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UNDERSTANDING POST-EARTHQUAKE HOSPITAL ARRIVAL TIMES THROUGH AGENT-BASED MODELLING

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Abstract: *Infrastructural and socio-economic factors controlling the post-earthquake transfer of injured people to hospitals are critical for decision-making on post-disaster medical assistance but remain largely unexplored in the literature. This work addresses this challenge through an agent-based modelling approach that comprises two computational steps (modules). The first module consists of a probabilistic multi-severity casualty estimation model for quantifying the number, severity, and distribution of casualties following an earthquake in a region. The second module incorporates an agent-based model simulating individual and collective community behaviour related to transporting injured people to hospitals during the post-disaster phase. The model assumes that injured people arrive at hospitals by their own means (in a vehicle) or by ambulance, depending on the severity of their injury. The proposed approach is demonstrated for a moment magnitude (Mw) 8.0 earthquake scenario earthquake in Lima, Peru, focusing on two districts (i.e., Santiago de Surco, San Juan de Miraflores). The main results of this study indicate that some characteristics of the built environment (i.e., the number of hospitals and ambulances in the area) and attributes of the population (i.e., car ownership) may be essential for guaranteeing access to adequate post-disaster medical care. The findings of this work can be used to help decision-makers in planning effective emergency response strategies for future earthquake disasters.*

Introduction

Major earthquakes and other natural hazards can result in devastating consequences in urban areas, including large numbers of casualties due to building damage. Following an earthquake, hospitals may face a sudden surge of incoming patients who require medical treatment or hospitalization, far exceeding hospital admissions in normal circumstances (Moitinho de Almeida *et al.*, 2020). Moreover, earthquake-induced damage to healthcare facilities can reduce their capacity to allocate patients and provide timely critical healthcare services. For example, after the moment magnitude (Mw) 8.8 earthquake that struck Chile in 2010, 73 hospitals were damaged, leaving more than 2000 patients to be transferred between hospitals and causing long wait times at the remaining functional facilities (American Red Cross Multi-Disciplinary Team, 2011). This delay in medical treatment can be especially critical for patients with life-threatening conditions (e.g., those who require amputation or blood transfusions), as their mortality risk increases without immediate access to medical care (Guttmann *et al.*, 2011). As cities are rapidly growing and become more densely populated, the impact of natural hazards on public health is also increasing in magnitude (Ceferino *et al.*, 2020). To address these challenges, international organizations, such as the World Health Organization (World Health Organization, 2016), continuously encourage countries to implement policies that strengthen the capacities and coordination of the hospital systems and facilitate related efficient resource allocation during the emergency response.

Given the urgent need to support policymakers in developing effective plans for hospital system response to earthquake emergencies (FEMA, 2020), many studies continue to propose methodologies and models for characterizing and improving the resilience of healthcare systems. Such methods and models typically incorporate different simulation modules such as hazard analysis, fragility modelling, surge and patient demand modelling, functionality and restoration modelling, etc. (Mahmoud *et al.*, 2023). When modelling patient demand in particular, previous

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studies have used empirical or simulation-based approaches to estimate the number of injured people, the arrival pattern, and the length of time taken for patients to arrive at hospital emergency departments (Palomino Romani *et al.*, 2023). Empirical methods consist of scaling arrival rate curves from previous earthquakes based on the earthquake intensity and/or hospital size

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(Cimellaro *et al.*, 2011; Malavisi *et al.*, 2015). However, these types of arrival rate curves are not easily available for many regions and may not be suitable for capturing the actual population distribution and building damage for different earthquake scenarios (Palomino Romani *et al.*, 2023).

