

A New Multi-level Gradual Coverage Location Model for Optimizing Fire Station Locations Based on Fire Risk

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ABSTRACT

Research on the locations of facilities has been very popular in many fields especially for emergency facilities. This study addresses the location of new fire stations based on dynamic fire risks. In order to give consideration to both fairness (well-performed coverage of demand points) and efficiency (rapid response and dealing with each demand point on its own weight) during the process of locating fire stations, a Multi-Level Gradual Coverage Location Model (MLGCLM), based on Maximal Covering Location Problem in the presence of Partial coverage (MCLP-P), is proposed to optimize fire station locations. A computational experiment tested on the data set used in MCLP-P validates that the proposed model has a better performance and demonstrates that the Genetic Algorithm (GA) procedure with adaptive operator designed on Matlab platform is able to effectively solve the problem. Then, this paper uses fire data of Hefei city to estimate the performance of the MLGCLM under different selected fire stations and compares the MLGCLM with the other two classic facility location models: p-median model and maximal covering location model. The results suggest that MLGCLM takes into account both p-median and maximal covering objectives and can be useful in guiding the future optimization scheme of new fire stations in a city.

KEYWORDS: Fire station, fire risk, genetic algorithm, multi-level gradual coverage, location model.

NOMENCLATURE

d_{ij}	Euclidean distance between demand point i and facility j (km)	R_i	ideal coverage radius of demand, point i (km)
D	maximum coverage distance of demand points (km)	x_{ij}	binary variable
$f_{ij}(d_{ij})$	coverage decay function	y_i	binary variable
I	set of demand points	z_i	binary variable
J	set of candidate facilities	Subscripts	
		i	index of a demand point
		j	index of a potential facility point

INTRODUCTION

The optimized selection of locations of public facilities has been very popular in many fields particularly for emergency facilities. A particular problem having attracted considerable attention from researchers is to locate optimally fire stations [1-3] that, like any other emergency service, should also consider a limited budget, universal coverage and rapid response among other factors.

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Naturally, there have been many location-allocation models for research during the past few decades.

Classical location theories divide traditional facility location problems into three main categories: covering problem, P-center problem and P-medial problem. One of the most popular among facility location models is the covering problem due to its applicability in practice, especially for emergency facilities. Schilling, Jayaraman and Barkhi [4] classified coverage models into two categories: (1) Set Covering Problem (SCP) where full coverage is required and (2) Maximal Covering Location Problem (MCLP) where coverage is optimized. Since then, an increasing number of publications has dealt with the covering problems. Farahani R. Z. et al. [5] wrote a good review of covering problems in facility location in 2011, which presents a trend of those covering studies over time (since 1992 till 2011) and divides the development of covering models into three kinds: the development of SCP, the development of MCLP and other extended models related to the nature of covering problems. Specifically, the SCP includes a series of direct extensions of the model, such as Location set covering problem (LSCP) Implicit and Explicit presented by Murray, Tong and Kim [6], Probabilistic SCP [7] and Stochastic SCP [8], etc. In addition, the main extensions of the MCLP are as follows: Generalized MCLP [9], Gradual Coverage Location Problem [10, 11], etc. Lastly, several extended models mainly include Anti-covering [12] and Spatial covering location problem [13], etc.

Despite the numerous location models mentioned above, there are few models incorporating equity factor which includes two different equity concepts referred to as horizontal equity and vertical equity. Horizontal equity suggests that all demand points are considered in an equal manner. It means that every demand point is treated without discrimination. Vertical equity is concerned with the distribution of the demand weight among demand points. Horizontal equity and vertical equity have been studied extensively in emergency facility locations separately [14]. Moreover, studying how to incorporate the equity concept from both a horizontal and vertical point of view is still an urgent need given the lack of a unitary measure of horizontal and vertical equity [15]. Besides, this paper adopts the future fire risk spatial distribution of the study area as the weights of demand points, which is a new trend in fire station locations [3].

