Location Optimization of Urban Fire Stations:

Access and Service Coverage

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Abstract

Fire and rescue services are among the most critical public services provided by governments to protect people, property and the environment from fires and other emergencies. Efficient deployment of fire stations is essential to ensure timely response to calls for service. Given the geographic nature of such problems, spatial optimization approaches have long been employed in public facility location modeling along these lines. In particular, median and coverage approaches have been widely adopted to help achieve travel-cost and service-coverage goals, respectively. This paper proposes a bi-objective spatial optimization model that integrates coverage and median goals in the service of demand areas. Based on the properties of derived objective functions, we presented a constraint-based solution procedure to generate the Pareto frontier, enabling the identification of alternative fire station siting scenarios. The developed model is applied to an empirical study that seeks to identify the best fire station locations in Nanjing, China. The results demonstrate the value of spatial optimization in assisting fire station planning and rescue resource deployment, highlighting important policy implications.

Keywords: Spatial optimization; Facility location; Fire stations; Access; Coverage

Introduction

Fires can be a great threat to human beings, the built-environment and nature, often causing injuries, deaths, economic loss and pollution. According to the International Association of Fire and Rescue Services (Brushlinsky et al., 2017), among the reported 31 countries there were on average about 3.5 fires per 1,000 inhabitants in 2015, resulting in 18,454 deaths and over 44,000 injuries. Fire and rescue services are among the most fundamental public services provided by governments to protect people, property and the environment from fires and other emergencies. Resources for fire prevention and

protection therefore need to be properly deployed to ensure efficient and reliable fire safety management. A fundamental concern in this regard is the spatial configuration of fire stations, since this is critical for timely response to emergency calls.

Locating fire stations in geographical space is a multi-dimensional problem that typically involves a number of factors, including construction budget, population distribution, water availability, potential fire risks and decision-makers' preferences (Hogg, 1968; Hodgart, 1978; Badri et al., 1998; Kanoun et al., 2010; Chevalier et al., 2012; Aktaş et al., 2013; Murray, 2013, 2015; Church and Li, 2016). For example, in a decision-support system for siting fire stations, Chevalier et al. (2012) considered queuing, staffing, and costs, among other factors, while Çatay (2011) and Aktaş et al. (2013) took into account previous fire incidents in siting additional fire stations. Further, it has been widely recognized that the locations of existing fire stations will affect where new ones should be placed (Plane and Hendrick, 1977; Schilling, et al., 1980; Reilly and Mirchandani, 1985; Kanoun et al., 2010; Murray, 2015).

Of interest in this research are two aspects of fire station location: access and service coverage. The former refers to the ease of reaching the place where an emergency occurs; the latter relates to the service area of a fire station, usually defined by the maximum distance (e.g. 2 or 3 km) or travel time (e.g. 4 or 5 minutes) from the station to an incident. Both factors reflect the dominant concern of response time in emergency services such as fire rescue and emergency medical services (EMS), as this determines the degree to which damage and loss can be mitigated.

Given the fact that access and service coverage are spatial, the problems related to fire station location have been extensively studied using spatial optimization approaches that integrate geographical information systems (GIS) and mathematical models (Liu et al., 2006; Murray and Tong, 2009; Chevalier et al., 2012; Aktaş et al., 2013; Murray, 2013, 2015). In terms of access, approaches like the *p*-median problem (PMP) (Hakimi, 1964) are commonly used to minimize the overall travel distance/time from fire stations to risk sites, i.e. to maximize access to places requesting services, such as in the work of Reilly and Mirchandani (1985). Regarding service coverage, approaches such as the location set covering problem (LSCP) (Toregas et al., 1971) and the maximal covering location problem (MCLP) (Church and ReVelle, 1974), as well as extensions, have long been

utilized in evaluating the locational efficiency of existing fire stations and seeking to identify sites for new fire stations (Murray and Tong, 2009; Chevalier et al., 2012; Murray, 2013; Church and Li, 2016). For example, instead of full service coverage, the threshold coverage model (Murray and Tong, 2009; Murray, 2013, 2015) allows to achieve certain level of coverage (usually represented as a percent).

Despite having been widely applied in the locational planning of fire stations, both median and coverage models have limitations. Median models usually require pre-specifying the number of stations to be sited, which might fail to meet coverage goals for a given service standard (Toregas et al., 1971). LSCP-based approaches, in contrast, can give the minimum number of stations necessary (and their location) that ensure full or certain level service coverage (Murray and Tong, 2009; Murray, 2013, 2015). As coverage models assume that the travel distance/time within the service standard is equally desirable, spatial access is not explicitly considered.

Integration of both concerns therefore makes sense and addresses a broader range of concerns. Accordingly, this paper develops a bi-objective spatial optimization model to account for service coverage and access. Further, a constraint-based solution procedure is employed to derive Pareto solutions thereby facilitating exploration of alternative fire station location scenarios. The next section reviews spatial optimization approaches that have been employed in the planning and selection of fire stations, with a focus on median and coverage approaches. Then, the mathematical formulation of the proposed model and the associated solution method are presented. This is followed by an empirical study of fire station location planning in Nanjing, China, relying on fire-incident data from 2002–2013. The paper concludes with the major findings and recommendations for future extensions.

