TTT_{max} distributions for ED-level patients (Figure 10a,) and quantified how their mean values, μ_{TTTmax}, vary with the change in ER resources. The mean μ_{TTTmax} increases nearly by 30% if the hospital loses 50% of the ER capacity, which represents a decrease of 5 examination rooms. In contrast, by adding five more examination rooms in the ED, the improvement in μ_{TTTmax} is of 50%. Although most patient types share medical resources at the ED level, TTT_{max} is less sensitive to changes in ER capacity for hospital-level patients (Figure 10b).

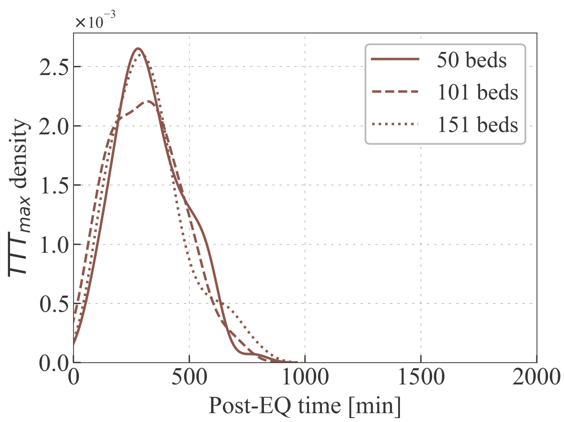
As it should be expected, TTT_{max} in hospital-level patient types is highly sensitive to the availability of hospitalization beds (Figures 10d). Our simulations consider a bed occupancy rate of 75% at the time of the earthquake. The mean μ_{TTTmax} increases by 15% if the hospital loses 50% of available beds, but we also found a strong reduction in μ_{TTTmax} of 60% if the bed occupancy rate decreases to 60%. There fore, the number of available beds at the time of the earthquake is a very relevant factor. For the scenarios of variable bed capacity, the mean μ_{TTTmax} of the ED-level patients is not affected, as our model considers that boarding waits are physically performed within the ED waiting rooms (Figure 10c). However, if such waits are carried out in the examination rooms due to an ED crisis, delays increase for all patient types requesting emergency assistance. Although this situation is possible, it might not be realistic in many public hospitals worldwide.



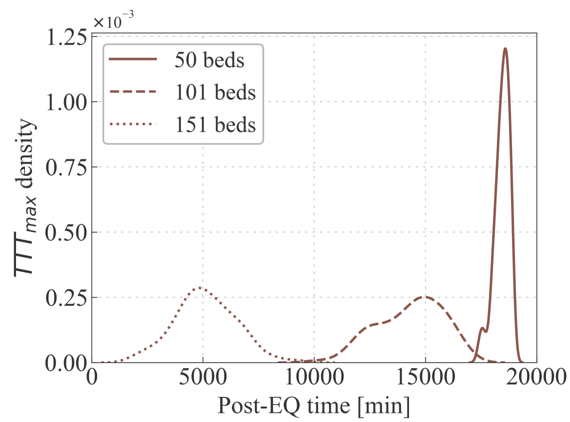
(a) PDF of TTT_{max} for ED-level patients with variable ER capacity.



(b) PDF of TTT_{max} for hospital-level patients with variable ER capacity+.



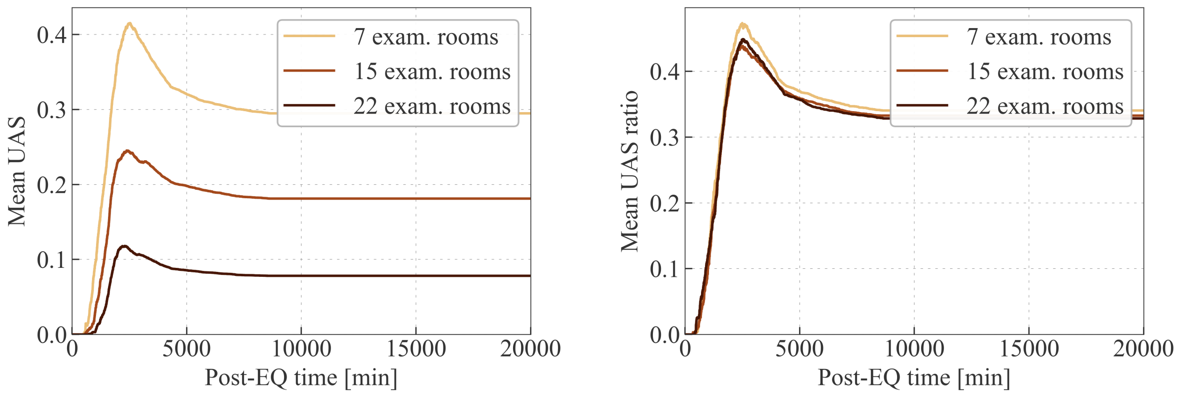
(c) PDF of TTT_{max} for ED-level patients with variable bed capacity.