Motivated by the lack of research in this area, this paper proposes the Multi-Level Gradual Coverage Location Model (MLGCLM) which is an expansion of the gradual coverage decay model. The objective function is to maximize the overall match degree. The match degree is a function of distance and demand weight, which indicates the satisfaction level of a demand point with its serving facilities. And this evaluation metric combines the horizontal equity with the vertical equity. In other words, the goal in this model considers both fairness (corresponding to the meaning of horizontal equity) and efficiency (equal to the definition of vertical equity). The details will be shown in the next section.

To solve the MLGCLM, this paper improves a Genetic Algorithm (GA) with adaptive crossover and mutation operators to find optimal solutions. In the remainder of this paper, the proposed model is first introduced. Then, the principles as well as the relative performance of the MCLP-P model and MLGCLM are compared and analyzed under simulated data. Data preparation and initial selection of the candidate sites in Hefei city are presented next. The following section outlines the implementation procedure for the model and discusses the results obtained. Finally, the section on conclusions and recommendations includes a discussion of practical application and conceptual limitations of the method along with ideas for further research.

MODEL FORMULATION

Karasakal and Karasakal [10] developed a model named MCLP-P, which relaxes the “all or nothing” assumption. In this model, service decays with the increasing distance from a “fully covered” level to a “partially covered” level and drops to a no-service level beyond the maximal coverage range. But it only involves the horizontal equity. In order to incorporate both kinds of equity concepts, this paper modifies the MCLP-P model. Consider the coverage decay function $f_i(d_{ij})$ as follows:

$$f_{ij}(d_{ij}) = \begin{cases} 1, & d_{ij} \leq R_i \\ 1 / \left(1 + \exp \left(A \left(d_{ij} - (R_i + D) / 2 \right) \right) \right), & R_i \leq d_{ij} \leq D, \quad A = 5. \\ 0, & d_{ij} > D \end{cases} \quad (1)$$

The function $f_i(d_{ij})$ depends on the distance between demand points and facilities, as well as the demand weights of demand points. On the one hand, $f_i(d_{ij})$ sets a maximum coverage distance D to cover as many as possible demand points and this corresponds to horizontal equity; on the other hand, vertical equity can be integrated by applying R_i to the proposed model, which is the ideal coverage radius of demand point i inversely proportional to its own demand weight. It means that demand point i with a larger weight should be served by one facility within a smaller distance R_i , A sample depicting the coverage decay function $f_i(d_{ij})$ is followed.

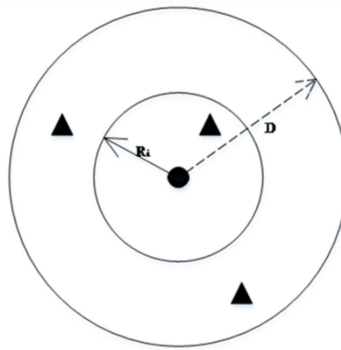


Fig. 1. Solid circle – demand point i , solid triangles – facility points

The example in Fig. 1 assumes that there is one demand point i , one candidate facility location within the ideal coverage radius R_i and two candidate facility locations within the maximum coverage distance D . Now the match degree of demand point i provided by the three facilities can be calculated based on the coverage decay function $f_i(d_{ij})$.

Eventually, the model is formulated as follows:

$$z = \max \sum_{i \in I} \sum_{j \in J} f_{ij}(d_{ij}) z_i, \quad (2)$$

Subject to

$$\sum_{j=1}^n y_j = p, \quad (3)$$

$$\sum_{j=1}^n x_{ij} \leq 1 \quad \forall i \in I, \quad (4)$$

$$x_{ij} \leq y_j \quad \forall i \in I, \forall j \in J, \quad (5)$$

$$x_{ij} = \begin{cases} 1 & \text{if the demand at point } i \text{ is covered by a facility at } j \text{ within } R_i, \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

$$y_j = \begin{cases} 1 & \text{if a facility is sited at } j \\ 0 & \text{otherwise} \end{cases}, \quad (7)$$

$$z_i = \begin{cases} 1 & \text{if the demand at point } i \text{ is covered within } D \\ 0 & \text{otherwise} \end{cases}, \quad (8)$$

Objective function (2) maximizes overall match degree that is the sum of match degree of all demand points. Constraint (3) imposes the selected number of facilities. Constraint (4) expresses that demand point i will be covered by at most one facility within R_i . Constraint (5) guarantees that demand point i is only covered by selected facilities. Constraints (6), (7) and (8) impose binary restrictions on the decision variables.