Background

Service facility location has long been an essential concern in urban and regional planning, as well as a research topic of long interest to many disciplines such as geography, urban planning, public policy, engineering and operations research (Hodgart, 1978; Drezner and Hamacher, 2001). Given the geographic nature of facility location problems, spatial optimization is well suited to address the factors involved in site selection as well as supporting relevant decision-making (Tong and Murray, 2009; Murray, 2010). Over the

last few decades, a range of location modeling approaches have been developed and applied in fire station siting (Hogg, 1968; Plane and Hendrick 1977; Schilling et al., 1980; Schreuder, 1981; ReVelle 1991; Badri et al. 1998; Liu et al., 2006; Tong and Murray, 2009; Chevalier et al., 2012; Aktaş et al., 2013; Murray 2013, 2015; Church and Li, 2016), many coupled with GIS in various ways. Most of the approaches can be broadly grouped into median and coverage models.

Median models, typically structured as a type of PMP (e.g., Hakimi, 1964; ReVelle and Swain, 1970), aim to select p facilities so that the total travel distance (or time) to fixed service demand is minimized. This is equivalent to maximizing geographical access. Reilly and Mirchandani (1985) proposed a median model for the selection of fire station locations in Albany, New York, with the aim of maximizing access so that each demand zone would have at least two fire stations within a desired travel time. Richard et al. (1990) applied a modified PMP to site fire stations in Luxembourg, Belgium, with a threshold on response time.

Coverage models usually involve a service standard (e.g., response distance or travel time) reflecting the spatial extent that demand sites can be reached by at least one facility. Two classic models of this type are the LSCP (Toregas et al., 1971) and the MCLP (Church and ReVelle, 1974). The former aims to locate a minimum number of facilities while ensuring each demand site can be served by at least one facility. The latter considers situations where complete coverage for an entire region within the standard is untenable, thus aiming instead to guarantee maximum service coverage for a given number of facilities or fixed level of investment. Both LSCP- and MCLP-based approaches have been widely adopted in siting fire stations and related emergency services. The seminal work by Hogg (1968) has since been followed by numerous studies, including Plane and Hendrick (1977), Schilling et al. (1980), Schreuder (1981), Badri et al. (1998), Çatay, B. (2011), Murray and Tong (2009), Chevalier et al. (2012) and Murray (2013, 2015). Murray and Tong (2009) explored various scenarios of locating fire stations in Massachusetts with the MCLP and the threshold coverage model. Chevalier et al. (2012) considered the coverage of recurring and sporadic risks using an LSCP for siting fire stations in Belgium. In a study of siting new fire stations in Elk Grove, California, USA, Murray (2015) extended the threshold coverage model by accounting for complementary coverage, where the service provided for a demand site can be achieved by multiple stations (Tong, 2012).

Aktaş et al. (2013) applied both the LSCP and MCLP to assess various scenarios of fire station locations in Istanbul, Turkey.

On the modeling and implementation side of things, there have been efforts attempting to incorporate median and coverage goals in order to account for both access and service standards. One approach is the constrained PMP proposed by Toregas et al. (1971), where a service standard is imposed in the formulation to limit potential assignment of demand to facilities. However, a feasible solution might not exist for a specified number of facilities and particular service standard. Another approach is built upon the MCLP, adding an additional objective (and decision variables and constraints) associated with minimizing travel distance/time for uncovered demand to their nearest facility (Church et al., 1991).

As discussed above, both median and coverage models address different concerns in the context of fire station siting. This research attempts to integrate both concerns through an extension of the constrained PMP, accounting for existing service stations as well.

Model Specification

The proposed spatial optimization model extends the LSCP and the PMP. This model includes a preference for selected facility locations to be closer to demand areas with higher fire risks and also accounts for existing fire stations in system design. Consider the following parameters:

I, J: set of demand areas and potential fire station locations, respectively;

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w_i: estimated fire risk in demand area i;

d_{ij}: distance or travel time between i and j;

S: service standard;

Ω_i: set of fire stations capable of suitably serving demand i, $\{j | d_{ij} \leq S\}$;

Φ: set of existing fire stations;

q: number of existing fire stations that are to remain in service system;

The decision variables:

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

X_{ij} = the fraction of demand at i that receives service from facility j

The proposed model is formulated as follows:

$$\text{Minimize} \quad \sum_{j \in J} Y_j \tag{1}$$

$$\text{Minimize} \quad \sum_{i \in I} \sum_{j \in \Omega_i} w_i d_{ij} X_{ij} \tag{2}$$

$$\text{Subject to} \quad \sum_{j \in \Omega_i} X_{ij} = 1 \quad \forall i \in I \tag{3}$$

$$X_{ij} \leq Y_j \quad \forall i, j \in \Omega_i \tag{4}$$

$$\sum_{j \in \Phi} Y_j = q \tag{5}$$

$$Y_j = \{0, 1\} \quad \forall j \in J \tag{6}$$

$$X_{ij} \geq 0 \quad \forall i, j \in \Omega_i \tag{7}$$

Objective (1) seeks to minimize the total number of fire stations sited. Objective (2) focuses on allocation in order to minimize the total weighted travel distance/time to the places requesting services, thereby encouraging the siting of fire stations near high-risk areas. Constraints (3) require that demand at each site be met by the qualified stations capable of suitable response. Constraints (4) ensure that a demand area can be served by a qualified station only if that station is sited. Constraint (5) specifies the number of existing fire stations that are to remain in the service system. It should be noted that $|\Phi| > q$ in general so some but not all existing stations need to remain open. Finally, constraints (6) and (7) impose binary integer and non-negativity restrictions on the location (Y_j) and allocation (X_{ij}) decision variables, respectively. Compared with the constrained PMP of Toregas et al. (1971), the number of stations in the system is derived as the value of objective (1) in the above model instead of being pre-specified as a constraint. Further, constraint (5) is added to account for the impact of existing stations as suggested by Schilling et al. (1980).