(d) PDF of TTT_{max} for hospital-level patients with variable bed capacity.

Figure 10: TTT_{max} distributions for ED-level patients (left column plots) and hospital-level patients (right column plots). The different plots show three capacity scenarios (0.50, 1.0 and 1.5 times the baseline capacity) for different resources (examination rooms in the ED, and hospitalization beds).

For ED-level patients, previous research on hospital response to earthquakes has commonly revealed the importance of examination rooms where physicians assess the initial patient's condition (Myrtle et al., 2005). Our results are consistent with such findings, but we also found that the importance of ED areas depends on the patient type. In Figure 11a, the sensitivity of mean *UAS* curves adding or reducing examination rooms in the ED is presented. For minor injury patients, changes in the number of examination rooms show a higher impact on *UAS* ratio than those related to patients with non-surgical injury, as the latter require other diagnosis support services such as X-rays imaging (Figure 11b). These patients have longer TTT values because more processes are involved in their treatment. It is apparent that healthcare outcomes are enhanced not only by protecting or increasing the front-line resources, but also the subsequent areas in the complete treatment chain.



(a) Minor injury patients.

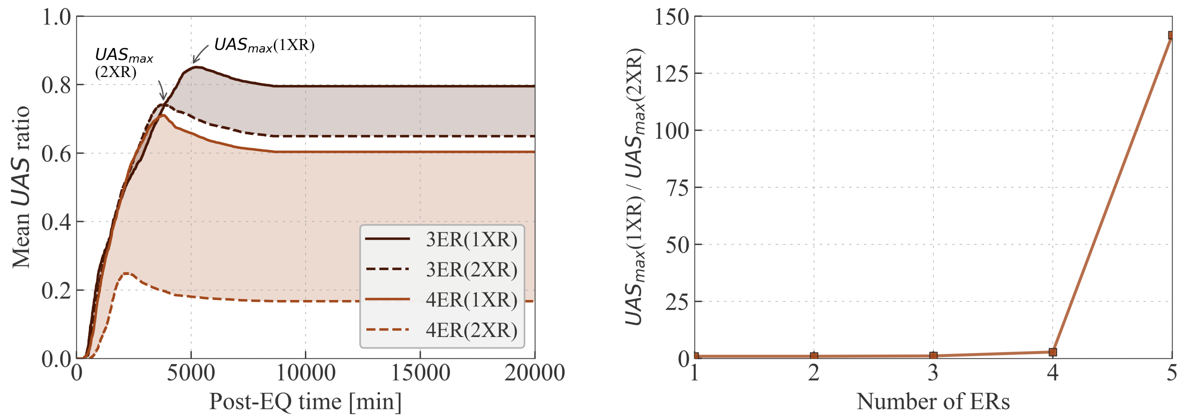
(b) Non-surgical injury patients.

Figure 11: Impact of changes in examination room (ERs) capacity for different ED-level patients with (b) and without (a) use of imaging resources.

The sensitivity of the UAS ratio was also analyzed with the number of imaging resources available for ED-level patients. After earthquakes, most trauma patients need imaging services in the ED. Some records from past disasters highlight the importance of medical equipment for diagnosing trauma (Gregan et al., 2016; Kakaei et al., 2013). The results presented in Figure 11 were computed with a single resource for imaging services, which is typical for most tertiary hospitals.

