GRADUAL OPTIMIZATION OF URBAN FIRE STATION LOCATIONS BASED ON GEOGRAPHICAL NETWORK MODEL

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KEY WORDS: Fire Station, Gradual Optimization, Coverage Areas, Geographical Network

ABSTRACT:

Many problems existed in the planning of urban fire station locations in China. Based on geographical network model and GIS, this paper proposes a method for gradual optimization of fire station locations, which considers its geographical network attribute, and optimizes the fire station locations as well as the coverage areas. The result of a case study on some city's fire station plan shows it is scientific and effective. The proposed method can also be used for locating other public facilities, such as clinics and hospitals.

1. INTRODUCTION

Fire disaster causes heavy causalities and great loss of social wealth, so the plan of fire station is significant for the city development. However, the plan was usually neglected in early city building in China, most of the locations of fire stations and those coverage areas were selected based on experience. Nowadays, there are a lot of problems in mostly cities of China, especially in old city zones, such as the scattered fire stations, large coverage areas, the random locations and so on(Chen Chi 2003). Time-lapse in fire protection is the most severe problem in them. Based on geographical network models and GIS spatial analyst, an optimized arithmetic of the fire station locations as well as the coverage area boundaries is designed. The result of a real example shows the method is effective.

1.1 Related Regulations

Stipulations of the Ministry of Public Security (GNJ 1-82): The primary principle of urban fire station distribution is that firemen can reach the farthest point of its coverage area in 5 minutes after he get the fire alarm. The suitable area of fire station's coverage area is 4~7 km^2. Fire station should be built on the center of the coverage area around, and the distance from its boundaries to populous public buildings and places, such as primary schools, hospitals, kindergartens, nurseries, cinemas, bazaars etc, should no less than 50m (Lu 2001). Other effect factors are natural geological conditions, urban land price, urban functional zone etc in addition.

1.2 Review of the fire station plan

Fire station plan had been attached importance in developed countries, and related research had been made extensively. Helly 1975 made a systematic study on the problem of fire station locations selection and coverage areas determination. In order to plan new fire stations and achieve optimized distributions of fire stations, he proposed an iterative analytical method. ① First, the boundaries of coverage areas of each fire station are predefined, and find out the optimum fire station locations in each coverage area. ② optimize those fire station locations, then find out the optimum division of coverage areas on the basis of the optimization result. Iteratively above two steps until we find out the optimization layout of the fire stations. Chen 2003 adopt Helly's method for the situation of China, analyze the fire station locations selection on the precondition of giving coverage areas boundaries.

Above mentioned schemes can get good result, but there are some problems as following: ① the distance is measured along the straight line, but the driving path of fire engine is a curve along the roads; ② before selecting locations we must divide the boundaries of each coverage areas manually, which increase subjective random of the results; ③It is impossible to make sure that all demand points are serviced in limited time. So a gradual optimization of fire station layout planning model is proposed in this paper based on geographical network model. In view of the problems in existed fire station layout planning model, this method select minimum fire fight path and partition coverage areas by real geographical network. Obviously this method can reduce the subjective factors, and ensure to satisfy the requests of time limitation, so can get scientific and reasonable results.

2. NETWORK MODEL FOR FIRE STATION LAYOUT OPTIMIZATION

The optimized fire station layout should be achieved based on real road network other than the beeline distance, which is to say that the optimization of fire station distribution has geographical network characteristic. The geographical network

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that used to optimize fire station locations is a roadway network consisted of roads and end points of those roads.

2.1 Geometrical description of the geographical network model for fire station layout optimization

Geographical network is mapped to an directed diagraph in GIS network analysis. In order to get the optimized layout of fire station locations, geographical network could be formalized as $G = (V, E, D, C, W_e)$. Here G is a directed diagraph with weight; V is the family of network nodes, which are the end points of roads; E is the set of all arcs of network, which are paths of fire engines; D is the set of the demanded points for fire control, which are the end points of fire engine route way, if all nodes of network need fire control, then D is equal to V; C is all the centers of network, which are the locations of the existed fire stations and candidate fire stations, they are start points of fire engine.; W_e is the weight of arc, which usually is replaced with the time used on road for fire engine. To optimize fire stations layout, we must select a optimal subset from C, which can fulfill demands of all nodes of D in limited time according to time shortest-path, and determine the nodes served by each center of the subset.

