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Location Optimization of Fire Stations: Trade-off between Accessibility and Service Coverage

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Abstract

Fire and rescue service is one of the fundamental public services provided by government in order to protect people, properties and environment from fires and other disasters, and thus promote a safe living environment. Efficient deployment of fire stations is necessary and essential if timely response to the emergencies is to be achieved. Spatial optimization approaches have been long employed in public facility location studies. In particular, coverage-based models, such as the location set covering problem (LSCP) and the maximum coverage location problem (MCLP), have been widely adopted to achieve complete or maximum coverage of service demand. This paper extends the LSCP by accounting for both partial coverage and access to the demand areas. The proposed model is applied to the optimization of fire station locations in Nanjing, China. The results can be used to assist future fire station location planning and rescue resource deployment.

1. Introduction

Fire caused by humans or nature can pose hazard to people, properties and environment, and lead to psychological damage, physical injuries (even death) and significant economic losses. Fire prevention and protection is necessary and essential for a safe living environment. The associated fire and rescue service therefore needs to be properly deployed to ensure efficient fire safety management. A fundamental concern in this regard is the spatial configuration of fire stations as it is critical to timely response to emergency calls.

Given the inherent spatial nature, fire station location problems have been well studied using geographical information system (GIS)-coupled location modelling (Chevalier *et al*. 2012; Aktaş *et al*. 2013; Murray 2013). In particular, LSCP (Toregas *et al*. 1971), MCLP (Church and ReVelle 1974) and their extensions have long been employed to evaluate the locational efficiency of existing fire stations as well as seek sites for new fire stations (Chevalier *et al*. 2012; Murray 2013). Common goals of locating fire stations include maximizing the access to provided services, covering as much demand as possible and minimizing total costs of service provision, usually subject to available resources. In practice, two or more objectives are often considered to capture different aspects in relation to fire service delivery.

The aim of this paper is to seek best locations of fire stations with spatial optimization approaches, particularly considering accessibility and service coverage. The proposed model is applied in an empirical study in Nanjing, China, to assist future fire station location planning and rescue resource deployment.

2. Methods

The proposed spatial optimization model is built on LSCP but with extensions from three aspects. One extension is to allow partial service coverage. That is, unlike the original LSCP where a neighbourhood (areal demand) is considered covered by fire service only if it is completely within the service area of one or more fire stations, we allow the demand to be partially covered by multiple fire services to achieve a full coverage. The second extension is to include a preference that the selected locations are closer to the demand areas with higher fire risks. Finally, we account for the impact of existing fire stations. Consider the following parameters:

I, J: set of demand areas and potential fire station locations, respectively;
i, j: index of demand areas and potential fire station locations, respectively;
w_i: estimated fire risk at i;
d_{ij}: distance between i and j;
a_{ij}: proportion of i's area covered by j;
Ω_i: set of fire stations that can provide service to i;
Φ: set of existing fire stations;
p: number of existing fire stations that remain in the final solution;

and the decision variable:

$$Y_j = \begin{cases} 1 & \text{if a fire station is sited at } j \\ 0 & \text{otherwise} \end{cases}$$

The proposed model can be formulated as follows:

$$\textit{Minimize} \quad \sum_{j \in J} Y_j \tag{1}$$
$$\textit{Minimize} \quad \sum_{i \in I} \sum_{j \in \Omega_i} w_i d_{ij} Y_j \tag{2}$$
$$\textit{Subject to} \quad \sum_{j \in \Omega_i} a_{ij} Y_j \geq 1 \quad \forall i \in I \tag{3}$$
$$\sum_{j \in \Phi} Y_j = p \tag{4}$$
$$Y_j \in \{0, 1\} \;\; \forall j \in J \tag{5}$$

In the above definition, objective (1) is to minimize the total number of fire stations, and objective (2) is to minimize the total weighted travel distance to the places requesting services, implicitly encouraging siting fire stations near the demand with higher fire risks. Constraints (3) require that each neighbourhood can be fully covered by the total services from the qualified stations, which are defined by Ω_i based on response time or service area. Constraint (4) from Schilling *et al*. (1980) limits the number of existing fire stations that will remain in the solution. Finally constraints (5) ensure that the decision variables only can have values 0 or 1.

