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Hierarchical earthquake shelter planning in urban areas: A case for Shanghai in China

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ABSTRACT

Proper pre-disaster emergency shelter locations and the corresponding victim allocation contribute to mitigating disaster loss in densely populated urban areas. The number of victims and their needs in emergency shelters change over the duration of the post-earthquake period, as evidenced by both actual earthquake records and theoretical analysis. To match the time-varying demand with the shelter planning, the hierarchical shelters that provide different level services should be projected. We first estimate the varying number of the victims in shelters during the post-earthquake period, and then model the locations for emergency shelters with a nested hierarchy, and also model the allocation of victims among shelters. Furthermore, we employ an efficient hybrid cross-entropy method to solve the location model and develop a better victim allocation scheme with a swap move to overcome the drawbacks of other allocation schemes. The empirical results from application to the Xuhui District in Shanghai of China show that emergency shelter planning based on a time-varying demand can reduce the construction cost of shelters and the averaged evacuation distance traveled by the victims, compared to the current policy based on the unvarying demand.

1. Introduction

The costs caused by natural hazards are rapidly increasing in urban areas, particularly in developing countries, where a number of megacities are growing. By 2050, 66% of the world population is expected to live in cities, where various human activities are concentrated. Thus, cities are more and more vulnerable to disasters, particularly to earthquakes, which can strike any city suddenly without warning. Once an earthquake takes place in a large city, the damage can be tremendous both in social and economic terms. Without proper disaster operations management, even an intermediate earthquake would become a destructive disaster to a city. Although it is not possible to prevent or predict the next earthquake, its adverse effects can be mitigated through various actions and strategies, e.g., operating emergency shelters. By planning emergency shelters effectively at the mitigation and preparedness phases, the exposure of affected population to earthquakes can be reduced dramatically and their resiliency to the disaster also can be improved [5].

According to the United Nations Disaster Relief Co-ordination Office, emergency shelter serves several vital functions: protection against the disaster, storage of belongings and protection of property, establishment of territorial claims, emotional security and privacy [21]. In the 2011 Tōhoku earthquake, over 2,000 emergency shelters were put into use immediately, providing over 360,000 victims with safe places and essential relief resources, and made better living conditions for the victims when the earthquake destroyed their houses [19]. There are various forms of shelters, for example, fixed temporary shelters, self-built shelters, replacing shelters, temporary outdoor shelters, and community or collective shelters [20]. Existing infrastructure in urban areas such as schools, gyms, arenas, green space, and fair market can be transformed to emergency shelters through adapting emergency facilities. These shelters can be classified into two main kinds: temporary shelters, which are used immediately after an earthquake (including tents accompanied by the provision of food, water and medical treatment); and temporary houses which are constructed in a temporary location, allowing for a return to normal daily activities (this can take the form of prefabricated housing) and are usually intended to be used for a longer time following an earthquake [22].

Because emergency shelters are important infrastructure in post-earthquake period, their planning has received increasing interest from both researchers and practitioners. Most research on emergency shelter planning considers that the total number of victims does not

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change throughout the post-earthquake period. For instance, HAZUS is widely used to estimate the number of people who will seek shelters in earthquake scenarios (http://www.fema.gov/hazus-software). The HAZUS methodology assumes that the number of people who will require short-term housing is a function of income, ethnicity, home ownership, and age. However, HAZUS may underestimate the shelter needs [28], also may fail to realize that the number of people who evacuate to shelters actually changes at different phases after an earthquake. According to the Central Disaster Prevention Council (CDPC)'s report on the Niigata Earthquake, Japan in 2004, the number of affected population who evacuated to shelters was peaked at over 100,000 on the fourth day after the earthquake and decreased to about only 10,000 people by the end of the first month (http://www.bousai.metro.tokyo.jp/taisaku/1000902/index.html). The variation of number of victims in shelters is affected by both physical and behavioral factors. The physical factor focuses on the ability of buildings to withstand an earthquake and on the seismic intensity; the behavioral factor focuses on people's choices under emergency scenario: some people would prefer to return to their homes, live with friends or relatives, or reside in a hotel, rather than evacuate to a public shelter [7]. In urban areas, interrupted water supplies and non-functioning elevators besides the damaged buildings would affect the seeking-shelter decision of the affected people, and the system dynamic method is proposed to analyze comprehensively all the factors to estimate the varying number of victims in shelters [32]. Besides that the number of victims in shelters varies, their needs for relief supplies and accommodation facilities would not be the same during the post-earthquake period. For example, victims in shelters show their low-level needs (e.g., instant food, camping tents) at the initial time and high-level needs (e.g., regular food, prefab housing) when they begin to recover. In this study, we consider the changing needs and varying number of the victims in shelters simultaneously, and view them as the time varying refuge demand (includes the needs and number).