To overcome the issues associated with empirical arrival rate curves, other studies have estimated patient arrivals by combining the number of predicted injuries based on building damage in the specific region of interest - estimated using casualty models such as HAZUS (FEMA, 2020) - with well-documented observational data of patient arrivals (Favier *et al.*, 2019). Further work suggests modelling the post-earthquake patient arrival rate as a Poisson distribution (Palomino Romani *et al.*, 2023). Despite these efforts, a detailed investigation of the specific factors (e.g., means of transportation, number of hospitals in the area) controlling the postearthquake transfer of injured people to hospitals after an earthquake, which is critical for constraining arrival rates and understanding *who* arrives *when*, remains largely absent from the literature. To address this challenge, this study investigates the influence of infrastructural and socio-economic factors on the post-earthquake accessibility of hospitals to injured populations. The proposed agent-based modelling approach is specifically demonstrated for a Mw 8.0 earthquake scenario in Lima, Peru, focusing on two districts in particular.

Materials and methods

The case-study area comprises two districts (out of a total of 43) in Lima, Peru, namely Santiago de Surco (herein referred to as Surco) and San Juan de Miraflores (herein referred to as San Juan). Surco and San Juan, located in the southern part of Lima, are contiguous and have populations of 329,238 and 355,249 inhabitants (INEI, 2017), respectively (see Figure 1, which also provides information on hospitals and road networks). The Mw 8.0 earthquake scenario investigated replicates the 1940 earthquake that occurred in the subduction zone on the coast of Lima and is described in detail in Ceferino et al. (2020). The proposed agent-based modelling approach for understanding the factors controlling the post-earthquake transfer of patients from these two districts involves two modules, which are explained in the following paragraphs.

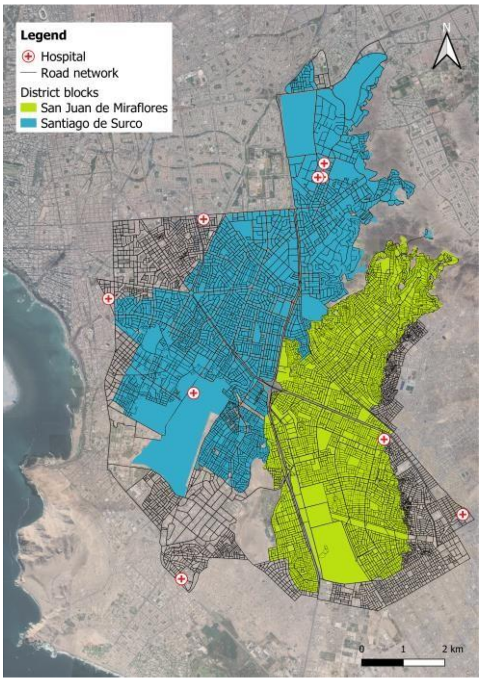

Figure 1. Study area. Basemap data: © Google Earth.

Module 1: Probabilistic regional multi-severity casualty model

The first module builds on a framework developed by Ceferino et al. (2020, 2018) to evaluate the spatial distribution of earthquake-induced injuries and fatalities. The model uses ground shaking estimates computed using the ground motion model of Abrahamson et al. (2016) and accounting for the correlation of intra-event (Markhvida *et al.*, 2018) and inter-event (Goda and Atkinson, 2009) residuals, as well as the site-specific soil conditions in Lima (Calderon, 2012). We simulate 100 realizations of each of the three required intensity measures. Specifically, the ground-shaking intensities are propagated to building damage using fragility relationships developed for the South American residential building stock (Villar-Vega *et al.*, 2017). In total, 36 structural typologies are considered, for which the associated fragility models depend on three different intensity measures that are peak ground acceleration, or PGA, and two spectral accelerations at the yielding/fundamental period, or Sa(T1): Sa(0.3 s) and Sa(1.0 s). The number of residential buildings corresponding to each typology is obtained at a district level from existing studies (Global Earthquake Model (GEM) Secretariat, 2015; Yepes-Estrada *et al.*, 2017) and is further disaggregated to a finer 1 km resolution according to the population distribution derived from Landscan Global (Oak Ridge National Laboratory, 2013). The fragility relationships describe six damage states (i.e., none, slight, moderate, extensive, complete without structural damage, and complete with structural damage). Casualty rates from HAZUS (FEMA, 2020), per damage state and structural typology, are used as marginal probabilities that an occupant has a certain casualty severity level. Casualties are categorized into five severity levels. Severity 1 represents the individuals whose treatment does not require hospitalization; severity 2 represents individuals whose treatment requires hospitalization, but the injuries are not life-threatening in the short term; and severity 3 represents the individuals whose treatment requires immediate hospitalization, as their injuries are life-threatening in the short term. The remaining two severity levels are "noninjured" and fatalities. The casualties are computed considering a nighttime scenario, assuming that 100% of the occupants are indoors during the earthquake event. The casualty distribution in the city is reported at 1 km spatial resolution.