COMPUTATIONAL EXPERIMENTS ON SIMULATED DATA

A similar simulated data set derived from the literature [10], is generated to compare the performance between MLGCLM and MCLP-P. Data pairs representing the demand points are provided from a uniform distribution within the ranges [0, 50] and [0, 100]. Data for the candidate facility sites are drawn from the same distribution within the ranges [5, 45] and [10, 90] for the respective sides of the rectangle. The coverage levels can be obtained by the decay function using the Euclidean distances between demand points and candidate facility sites.

Additionally, this paper presets some parameters for the two models. For one thing, the R_i in the MLGCLM is determined by the weights of demand points selected from a uniform distribution within the ranges [0, 1]. More concretely, the demand weight needs to be divided into 3 levels, namely 0-0.333, 0.333-0.667 and finally greater than 0.667, and then the ideal covering radius of demand points in first level (the highest demand weight) is 10; the second level is 15; the third level is 20. The reason why the ideal covering radius is set as the above values is that the higher the demand weight of each demand point, the shorter the ideal covering radius (equal to response time). Furthermore, the coverage radius D is deemed to be the maximum coverage distance of demand points. For another, the MCLP-P deals with the coverage problem from the point of view of facilities, which supposes that the facility sites are likely to fully cover the demand points within the range of R_i (the constant should be equal to 20). A 10% increase in the coverage range is assumed in the presence of partial coverage ($D = 22$).

Figure 2 shows an example of the randomly generated sample with 200 demand points and 10 candidate facility sites. It also depicts the optimal solutions of two different models for selecting 3 facilities. Table 1 presents a significant evidence that all kinds of measurement metrics in MLGCLM are larger than those in MCLP-P. Intuitively, the larger the first two measurement metrics, the shorter the response time of demand point. Besides, the larger the overall coverage rate, the greater the responsibility area of selected facilities. So, MLGCLM has a better performance than MCLP-P. With regard to the reasons, firstly, the former formulates its own ideal coverage radius based on the demand weights, which possibly provides a corresponding response time for demand points in different levels. This point is extremely significant for emergency service. Secondly, the latter fails to consider the demand weights and requires that demand points should only be either partially

covered or fully covered by at most one of the selected facilities, causing some of them (demand points under first and second level) to be ill served by located facilities.

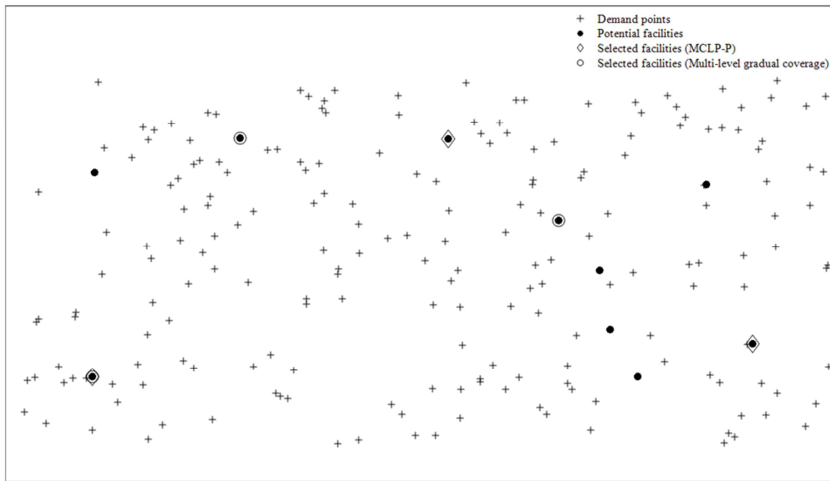


Fig. 2. Example of a random problem and its solutions.

Table 1. Results of MCLP-P and multi-level gradual coverage model

Location models	Overall match degree	Effective match rate	Overall coverage rate
MCLP-P	93.9	0.34	0.595
MLGCLM	109.1	0.425	0.685

^a Overall match degree is the sum of match degree of all demand points.