Given the multi-objective (bi-objective) nature of the above model, Pareto-optimal solutions are desired. Such a solution is characterized by the fact one objective cannot be improved without degrading the other objective, thereby making it non-dominated (Cohon, 1978; Grubesic and Murray, 2002; Deb, 2014). Considering that the value of objective (1) represents the total number of sited stations (denoted by p hereafter), and

this can only be integer in value, the proposed model can be solved by the constraint method commonly adopted in multi-objective optimization.

The detailed solution procedure is as follows:

Step 1. Solve the model by only optimizing objective (1). The total number of sited stations is denoted p_{min}, which is a lower bound on p given the nature of objective (1). If only considering objective (2), it can be observed that the upper bound on p is the total number of candidate locations, denoted $|J|$.

Step 2. Reformulate model by incorporating objective (1) into the constraints and solve as single-objective optimization problem. Specifically, constraint (8) can be added to the above model where $p \geq p_{min}$:

$$\Sigma_{j \in J} Y_j \leq p \qquad (8)$$

Different Pareto-optimal solutions can be obtained by solving the model defined by (2)–(8) varying p values.

Therefore, for a given number of existing fire stations (q), first the lower bound (p_{min}) of p can be obtained by solving the single-objective problem (e.g. objective (1)). Then, the Pareto-optimal solutions can be obtained by increasing p where $p \in [p_{min}, |J|]$ and solving the corresponding single-objective problem (e.g. objective (2)) as indicated in Step 2. This would be done many times, but no more than $|J| - p_{min}$.

It should be noted that any two solutions obtained from Steps 1 and 2 do not necessarily generate a unique set of selected sites. This is because there might be alternative solutions for the same value of p_{min}, which, however, could result in different values of objective (2). Further, given the nature of objective (2), the value of the allocation variables X_{ij} will always be 0 or 1 (Toregas et al., 1971). That is, the service demand for an area will be met by its nearest sited fire station.

Empirical Study

The proposed model is implemented and applied in an empirical study evaluating fire service in Nanjing, China. The interest is locational efficiency for existing fire services as well as siting system configuration for new fire stations. Two scenarios are considered

here: one is to assume no existing fire stations, and the other is to keep some or all of the existing 19 fire stations in the service system. The model is solved using commercial optimization software, Gurobi (version 7.0.2), with spatial data processed using commercial GIS software, ArcGIS (version 10.3), combined using the Python programming language and associated libraries.

Study area and context of fire station planning

The study area is located to the south of the Yangtze River within Nanjing, bounded by the expressway ring road in the city, considered to be the main urban area that covers seven districts: Xuanwu, Qinhuai, Gulou, Yuhuatai, Jianye, Qixia (about 40% area included) and Jiangning (about 15% area included). The total area is about 598.1 km^2 (9.1% of the total area of Nanjing) and the total population (permanent residents) is about 5.7 million (2015) (69.2% of the total population of Nanjing) (NMBS, 2016), and is currently served by 19 fire stations.

Nanjing, located in the lower reaches of the Yangtze River and about 300 km northwest of Shanghai, is the capital of Jiangsu province and is a major city of the Yangtze River Delta economic zone. Like many other Chinese cities, Nanjing has experienced rapid urban growth in recent years, with the population having increased by 25.5% and the urban area having expanded by 228.0% since 2000 (NMBS, 2016). Associated with the growth and expansion, there are increasing fire risks, particularly in places like urban villages, warehouses, underground transport and high-rise buildings. The occurrence of urban fires has increased by 116.1% since 2000 (FDMPS, 2016). Unfortunately, capacity-building for firefighting has lagged far behind the speed of urban growth, failing to be commensurate with the needs of daily life and economic development. All 19 fire stations within the study area were built in the 1980s, and no longer match the changing urban landscape and spatial organization of socioeconomic activities. In Nanjing, only 26.3% of required fire engines were allocated in the period 2011–2015 (NMBS, 2016). This shortage of fire and rescue resources, and/or their inefficient deployment, can prevent timely response, which might put lives and property in danger. Therefore, it is necessary and important to understand the locational efficiency of existing fire stations as well as plan future fire stations to improve overall urban fire response.

Data

In this research, the study area is represented by a set of 1 x 1 *km* grid cells as this is the finest spatial scale available for the population data used in fire risk estimation, and is defined by the National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://www.geodata.cn). In total, the study area consists of 658 grid cells. Each grid cell thus represents a demand area with the associated fire risk estimated by the number of fire incidents per thousand population within that area. The population data are taken from the sixth Census of China (NBSC, 2011). Data on fire events are provided by the Fire Department of Ministry of Public Security (FDMPS) of Nanjing, Jiangsu, China, including all the incidents that occurred during 2002-2013 within the study area. In total, there were approximately 28,400 fires in this region. The potential fire station locations are represented by the center of each demand area. In terms of coverage standard, previous studies have indicated that straight-line distance can be a satisfactory surrogate of network travel time (e.g. Cudnik et al., 2012), and this has been commonly adopted in fire station siting (e.g. Murray, 2013, 2015). Further, the road network in Nanjing has undergone tremendous changes during the rapid urbanization over the last decade and fire engines in an emergency are often not limited by the standard speed limits. As a result, a straight-line distance of 4 *km* is employed as the coverage standard through consultation with the Fire Department of Ministry of Public Security of Nanjing.