Here, we wanted to assess the ED performance with increased capacity of the imaging services, which can represent mobile X-rays or ultrasound that are typically deployed after large earthquakes. For example, only an additional X-ray resource makes TTT values be below the critical time threshold, resulting in a drop of UAS to zero for our case study (Figure 12a).

Also, we found that the benefit of increasing the number of X-rays rooms/machines is significant only when the hospital ensures more that three ERs available (Figure 12b). Figure 12a evaluates the impact of adding one X-rays resource on the mean UAS ratio of ED-level patients requiring imaging (i.e., non-surgical injury), simulating thr different ER capacity. The ratio between maximum values of the mean UAS curves with 1 or 2 X-ray (XR) resources is presented in Figure 12b. Results indicate that if hospitals lose functionality of several ERs, then ERs become a bottleneck and changes in imaging resources have a smaller impact on treatment times.



(a) Improved mean curves of *UAS* ratio

(b) Increasing performance of peak *UAS*

Figure 12: Impact of increased imaging capacity (X-ray resources: XRs) on the performance metrics for ED-level patients including variability in the number of examination rooms (ERs). Plots show the enhanced curves for some ERs cases (a), and also the changes on the ratio between maximum values of the mean *UAS* curves considering 1 and 2 imaging resources, respectively (b).

5 Conclusions

After large earthquakes, hospitals are required to meet the demand for acute care of injured patients with a timely approach. This research presents a new model for post-earthquake hospital operations based on discrete event simulation. The proposed hospital model is based on the healthcare needs of earthquake-related patients from the perspective of the physical resources required for supporting hospital emergency processes. Our model presents an enhanced characterization of patient profiles, including the epidemiological outcomes from several past earthquakes. Our definition of healthcare processes improves the commonly used flows in the literature based on the injury severity, which lumps together needs for life-threatening and non-life-threatening conditions. Our model accounts for the diverse earthquake-induced healthcare needs of a defined set of patient types, and finds the physical capacity needed for an effective hospital response during the aftermath of the earthquake .

We found that the priority of functional areas within the hospital is determined by the distribution of patient types arriving at the ED, which directly impacts use of resources. We analyzed distribution of patient types frequently observed after large earthquake, and showed that the examination room is key to providing a physician-based treatment decision for trauma patients at the ED level (minor injury and non-surgical injury). Results from our case-study analysis demonstrate that maximum time-to-treatment for ED-level patients could increase up to 40% if the functional examination rooms in the ED decreases to half. The timely healthcare assistance for these patients relies mainly on the physician's examination and minor trauma treatment rather than the availability of complex resources for other procedures such as surgery.

For those patients requiring hospital-level assistance (e.g., surgical fractures, crush syndrome, amputation, ischemic illness), the availability of functional hospitalization beds and

ICUs become more neccesary than the resources in the ED. The need for these resources restricts the performance of surgical procedures, and their occupation times are significantly longer compared to the inter-arrival time of admitted patients. Figure 10d shows how mean values of maximum time-to-treatment increase 20% if the bed occupation rate changes from 75% to 87% after the earthquake. Results also demonstrate the improvement in wait times when the bed occupancy rate is reduced in response to the crisis in a reverse triage measure. If this rate decreases from 75% to 60%, we showed that maximum TTT significantly decrease up to 60%.

We found that resource usage is highly governed by the emergency processes defined to respond to the surge in patient arrivals. For example, our model considers that the examination room remains busy while patients receive imaging services. After earthquakes, trauma patients require imaging to determine the proper medical treatment. Hence, the usage time of ERs will be extended according to the availability of X-rays/US rooms, mobile machines, or CT scans, and hence, the patient waiting times (Figure 12a). Thus, ERs are critical for many patient types, as it is considered a mandatory step in most treatment paths. Figure 11 shows that the ER availability impacts the unassisted-patients ratio for ED-level patients, mainly if they do not need the imaging resources (minor trauma patients).

If alternative processes are adopted (e.g., a fast-track system in ER), and the examination room is released once the physician sees the patient, the bottleneck areas are expected to change for ED-level and hospitalization-level patient types. In this case, the availability of beds is no longer a surgery restriction, and the operating room will probably become the most important resource, as it has been evidenced in field hospitals (Schreeb et al., 2008).

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