^b Effective match rate means the percentage of demand points whose match degree provided by selected facilities is over 1 among all demand points, indicating these demand points can be well served.

^c Overall coverage rate refers to the percentage of demand points covered by selected facilities at least once.

DATA PREPARATION

The study area is located in Hefei city that is the provincial capital of Anhui. Along with the acceleration of urbanization, the increasing numbers of people migrating to urban centers has resulted in more security problems and the enlargement of original urban centers has led to the fire risk changing in the spatio-temporal scale. Therefore, it is necessary to reallocate the fire resources in Hefei city. On the basis of the future development mode and fire risk in the city of Hefei, this paper is aimed at guiding the fire protection planning from “catch-up planning” to “planning ahead”.

Determination of the distribution of demand points

In this paper, the layout optimization of new fire stations is guided by the future fire risk spatial distribution in Hefei. Consequently, the discrete distribution of the future fire risk is used to replace the distribution of demand points.

Fire risk is determined by fire probability and fire consequence. The fire probability can be briefly expressed by annual average fire density (number of fires per square kilometer every year). Due to

the lack of related historical fire loss data, the direct fire property loss density (amount of property loss per square kilometer) in 2011, which is generated through the kernel density analysis tool in GIS, is simply applied to represent the future distribution of annual average fire consequence from 2011 to 2020 across Hefei. When using the kernel density to express its distribution, this paper uses a 5 km fixed window width to obtain the result as shown in Fig. 3. The resolution is 1 km by 1 km and the study area has been subdivided into a total of 1317 grids. The pixel value in each grid represents the fire consequence of its centroid, which can be obtained from the kernel density surface using the “extract to points” tool in GIS.

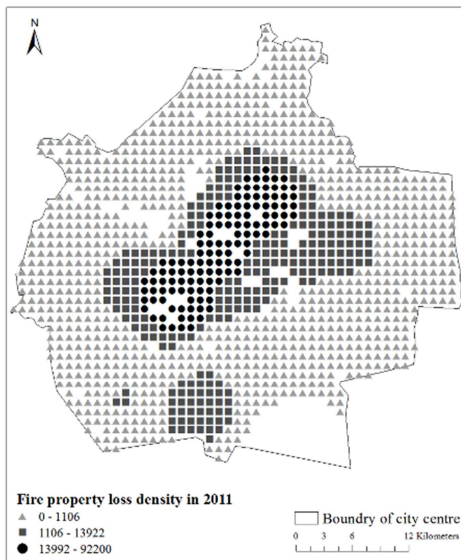


Fig. 3. Fire property loss density in 2011.

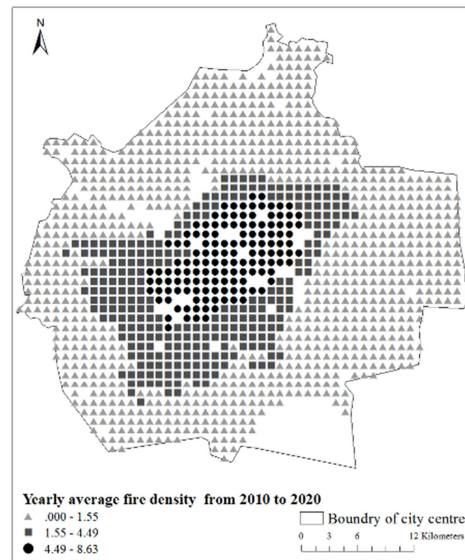


Fig. 4. Annual average fire density.

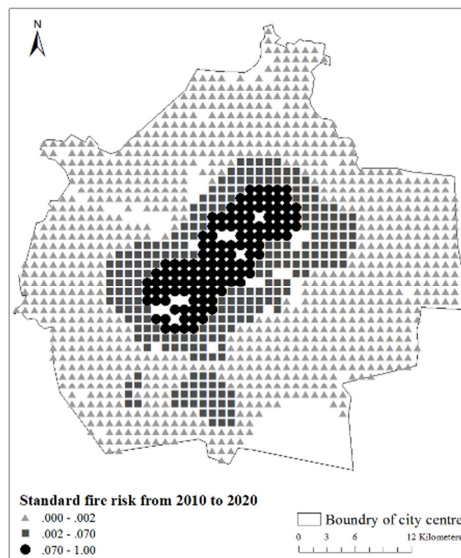


Fig. 5. Distribution of annual average fire risk.