Figure 1 shows the study area, estimated fire risks, and the locations of existing fire stations. It can be seen that the higher fire risks are largely clustered at the urban core, including Gulou, Xuanwu and Qinhuai. All the urban districts within the study area have two or three fire stations, except for Qinhuai which has five. Further, there are 263 demand areas (about 37.7% of entire region) having no stations within the 4 *km* service standard, containing about 18.0% of the overall fire risk. The total weighted distance (TWD) from the demand areas to the corresponding nearest station is about 25.4 *km*.

<Figure 1 about here>

Scenario I: optimal locations of fire stations

In this scenario the model is solved assuming no existing fire stations, i.e., q = 0 in Constraint (5). The resulting solutions thus represent the best locations in a service system for fire stations. Using the solution method detailed above to obtain bi-objective

tradeoffs, the lower bound of p is 22, i.e., $p_{min} = 22$, indicating that at least 22 stations are needed to achieve complete coverage for the entire study area within the service standard. Therefore, p in Constraint (8) will have a value equal to or larger than 22 in obtaining other tradeoff solutions. Figure 2 shows the selected locations for fire stations that attain the best access and complete coverage goals when $p = p_{min} = 22$. It can be observed that the stations are fairly evenly distributed over space, with service coverage delineated by solid boundaries.

<Figure 2 about here>

Further, the Pareto-optimal solutions are obtained by increasing the value of p by one at a time and re-solving the model. Figure 3(a) shows the solutions for p ranging from 22 to 32. It can be observed that the TWD declines with the increase of p. That is, the average access is improved when more stations are sited. Further, Figure 3(b) shows the improvement of access for each corresponding solution in Figure 3(a), and this is compared with the current service system consisting of existing 19 stations (see Figure1) in terms of total weighted distance (access). For example, if planning a new system of fire services, access can be improved by about 10% if siting 23 stations (i.e., $p = 23$). However, further improvement of 20% and 30% can achieved by optimally siting 26 and 31 stations, respectively.

<Figure 3 about here>

Scenario II: accounting for existing fire stations

As indicated in Figure 1, the existing 19 stations cannot provide complete service-coverage to the study area. Further, analysis carried out in scenario I indicates that at least 22 stations are needed to achieve the complete coverage goal. It may be unrealistic to build 22 new stations. Instead, a more practical approach may be to retain or relocate some of existing stations while seeking the best sites for new stations, which is the purpose of scenario II. In this case, a requirement is now enforced in the model to maintain an existing number of facilities, q, in the service system. As a result, the number of existing stations retained can vary between 1 and 19.

Figure 4 shows the minimum number of stations (p_{min}) for different values of q. For example, if only one of the 19 existing stations can be retained in the service system, at

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least 22 stations are needed to achieve the service coverage goal. This is the same for the situations where 2 – 5 stations are to be kept, indicating that 17 to 14 of current stations are to be closed or relocated. Similarly, p_{min} remains the same for $q = \{6, 7, 8\}$ ($p_{min} = 23$) and $q = \{9, 10, 11\}$ ($p_{min} = 24$), respectively. For $q \geq 12$, the increase in q results in the same growth in p_{min}. That is, the minimum number of sited stations will increase by one if one more current station is to be retained to meet the coverage goal.

<Figure 4 about here>

Taking $p_{min} = 24$ as an example from Figure 4, Figure 5 further shows the three associated solutions for $q = \{9, 10, 11\}$. In all the three cases (Figures 5(a)-(c)), there are four stations in the city center, where the higher fire risk is, to be closed or relocated to other locations indicated by red triangles. Given the spatial distribution of existing stations, the new stations are largely in the south and the east along the boundary of the study area. Interestingly, except for the relocated existing station (represented by a pentagon) in the west to a nearby location for which the service coverage is depicted by a thick line, the solution in Figure 5(a) ($q = 9$) is exactly the same as that shown in Figure 5(b) ($q = 10$), yet completely different from that in Figure 5(c) ($q = 11$).

<Figure 5 about here>

Similarly, as demonstrated by Figure 3, the Pareto-optimal solutions for scenario II can be further explored for each q. Again, compared with current service system, Figure 6 shows the access improvement of the Pareto-optimal solutions for $q = \{9, 10, 11\}$ where p ranges from 24 to 34. As expected, for each q, access will increase if more stations are sited. Figure 6(a) indicates that the access can be improved about 7.2% if siting 24 stations among which 9 are from current system. Comparatively, Figures 6(b) and 6(c) suggests that the improvement of access will be much lower, 4.2% and 1.1%, respectively, if 10 or 11 existing stations are to be retained given the same number of total sited stations. It can be observed that for the same p, lower q values always result in higher relative improvement in access. However, it seems that the difference in access improvement becomes smaller when p increases. For example, the improvement of access is 30.0% ($q = 9$), 29.6% ($q = 10$) and 28.9% ($q = 11$) if a total of 32 stations are to be sited, where the difference is less than that when siting 24 stations.

<Figure 6 about here>

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Discussion and Conclusions

Fire and rescue services remain fundamental to the safety of humans, property and the physical environment. Efficient fire prevention and protection can greatly reduce the loss of lives and lessen economic damage. This paper has proposed a bi-objective optimization model to seek the best locations for fire stations, accounting for access, service coverage and the impact of existing stations. Although such spatial concerns in siting fire stations have been touched upon to some extent in literature, we have integrated these concerns into a spatial optimization model utilizing coverage and median approaches. A constraint technique was employed to derive and explore Pareto-optimal solutions. The proposed model and solution method were applied in a case study in Nanjing, China, to examine various planning scenarios for fire station locations.