Module 2: Agent-based model

The second module consists of an agent-based model that simulates individual and collective community behaviour related to transferring injured people to hospitals during the post-disaster phase. We develop the agent-based model in the GAMA (GIS Agent-based Modeling Architecture) Platform, an open-source platform for multi-agent simulations in a spatially explicit environment (Taillandier *et al.*, 2019). The architecture of the agent-based model consists of four types of agents (namely "species" in the GAMA modelling language): people, hospitals, ambulances, and roads. A specie is a template for an agent; when we initialize the model and run a simulation, many agents for each specie are created following this template.

The people agent contains the following attributes: ID_people, district, block, household, casualty category, private car ownership, car speed, target hospital, and target ambulance. The people agent is defined by creating a synthetic population dataset based on block-level data from the 2017 National Population and Housing Census (INEI, 2017) and various assumptions about the characteristics of households. All data processing for the creation of the synthetic population dataset is conducted using MATLAB and QGIS software. The census dataset reports the number of households, the number of people, and other demographic and socio-economic attributes of the population for each block in the city. We assume each household lives in a separate building (since the number of households and buildings reported by the census are fairly similar). We also assume that buildings in a given block are equally distributed within the block's perimeter. As the distribution of household sizes is not reported by the census, we assume a uniform household size for each block (i.e., households in a given block contain approximately the same number of people). The uniform household size for a given block is determined by dividing the number of people by the number of households; in some cases, households may have one person more than the other households (e.g., 20 people and six households in a given block are distributed as four households with three people and two households with four people). To define the value of the "private car ownership" people agent attribute, we randomly select households in each block to match the number of households with private cars reported by the census. All people living in the selected households are assigned the value "yes" for this attribute. Since the casualty distribution in Module 1 relies on estimates of the population (Oak Ridge National Laboratory, 2013) that differ from the actual census population (INEI, 2017) used in Module 2, we perform some additional calculations. First, we update the distribution of casualties per km^2 by multiplying the percentages of people per casualty category from module 1 by the number of people from module 2. Then, we randomly select people in a given km^2 to match the updated number of people per casualty category for that km^2. The value of the "casualty category" attribute for each people agent varies in each simulation per the results of the casualty module, which are influenced by the underlying ground-motion variability.

The hospital agent contains the following attributes: ID_hospital. The hospital agent is defined using a hospital inventory dataset (Santa Cruz *et al.*, 2013; Liguori *et al.*, 2019) that includes information on hospital campuses from EsSalud (Social Security), one of the two major public healthcare systems in Lima. We also include hospitals from the private healthcare system, as public and private healthcare systems are expected to provide medical services after a major earthquake in the city, according to the regional authorities (Ministerio de Salud, 2021). In total, we consider nine hospitals operating across the two districts. Note that the analysis of the postearthquake hospitals' functionality is not within the scope of this study. The ambulance agent is defined considering that each hospital assigns one ambulance to mobilize patients in the two districts. Although some hospitals have more than one ambulance, we assume (somewhat conservatively) that other ambulances will be used to mobilize patients from the surrounding districts. The road agent is defined using a high-resolution road network dataset provided by the national authorities, which contains all streets, avenues and roads in the city. We assume the road network will remain undamaged (i.e., fully functional) after the earthquake. We do not consider the impact of collapsed-building debris accumulation on the road network because models to estimate debris require the use of high-resolution building-level datasets (i.e., with information on their structural typology, number of floors, etc.; Iskandar et al., 2020; Xu et al., 2022) that are not available for the case study.