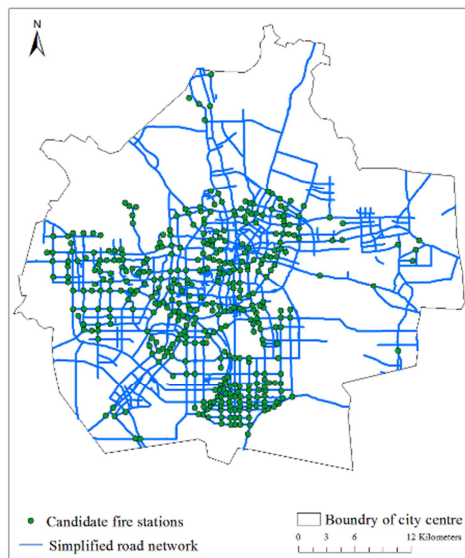


Fig. 6. Candidate fire stations.

In Fig. 4, the annual average fire density distribution from 2011 to 2020 is referenced from “A Comparison between Spatial Econometric Models and Random Forest for Modeling Fire Occurrence [16]” and it has been predicted by the Random Forest (RF) algorithm based on historical fire data from 2002 to 2005. Next, fire probabilities for centroids of abovementioned 1317 grids can also be extracted.

Eventually, combined with GIS technology, the standard spatial distribution of fire risk from 2011 to 2020 can be obtained by the product of fire density and the kernel density of fire property loss, which means that the fire risk in the center of each grid is the product of its fire probability and fire consequence. Consequently, every demand point shown in Fig. 5 has its own fire risk. Furthermore, different demand points should correspond to different ideal coverage radiuses based on the fire risk to reflect actual fire "rank corresponding" thought (different levels of fire risk should be consistent with the level of fire resources). To be specific, the higher the fire risk of each demand point, the shorter the ideal coverage radius (equal to response time). In light of the fire risk of demand point, this paper divides it into three levels, namely 0-0.002 (about 70 percent of demand points), 0.002-0.07 (about 20 percent) and finally greater than 0.07 (the remaining 10 percent). Fire fighting code of Hefei has estimated the speed of fire engines is approximately from 40 to 60 kilometers per hour on trunk roads and secondary trunk roads and the response time of high fire risk areas is around 2 minutes. So, this paper sets the ideal covering radius of demand points in first level (the highest fire risk) as 1 km; the second level is 1.5 km; the third level is 2 km. The ideal coverage radius interval between two levels is set as 0.5 km due to the linear distance approximately equal to two-minute driving distance. Moreover, the coverage radius of demand points called D is set as 5 km because of the speed of fire engines and the response time of fire areas within 5 minutes.

Determination of the candidate fire stations

The selection of candidate fire stations relies on fire passage simplified by main road network. Firstly, through use of GIS functions as well as network analysis tools, the fire passage is applicable for construction of the network dataset. Then, the initial candidate sites of fire stations are selected according to the nodes in the road network dataset. After that, the analysis function of “buffer calculation” and “attribute selection” make it feasible to remove the sites that are quite close to POI as well as the existing fire stations. Lastly, 396 potential fire stations are selected in Fig. 6.

The “City Fire Planning Manual” established by Hefei city planning bureau in 2008 determined to build 21 standard ordinary fire stations, 5 small ordinary fire stations, 1 fire station involving air duty and 1 fire station on the water on the basis of the existing 34 fire stations. Taking into account the cost of fire investment and the study area restricted to the central area of Hefei, the number of new fire stations will be set as 20 for the discussion in the last section.