The empirical findings have significant policy implications. For example, as suggested by Figures 5, although most of the existing fire stations are located in the urban core, access and coverage can be greatly enhanced if some existing stations are closed or relocated in order to account for the changing urban landscape and population distribution. Also, Figures 1 suggests that more stations are needed in the Qixia and Jiangning districts when service-coverage goals are considered. This is also true for the alternatives summarized in Figure 5. In fact, associated areas do need more fire services due to increasing risks caused by population growth and economic development in recent years. For example, as a new subcenter of Nanjing since 2000, Jiangning has witnessed extensive urban construction and rapid economic and population growth. In 2013, Jiangning had a population (permanent residents) of 1.18 million, having increased by 57.3% since 2002, as well as the highest gross domestic product (GDP) among all the urban districts in Nanjing (NMBS, 2014). Therefore, the results from the empirical study offer local policy-makers a guideline for effective spatial deployment of fire and rescue services.

Among various factors relevant to fire station location, access and service coverage are prioritized here. In the proposed model, the former is represented by travel distance weighted by potential fire risks, and the latter is defined by a service standard. As pointed by Toregas et al. (1971), the model defined by (2)-(8) might have no feasible solutions for certain combinations of service standard S and number of sited stations p. This is addressed in this research by first obtaining the lower bound of p, p_{min}, in Step 1 using

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only objective (1) as an LSCP, which ensures feasible solutions in Step 2. Further, for a given p, different spatial layout of sited stations might be obtained when retaining a different number of existing stations, as indicated by Figures 4 and 5.

The two scenarios considered in the empirical study actually reflect the three common forms of central facility location problems suggested by Hodgart (1978). The first form is presented by scenario I, which assumes no existing fire stations in the study area. The other two forms are considered by scenario II, allowing for the addition of fire stations while keeping all or some of the existing stations. Compared with scenario I, scenario II may be more appealing for cities like Nanjing where the changing urban environment and spatial layout of socioeconomic activities has presented significant challenges to public service provision and where it is often necessary to open new stations and close/relocate old ones.

Regarding future research, current work can be extended from several perspectives. In terms of the proposed model, an MCLP- instead of LSCP- formulation can be adopted by modifying objective (1) to maximizing overall service coverage, which is usually desirable when available resources are limited. Thus, rather than being derived from the solution, the total number of stations p would be a model parameter and various coverage achievements can be assessed by changing its value. Also, more objectives (e.g. maximizing service availability) and constraints (e.g. backup coverage and service capacity of each station) could be considered and incorporated into the model in order to address other concerns in fire service planning. In addition, stochastic variants of the above models can be adopted to account for the uncertainties in the location and time of fire events (Gholami-Zanjani et al., 2018). Regarding the empirical study, in addition to population, other factors such as the construction materials of buildings and the densities of warehouses storing dangerous goods could also be incorporated in fire risk estimation. Further, distances other than 4 *km* could be adopted to explore the impact of the service response standards. Finally, fire station planning in practice is usually implemented in multiple time periods, and therefore taking into consideration urban growth and population changes is often desirable.

In summary, fire and rescue services play a crucial role in urban safety management. With the trend of global urbanization and the emerging initiatives of smart cities worldwide,

optimal spatial configuration of fire stations is key to efficient fire services in urban environments. This requires collective efforts and contributions from various sectors, such as engineers, geographers, developers and policy-makers. With the increasing availability of fine-resolution spatial-temporal fire incident data that can be incorporated into the modelling process, spatial optimization is a powerful tool in selecting good locations for public facilities, especially fire stations.

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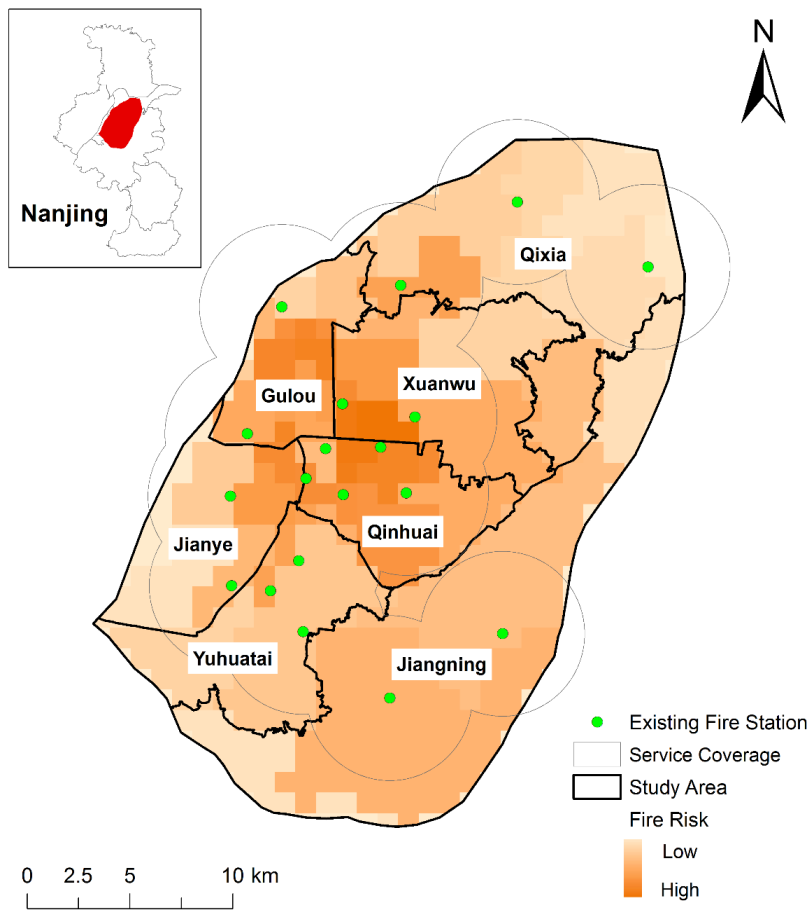Figure 1 Study area, existing fire stations and fire risk