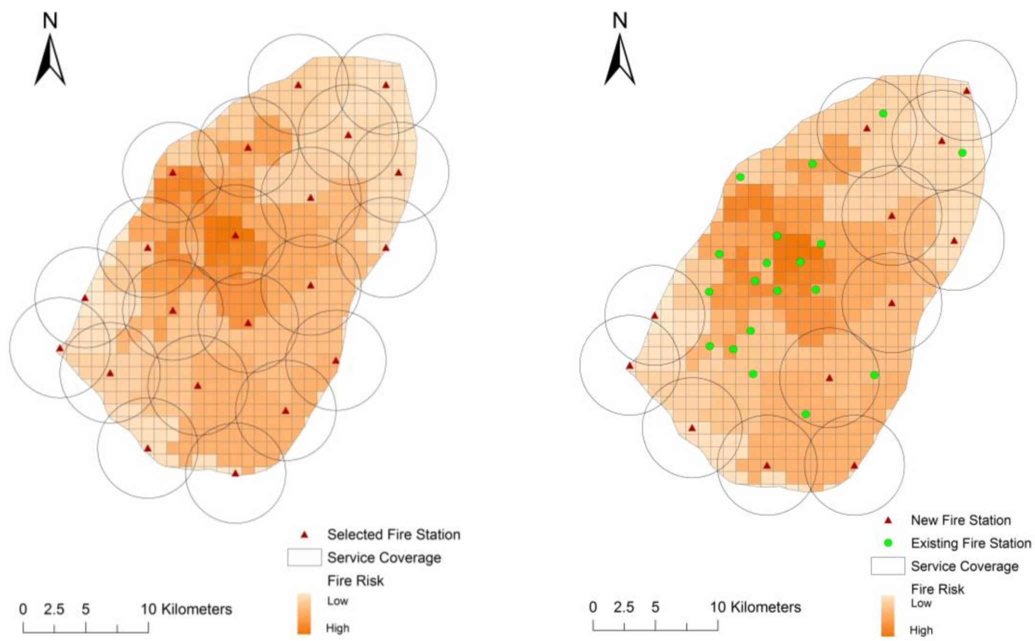
It is worth noting that although constraints (3) extend LSCP by allowing the full service coverage to be achieved through the overall partial coverage, the complete service coverage for a neighbourhood might not be necessarily guaranteed due to the overlap among partial coverage. Nevertheless, according to objective (1), the model implicitly will disperse the selected fire stations to minimize the total number while satisfying constraints (3). Tong (2012) showed that MCLP using partial coverage could improve computation efficiency while generating satisfactory results. Similar method was also employed in Murray (2013) for location modelling of fire stations.

3. Preliminary Results

The above model is applied in an empirical study in Nanjing, China, to evaluate the locational efficiency of existing fire services and seek locations for new fire station location. The study area is located in the south of Yangtze River within Nanjing, China, covering seven main districts of the city. The total area is about 598.1 km^2 (9.1% of total area of Nanjing) and the total population is about 5.06 million (2010) (54.4% of total population of Nanjing), currently served by 19 fire stations.

The study area is discretised into a set of 1 km * 1 km grid cells as this is the finest scale available for the population data. Thus, each grid cell represents a demand area with the fire risk estimated by a combination of population information and the fire incidents during 2002 – 2013. The potential fire station locations are represented by the centroids of those grid cells. To solve the model, the two objectives are combined through a weighted sum. That is, a weight ranging from 0 to 1 is assigned to each objective so that the sum of the two weights equals one, which is commonly used in solving multi-objective optimization problems.

Two scenarios are considered here: one is to assume no existing fire stations, and the other is to keep all the existing 19 fire stations in the final solution. The results are presented by Figure 1. For both scenarios, the two objectives have equal weights, that is, 0.5 and 0.5, respectively.



(a) (b)

Figure 1. Optimal Solutions:
(a) assuming no existing fire stations; (b) including existing fire stations.

As shown in Figure 1(a), ideally total 21 fire stations are needed to obtain a trade-off between the proximity to high-risk areas and the service coverage. If keeping all the 19 existing fire stations, Figure 1(b) shows that additional 12 new sites are necessary to achieve the same goals. Also, it can be seen that most areas with higher fire risks have been covered by the existing stations around the city center.

4. Summary

Fire and rescue services remain fundamental to the safety of human beings, properties and the physical environment. Efficient fire prevention and protection can greatly reduce the losses of lives and economies. This paper proposed a spatial optimization model to find the best locations for fire stations, particularly considering the trade-off between accessibility and service coverage. The empirical results demonstrated that spatial optimization can be a powerful tool to assist with the spatial deployment of fire service resources.

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