The actions defined for the people agent are summarized in Figure 2. We assume that only people whose "casualty category" attribute is severity 2 or severity 3 (i.e., those who require hospitalization) are transferred to hospitals. People whose "casualty category" attribute is severity 1 could receive medical attention in small medical centres; thus, their mobilization is not represented in the model. Severity-2 patients go to the nearest hospital immediately after the earthquake by their own means if two conditions are met: i) there is at least one non-injured person in their household; and ii) their household owns a private car. Otherwise, severity-2 patients call for an ambulance and wait for their transfer to any hospital in the area. Severity-3 patients always call for an ambulance and wait for their transfer to any hospital in the area. Given the significant extent of their injuries, we neglect the possibility of severity-3 patients being mobilized by their own means.

In addition, we develop a modified set of actions for the "People" agent to evaluate the potential impact of collective community help in transporting injured people to hospitals. These set of actions assume that severity-2 patients can go to the nearest hospital immediately after the earthquake aided by people from their block if two conditions are met: i) there is at least one noninjured person in any household of their block; and ii) they own a private car. These changes will modify the decision box to be evaluated for severity-2 patients in Figure 2.

The ambulance agent contains the following attributes: ID_ambulance, ID_hospital, and patient. The actions defined for the "ambulance" agent are summarized in Figure 3. These actions assume that the emergency response agencies in Lima (i.e., Servicio de Atención Móvil de Urgencia and Sistema de Transporte Asistido de Emergencia) have capacities to coordinate patient mobilization across multiple hospitals (Ceferino *et al.*, 2020). We assume that ambulances transport all severity-3 patients first, given their higher priority for medical care over those in severity 2. Both the origin and destination of ambulance trips are the location of the assigned hospital. The allocation of ambulances is not based on the distance to the patient's home, ambulances can transport patients from any location in the city. For instance, the transfer of a patient living in San Juan could be assigned to an ambulance of a hospital in Surco; thus, patients are not necessarily transferred to their nearest hospital. The existing capacity of hospitals is not accounted for in the allocation of ambulances. Ambulances work 24 hours each day, and there is no waiting time between ambulance trips. As the road segments contained in the road network are not distinguished between streets and avenues, the travel speed for private cars is sampled from a uniform distribution between 30 km/h and 50 km/h, which are the speed-limit values for streets and avenues in Lima, respectively (Ministerio de Transporte, 2021). Since there is no restriction on the speed of ambulances, we assume their speed to be an increase of 50% over the travel speed allowed for private vehicles. Thus, the travel speed for ambulances is sampled from a uniform distribution between 45 km/h and 75 km/h.