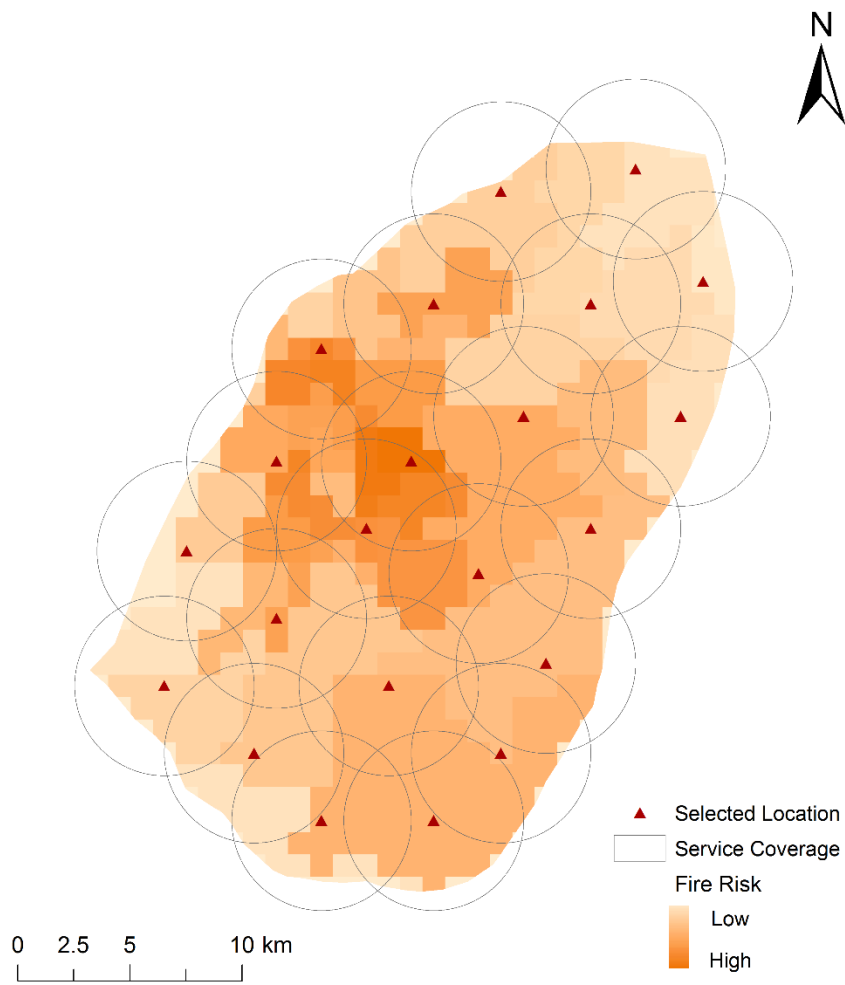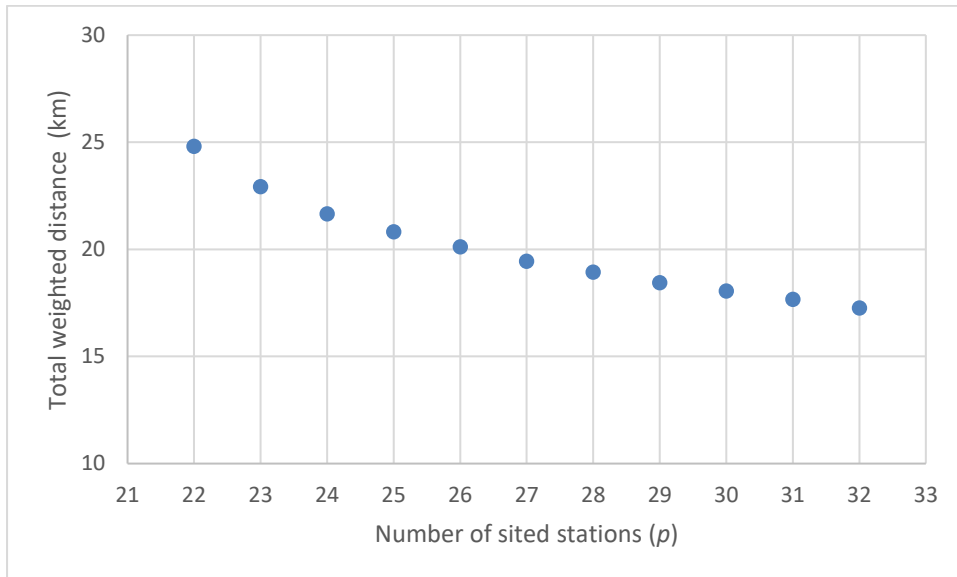Figure 2 Selected fire station locations for scenario I ($p = 22$)