RESULTS AND DISCUSSION

This paper uses GA to solve the MLGCLM and find the optimal locations. The key of using GA is to construct a fitness function, which is the objective function of the model. For each individual solution, it is encoded as a real number string of N bits, and the population size is 50. Note that the string is random and without repetition, in the range of 1 to 396 candidate sites. To improve the diversity of the solutions found, the GA function implemented in the Matlab platform utilizes two mechanism called elitism and adaptive evolution, which dynamically maintains the best solution in each iteration and contributes to exploring the solution space sufficiently. For more details about the use of GA, the readers can refer to the relevant literature [17]. Now the results for the location model are presented in the following section.

Sensitivity analysis for the MLGCLM

In Fig. 7 a, each point represents an optimal solution. The overall match degree (defined on Table 1) linearly increases with the number of stations. It has concluded that the number of fire locations has a positive relationship with the qualities of fire service. The trend of diminishing gain of effective match rate (defined on Table 1) has been displayed. For example, a gain of 17 percent in effective match rate can be achieved when the number of fire stations increases from 10 to 20, while a mere 3 percent increase is reached when the number of fire stations increases from 40 to 50. The most probable reason is that it requires further stations to provide fire resources for any other demand points. In Fig. 7 b, the coverage distance D is set as 5 km to calculate overall coverage rate (defined in Table 1), multiple coverage rate (the percentage of demand points covered by multi fire stations) and fire risk coverage rate (the percentage of demand points at the first or second level covered by fire stations among those points). And then a similar trend can be observed between the number of stations and the three kinds of coverage rates, for which the curves gradually flatten out. Intuitively, a high rate of overall coverage, multiple coverage and fire risk coverage may be possible by increasing the number of fire stations, but may be at a higher cost per unit.

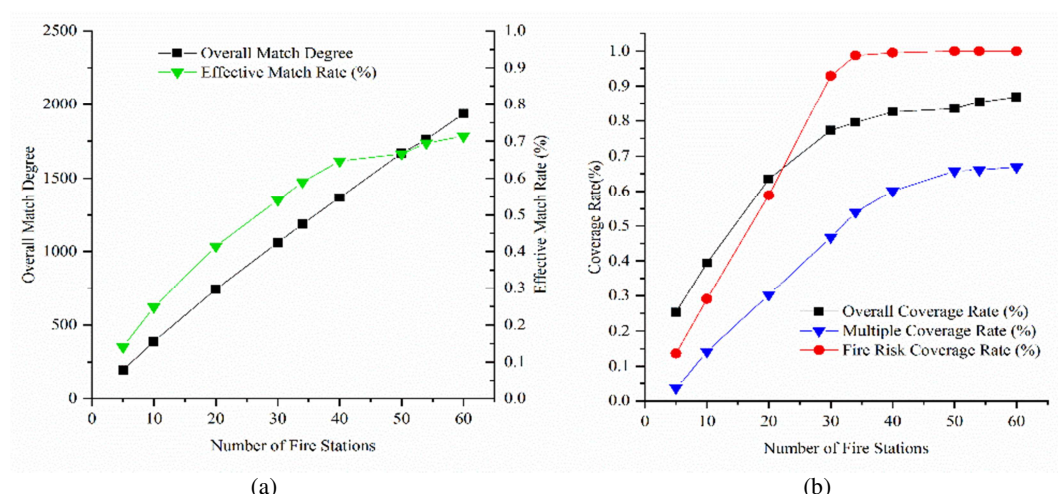


Fig. 7. Relationship between the number of fire stations and all kinds of evaluation metrics.

(a) followed by overall match degree and effective match rate;

(b) ordered by overall coverage rate, multiple coverage rate and fire risk coverage rate.

Additionally, notice that the solutions take an abrupt turn when the number of fire stations is around 40 in Fig. 7 a and 35 in Fig. 7 b. The most probable cause is that 35 stations are just sufficient to provide coverage service but inadequate to offer strong fire service for high fire risk areas, which need more fire resources. For simplicity, this paper sets 30 fire stations to test the performance of the three kinds of location models during the discussion of the next section.