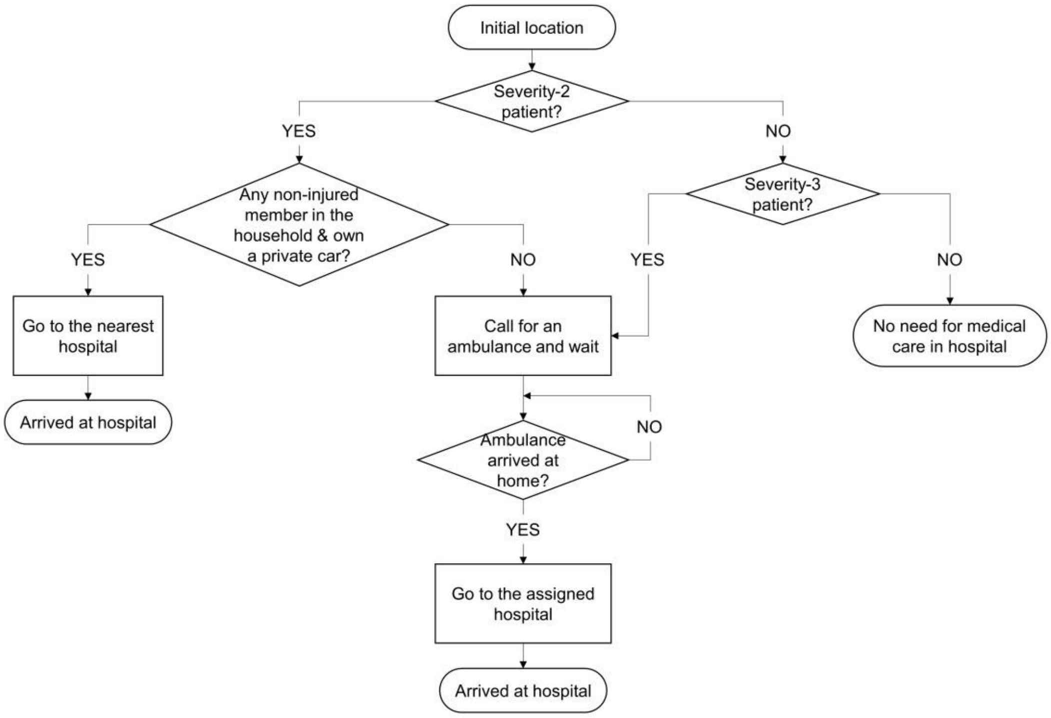

Figure 2. Flowchart of actions defined for the people agent

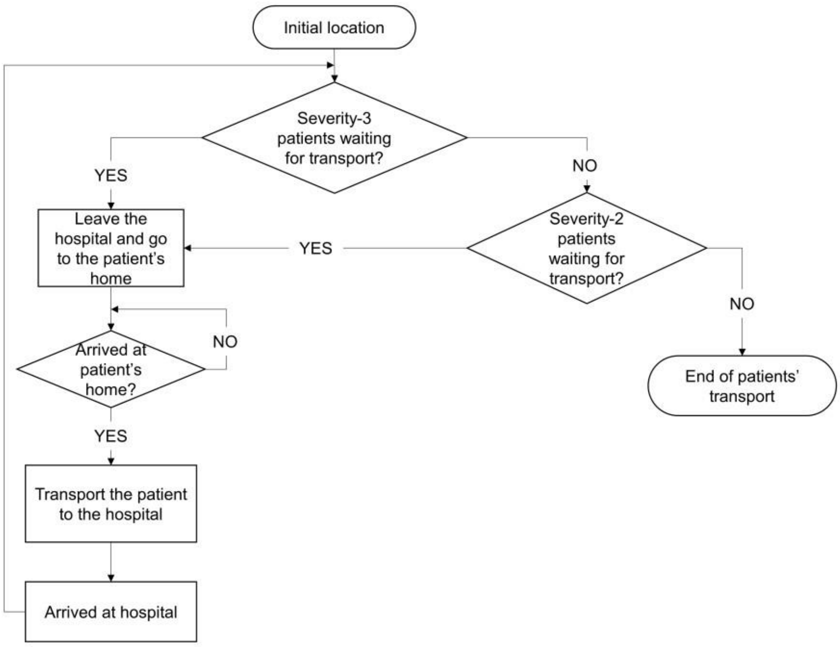

Figure 3. Flowchart of actions defined for the ambulance agent

Results from the agent-based model are the absolute number of patients who arrived at hospitals at each temporal instant of interest, which can be disaggregated by district, casualty category, hospital destination, etc. We translate these absolute values into a relative metric (i.e., the ratio of patients successfully transferred to hospitals to the total injured population at each time step) because i) we are simply interested in the successful transfer of patients to hospitals, which is related to the relative proportion of patients transferred rather than the exact number; and ii) we are not comparing hospital demand and capacity, which would require absolute numbers to be investigated; this is left to other studies (e.g., Ceferino et al., 2020; Liguori et al., 2019).