Figure 3 The Pareto-optimal solutions for scenario I ($p \in [22,32]$) (a) Objective values; (b) Improvement of access
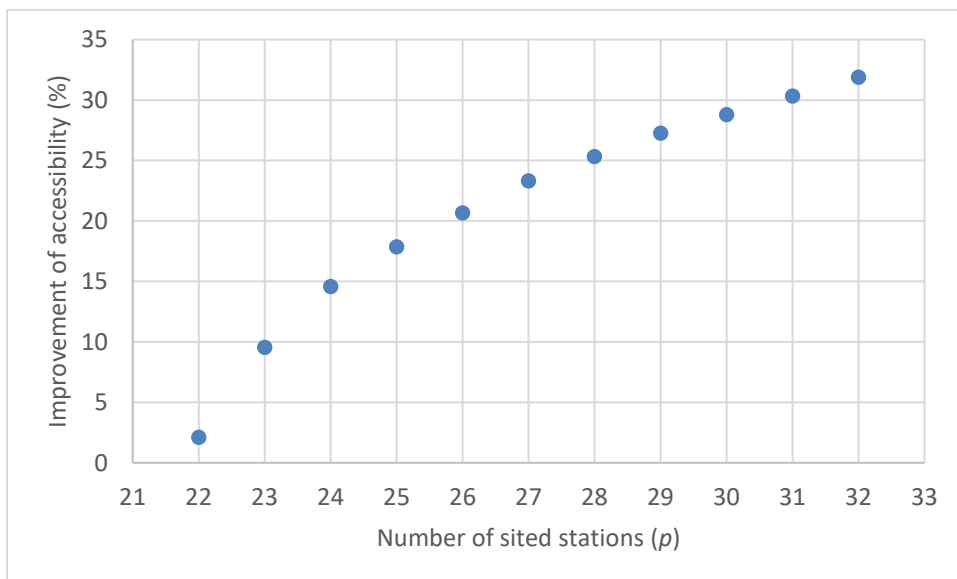
Figure 4 The minimum number of stations (p_{min}) for all possible q values
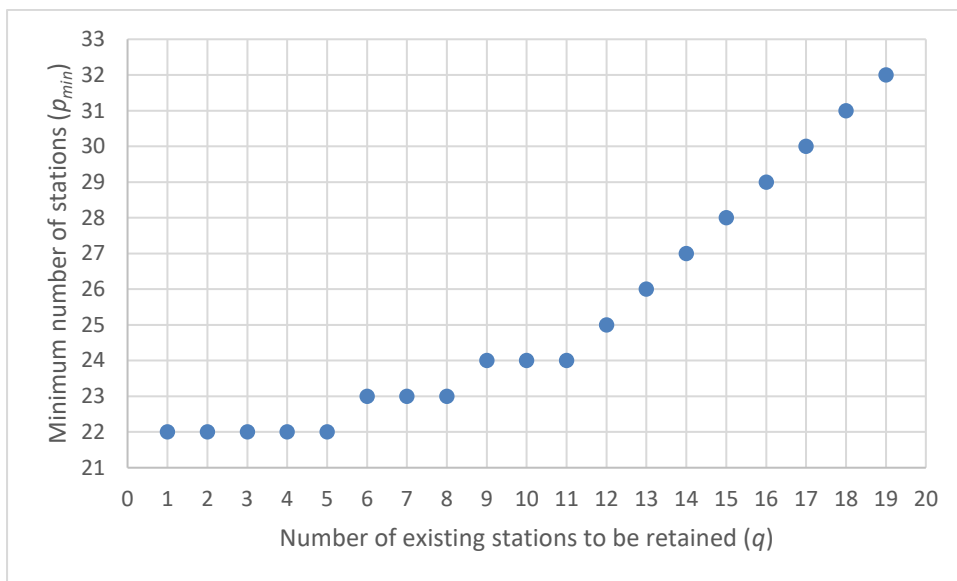
Figure 5 Selected fire station locations for scenario II ($p = 24$): (a) $q = 9$; (b) $q = 10$; (c) $q = 11$

Figure 6 Improvement of access of the Pareto-optimal solutions for scenario II ($p \in [24,34]$): (a) $q = 9$; (b) $q = 10$; (c) $q = 11$