Mathematical programming models and optimization models are widely used in shelter planning. They can be applied to the shelters location problem and the victims allocation problem. Firstly, determining where to locate emergency shelters in urban areas can be performed using Facility Location Models (FLMs). In an actual evacuation period, emergency shelters perform different functions and offer different levels of service to meet the varying needs of victims. Thus, Hierarchical Facility Location Models (HFLMs) that deal with multi-level configurations of facility location can be adopted [24]. HFLMs have been widely applied to various fields such as educational systems [29], medicine [25,3], emergency systems [33], and waste management [1,14]. To the best of our knowledge, only one study applies HFLMs to model the hierarchical feature of emergency shelters [6]. Secondly, allocating victims to selected shelters is essentially an assignment problem. Assignment problems have been extensively studied by researchers using FLMs [4]. When FLMs have a capacity constraint, they usually use the allocation solution generated in location procedures [9]. When FLMs do not have a capacity constraint, the most-used type of assignment method is the closest assignment constraint [10]. Moreover, the path assignment is adopted to achieve the trade-off between the capacity and the closest distance consideration [29]. Next, we intend to provide a framework outlining the characteristics of the modeling efforts from literature. The characteristics using which we classify the models include the followings (summarized in Table 1).

- Demand: This includes fixed and unfixed patterns. Fixed demand means the number of victims is viewed as a constant, while unfixed demand represents the number is uncertain or stochastic.
- Objective: Two types of objective function are selected: construction cost and evacuation cost (time or distance).
- Coverage: For models with coverage constraint, every community should be covered by at least one shelter, that is, the full coverage. For models without coverage constraint, no specified coverage constraint exists.
- Assignment: This relates to the allocation of victims, as previously referred, it uses either the solution generated from location procedure (general case) or the solution with Closest Allocation consideration (closest case).

Table 1
Characteristics used for classifying the literature.

Demand	F	Fixed
	UF	Unfixed
Objective	EC	Evacuation Cost
	CC	Construction Cost
Coverage	FC	Full Coverage
	–	Non-specified
Assignment	G	General case
	C	Closest case

Table 2
Summary characteristics of modeling efforts.

Arthur year	Demand	Objective	Coverage	Assignment
[26]	F	EC	–	G
[8]	F	CC	FC	G
[15]	UF	CC	–	G
[18]	UF	CC/EC	–	G
[11]	F	CC	FC	G
[17]	UF	EC	–	C
[6]	F	EC	FC	G
[12]	UF	CC/EC	–	G
[27]	UF	CC/EC	–	G
[13]	F	CC	FC	C
[34]	F	EC	FC	G

Given the above modeling attributes (see Table 1), characteristics of the literature are presented in Table 2. The presented models are sorted based on their year of publication in ascending order to provide better insights on the evolution of the field.

The classification of literature presented in Table 2 presents some gaps in current literature that our work intends to fit in: (1) Neither fixed demand or unfixed demand consider the varying refuge demand of victims comprehensively. The varying refuge demand indicates the changing needs and varying number of victims in the shelters, and all the references consider the number of victims only. (2) The assignment used in current references to allocate victims wouldn't achieve the trade-off between distance and capacity consideration, because they either use the allocation generated by location procedure or the solution with closest assignment consideration.

Shanghai is a mega-city with more than 24 million people and is the largest economic center in China. By 2015, the GDP of Shanghai reached 379.2 billion dollars, with an average growth of 22.3 billion dollars per year since 2003. Shanghai has widespread slowly accumulated soft clay layers, making it a typical soft-soil area with a fragile geographic environment. Many tall buildings proliferate in its central area, and the surrounding environment of the city lies on several moderate-scale earthquake faults. A small area, huge population, intensive new construction and a high concentration of economic activities can characterize Shanghai; meanwhile it also has great seismic risk. Therefore, we select a central district of Shanghai-the Xuhui district as case study, aiming to give some insights to guide the practice of shelter planning.

The remainder of this article is organized as follows. Section 2 introduces the methodology used in this paper. Firstly, we propose the estimation method of the changing needs and varying number of victims in shelters after an earthquake. It is therefore necessary to determine how shelters should be structured to accommodate these variations. Secondly, we propose a hierarchal emergency shelters