Results

Earthquake casualties

Table 1 summarizes the mean number of people per casualty category estimated for the Mw 8.0 earthquake scenario occurring at nighttime. On average, 1707 patients will require to be transferred to hospitals by their own means (i.e., using private cars) or using ambulances.

Casualty category	**Mean number of people**
Non-injured	677636
Severity 1	4693
Severity 2	1475
Severity 3	232
Fatalities	451

Table 1. Mean number of people per district and casualty category

Patient arrival curves by district and casualty category

Figure 4a presents the arrival curves for severity-2 patients disaggregated by the district for the baseline set of people's actions. It can be observed that a significant proportion of the patients are transferred in the first hours after the earthquake. For instance, 57% of severity-2 patients in Surco and 26% in San Juan are successfully transferred in the first hour after the earthquake. The larger immediate post-earthquake accessibility to hospitals for people in Surco can be explained by the higher proportion of households with private cars in this district, which may reflect the higher income level of its population. It may also be explained by the fact that seven hospitals are located in Surco or its proximities, while only two hospitals are located in San Juan or its proximities. Thus, patients from Surco spend less time going to the nearest hospital than patients in San Juan. Hospitals remain more accessible to Surco's injured people during the following days, although the relative differences in accessibility between the two districts decrease over time. 95% of severity-2 patients in Surco are successfully transferred approximately 4 days after the earthquake. The same statistic is achieved for San Juan in around 6.2 days. At this point, ambulances play a critical role in transporting severity-2 injured people (after completing the transfer of severity-3 patients). All severity-2 patients are expected to be transferred in 23 days. Note that this value is influenced by the choice of probabilistic casualty model, which has a notably heavy right tail that can result in some very long arrival times.

Figure 4b presents the arrival curves for severity-3 patients disaggregated by district for the baseline set of people actions. The curves from both districts show almost identical trends over time, which is explained by the fact that ambulances can transport patients from either district to any hospital in the area. Thereby, differences in hospital infrastructure between districts (i.e., the fact that Surco has more hospitals than San Juan) do not influence accessibility to hospitals for severity-3 patients. Moreover, prioritization of ambulance use for transferring severity-3 patients, the faster travel speeds of ambulances compared to private cars, and the smaller number of injured people in this casualty category result in shorter arrival curves for severity-3 patients compared to those in severity 2. 50% of severity-3 patients in both districts are successfully transferred approximately 1.7 hours after the earthquake, and 95% are transferred around 1.2 days after the earthquake.