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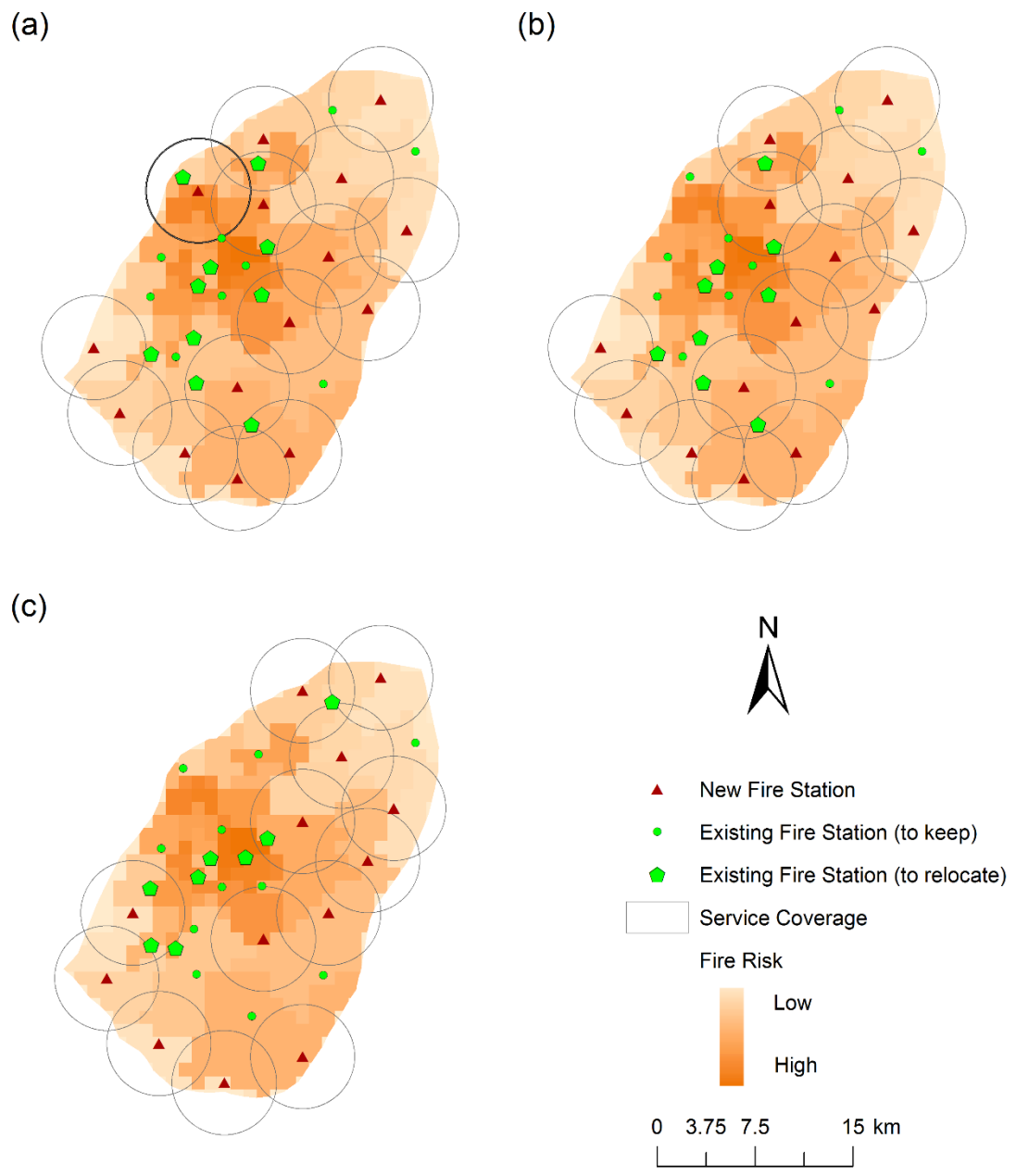Figure 5 Selected fire station locations for scenario II ($p = 24$): (a) $q = 9$; (b) $q = 10$; (c) $q = 11$
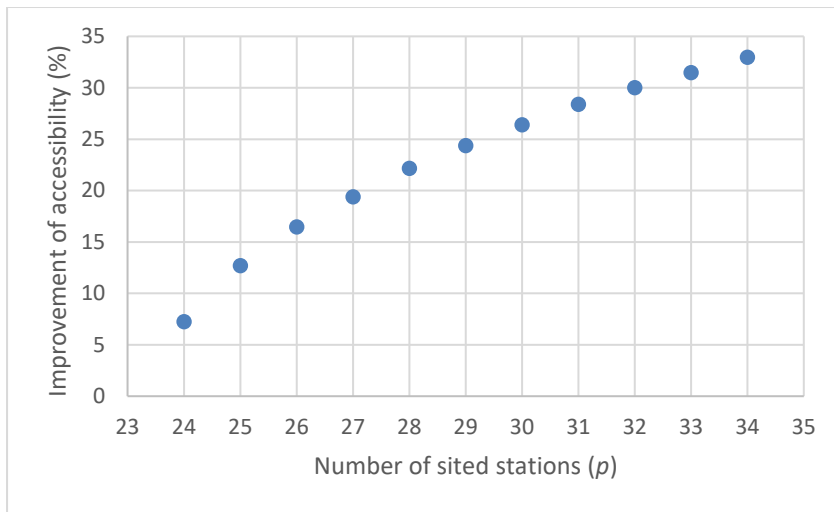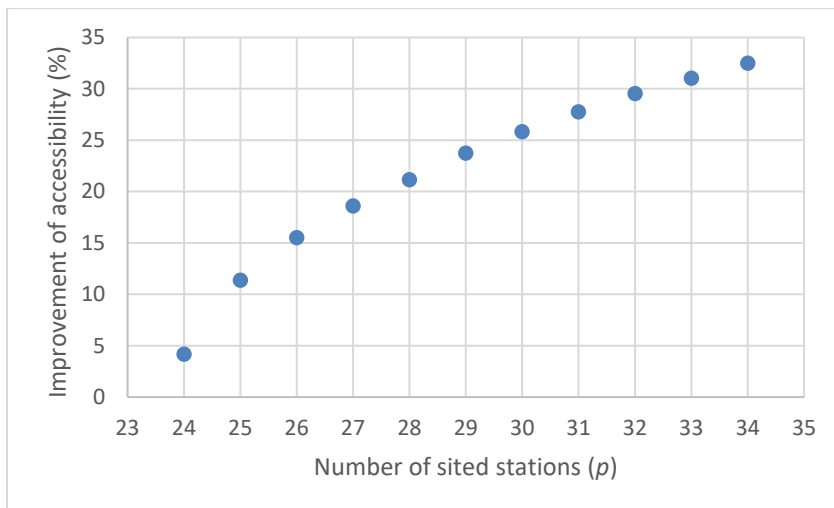
Figure 6 Improvement of accessibility of the Pareto-optimal solutions for scenario II ($p \in [24,34]$): (a) $q = 9$; (b) $q = 10$; (c) $q = 11$

(a)

(b)

(c)