Evaluation and comparison of the three location models

As was mentioned earlier, the number of selected fire stations is set as 30. Then the optimal location solutions to the three models are presented in Table 2. When the measurement metric is overall match degree, the sorted results are successively p-median, maximum coverage, multi-level gradual coverage which means MLGCLM has the best performance. When it comes to the other two metrics including area coverage (fairness) and fire risk coverage (efficiency), the result in our model has a median performance between p-median model (fire risk coverage) and maximal coverage model (area coverage), which validates the model's ability to simultaneously consider horizontal equity and vertical equity. Note that the demand weights in high fire risk area are far greater than those in

median and low fire risk areas, leading to extensive fire resources used. Therefore, the fire risk coverage rate in p-median model is at the minimum level.

Moreover, for the purpose of further exploring how the results of the three kinds of location models influence the overall coverage, multi ring buffer analysis from 1 km to 5 km is depicted in Fig. 8. The outcomes imply that the optimal solution in the p-median model concentrates excessively in the central region, thus leading to a significant overlap of coverage and waste of fire resources, and the optimal solution in the maximum coverage model is too discrete resulting in many new fire stations built in areas with low fire risk and high fire risk areas with inadequate fire resources. While the optimal solution in the multi-level gradual coverage model combines the advantages of the other two models, coordinating area coverage and fire risk coverage. So, it makes use of fire resources effectively and reasonably. Meanwhile, the locations of new fire stations from MLGCLM mainly expand to the southwest which is consistent with the overall direction of Hefei city planning in the future.

Table 2. Results of three location models with selected fire stations

Location models	Overall match degree	Overall coverage rate	Fire risk coverage rate
P-median	980.1	0.3759	0.9596
MCLP	1147.2	0.8876	1
MLGCLM	1223.0	0.8246	0.9950

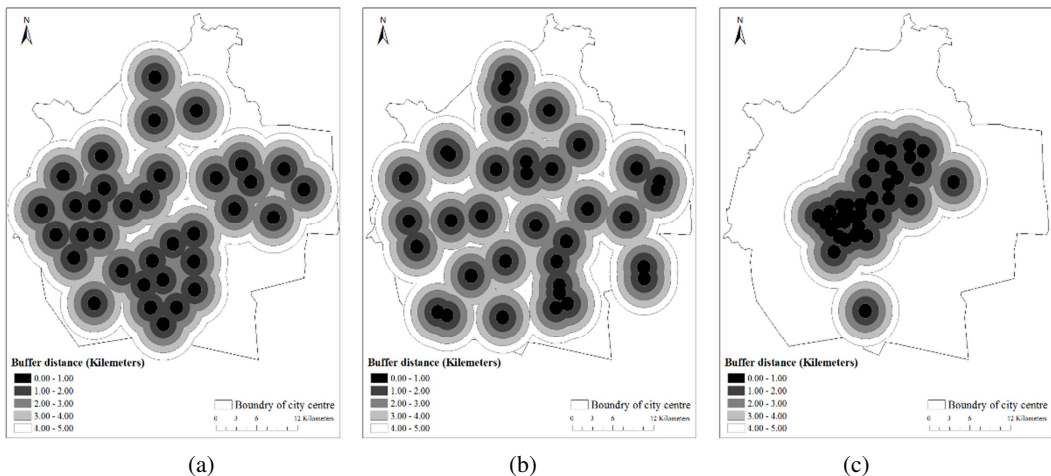


Fig. 8. Multi ring buffer analysis of the three models' optimal results: (a) the solution in multi-level gradual coverage combines the advantages of the other two models, including area coverage and fire risk rank coverage which means that the higher fire risk areas correspond to the shorter response time; (b) the solution in maximal coverage is too discrete resulting in many new fire stations built in areas with low fire risk and high fire risk areas with inadequate fire resources; (c) the solution in p-median concentrates excessively in the central region leading to a significant overlap of coverage and waste of fire resources.