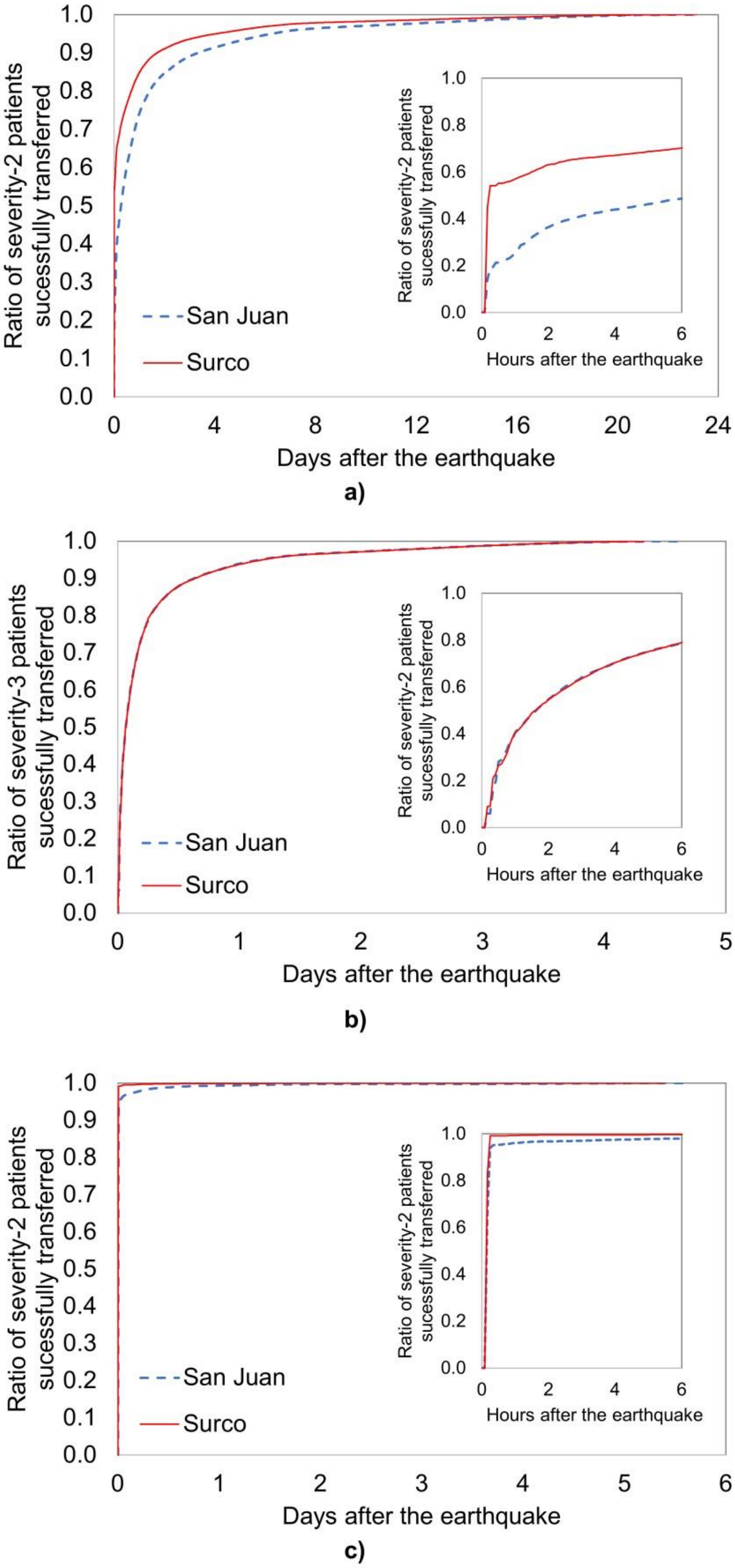

Figure 4. Arrival curves for a) severity-2 patients and b) severity-3 patients in the baseline scenario; and severity-2 patients in the modified scenario

Figure 4c presents the arrival curves for severity-2 patients disaggregated by the district for the modified (additional) set of people actions. Incorporating community solidarity actions into the emergency response results in benefits for the affected population (i.e., increased timely hospital accessibility) and reduces disparities in hospital accessibility between both districts. 99% of severity-2 patients in Surco and 96% in San Juan are successfully transferred in the first hour after the earthquake, representing relative improvements of 74% and 271%, compared to the baseline set of people actions considered. Although the modified set of actions may be considered somewhat idealistic (i.e., since the underlying assumption is a widespread willingness of people to assist others), the results demonstrate that relatively small individual actions taken at the neighbourhood level can have an enormous benefit at the district/city level.

Conclusions

This study investigates the influence of various factors - including characteristics of the healthcare system and population attributes - on the post-earthquake arrival of patients to hospitals, considering an 8.0 Mw scenario in Lima, Peru. The results reveal that car ownership and the number of hospitals can be important influences on the arrival of patients to hospitals in the first hours after the earthquake. In addition, the support provided by non-injured people to those injured in their neighbourhood can significantly improve post-earthquake accessibility to medical care. Note that this study assumes that only one ambulance is assigned to each hospital; a higher number of emergency vehicles in the area would reduce the arrival times for injured people in both casualty categories (this will be investigated in a further study). Moreover, further work could be done to refine some assumptions (e.g., roads remain fully functional after the earthquake, ambulances are exclusively used for earthquake-induced injuries) of the model. While the findings of this work are limited to one case study, the adopted approach can be used to help decisionmakers in planning an effective emergency response to future earthquakes.

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