Relaxing fixed existing fire stations

In order to examine the impact of existing fire stations, this section relaxes the fixed existing fire stations. In other words, assuming they can be relocated. In this case, all the 396 candidate locations with the existing 34 locations are able to be considered. As mentioned in the section discussing the selection of the candidate sites, two scenarios are tested: reconstructing 34 fire stations compared

with the performance of the existing stations, reconstructing 54 fire stations compared with the performance of constructing 20 new fire stations on the basis of the existing fire stations. Table 3 summarizes the results. Under the condition of 34 existing fire stations built in Hefei city, solution A1 is known without calculation, and solution A2 is calculated by assuming the existing locations can be relocated. In comparison with solution A1, solution A2 probably covers more demand points by including those that are not served under solution A1 and by reducing those that are included by multi fire stations. Moreover, the effective match rate in solution A2 is greater than that in solution A1, which means more demand points can be served well by the selected fire stations. The relationship of fire risk coverage rate between A1 and A2 is the same as above. Under the condition of 54 fire stations built in Hefei city, solutions B1 (fixed existing fire stations) and B2 (existing fire stations can move) are calculated. The results demonstrate that the latter has a larger effective match rate and overall coverage rate, which makes it possible to reduce the total number of fire stations and reach the same objective if the existing fire stations could have been built at different locations.

Table 3. Results of multi-level gradual coverage model

Location models	Effective match rate	Overall coverage rate	Fire risk coverage rate
A1	0.5163	0.6993	0.9848
A2	0.59	0.795	0.9874
B1	0.6651	0.8413	1
B2	0.6948	0.8542	1

^a A1 means the existing 34 fire stations as a solution.

^b A2 means reconstructing 34 fire stations with existing fire stations relocated as a solution.

^c B1 means constructing 20 new fire stations with existing fire stations fixed as a solution.

^d B2 means reconstructing 54 fire stations with existing fire stations relocated as a solution.

CONCLUSIONS AND RECOMMENDATIONS

This paper illuminates the MLGCLM for the purpose of simultaneously considering two goals: well-performed coverage and hierarchical rapid response based on the fire risk. GA is used to solve the problem for locating fire stations. The main contents in this paper are divided into three parts: (i) a simple computational experiment validating that the model has a better performance than MCLP-P; (ii) data preparation including the determination of demand points and candidate location sites by using GIS; (iii) the results of the model demonstrated from three aspects, as previously mentioned, to reveal how the model affects the two goals (fairness and efficiency) with only one objective, namely, overall match degree. Even though this paper mainly focuses on the location of fire stations, the model developed can be applied in a broader context including all kinds of emergency facility location problems (ambulance, hospital and fire brigade, etc.). The key to applying the model in different situations is to determine the ideal covering radius of demand points. In this research, the speed of fire engine and the response time of high-risk areas are used to predefine them. Eventually, according to the fire risk of Hefei in the future, an optimized location solution on the basis of the existing fire stations is developed so that it is able to guide the future strategic planning and layout of fire stations in Hefei.

In this research, there are certainly many aspects to be further studied. Firstly, the Euclidean distance between the demand points and the candidate location sites proves to be the basis of the optimization. Nevertheless, like many other distance related problems, the usage of network distance has been more convincing. On the one hand, it can provide travel distance under real traffic flow between accident points and fire stations; on the other hand, it also offers a favourable

condition for the incorporation of multi-period into the model because the traffic statuses at different times of the day are obviously different. Secondly, the initial candidate sites, which are important and critical for the establishment of fire stations, are just selected by using the nodes of the main road network with several constraints in relation to distance and spatial distribution. However, it is essential to select the candidate sites by combining more details relevant to the fire stations. Thirdly, simultaneous use of different quantities and types of vehicles, limited to the capacity of fire stations and the demand for fire service in real-world fire emergency rescue process, is one of most important requirements which should also be incorporated into the location model. If so, the optimal solutions to the model not only determine where to establish new fire stations but also define how many quantities and types of fire vehicles in each station, which would be more useful for fire service personnel. Fourthly, in this thesis, it seems somewhat simple for the approach to determining the future spatial distribution of fire risk described as the product of future fire density (shown as fire probability) and kernel density of future direct fire property loss (indicated as fire consequence). Particularly, the determination of future fire consequence appears to be oversimplified because it consists of not only economic losses but also casualties. So, it might be necessary to study how to forecast fire consequence with a unified metric. Other areas of future work may be extended to cost-benefit analysis of adding additional stations for which a limit budget should be integrated into the model and priority sequence for the selected new fire stations that can be achieved by the inclusion of extra constraints. To summarize, a more comprehensive location model might be a realistic and appropriate method in future research.

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