2.2 Conceptual description of geographical network model for fire station layout optimization

The primary elements of this geographical network model are showed in the figure 1:

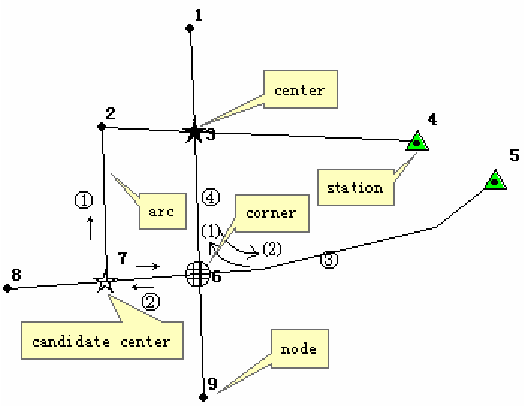

Fig.1 Geographical network model of fire station location optimization

Geographical network arcs are all ranks of roads in city area, whose attribution is bi-directional weight of arc, which is the driving time of fire engine needed on both sides. Network nodes stands for ends of roads. Station points are all points with fire control demand, which are the service objects of fire stations. The center is the location of fire station including constructed fire stations and candidate site of planning to build. They have three attributes: resources capacity, barrier limit and optional parameters. According to the actual conditions of China, the center has not capacity limitation. The barrier limit is the maximum service scope of center, which usually be set to 5 minutes. If a city has built some fire stations, those constructed fire stations must be chosen to be centers, while those planning stations should be regard as candidate centers. The turning of driving have the attribute of the corner hindrance intensity, which is the hindrance time at the corner. According to fire control regulation in China, fire engine driving should not be delayed by traffic light, therefore the corner hindrance intensity may set to be zero. But if the traffic jam is heavily at those corners, the hindrance intensity should be set in view of experience.

3. OPTIMIZATION METHOD OF FIRE STATIONS LAYOUT BASED ON GEOGRAPHIC NETWORK MODEL

3.1 Mathematic model

Supposing the number of demand points is n, the number of supply points is q ($q \geqslant 0$, when there is no known supply point, then q = 0). The number of candidate supply points is m, the number of constraint points is k, and the maximal service time of every supply point is t_0. Now we need to select p supply points (the number of p is unknown) from m candidate points to satisfy the demand that every demand point i can get service from the supply points and the number of supply points is minimum, meanwhile every demand point i can be serviced by the closest support point j according to the minimum time-path, where every distance between support point j and k constraint points must no less than d_0, and the coverage areas of every support point j is a set of demand points which service time is less than t_0 based on its minimum time-path. Then the objective function is: $\min(p)$, $S(j) = \{i, t(i, j) \leqslant t_0, t_{ij} = \min\}$

The constraint conditions are:

$$\sum_{j=1}^{m} f_{ij} = 1, \quad i = 1, 2, \cdots, n \qquad \sum_{j=1}^{m} \Big(\prod_{i=1}^{n} f_{ij} = p\Big)$$

$$p \leqslant m \leqslant n \qquad 0 \leqslant t_{ij} \leqslant t_0 \qquad d_{jk} \geqslant d_0$$

Here t_{ij} is the minimum drive time from supply point j to demand point i; d_{jk} is the Euclidean distance from support point j to constraint point k; f_{ij} is the coefficient of service that supply point j provides service to demand point i. The value of f_{ij} is set to one if demand point i receive service from supply point j, or else the value is set to zero.

$$f_{ij} = \begin{cases} 1 & \text{when i is severed by j} \\ 0 & \text{the others} \end{cases}$$

3.2 Methodology and workflow

Based on the mathematic model we can design the following steps to implement it:

① Establish geographical network for fire station locations optimization, and calculate the minimum service time between each pair of points, then the matrix of minimum service time T_{ij} can be constructed, at the same time the minimum time path can determined.

② Evaluate the capacity condition of constructed fire stations, which is to establish coverage areas with the constraint of maximal service time and to judge whether those coverage areas have covered the whole area, if they do then the fire station meets the requirements and the arithmetic is over, else go to the next step.

③Based on Voronoi graph to determine the initial number of new fire station p with gradual method, here the number may be a little big, and the fire station locations and those coverage areas are determined at the same time.

④For each of the (q + p) coverage areas to calculate theirs center point according to that geographical network, then determine coverage areas and repartition the coverage areas based on those centers.

⑤If those new coverage areas can not cover the whole area, revise the fire station locations until their coverage areas can cover the whole area with iterative method.

⑥Gradually approaching to the true value of p by decreasing the number of p gradually, and repeat the above steps. The result number of p have got when the number of p is decreased again, those coverage areas can not cover the whole area. Here the value of p is the primary number of fire station planning to build.
⑦ Justify the number P of fire station locations with constraint condition of $d_{jk} \geqslant d_0$ (the distance between fire stations and populous locations is no less than 50 m), if the condition is satisfied, the P number fire station locations is the ultimate result, or else those locations must be revised.
⑧ The value of P and their coverage areas are the optimized ultimate results of fire stations, and the path from each fire station to its demand points can be obtained and should be recorded at the same time.

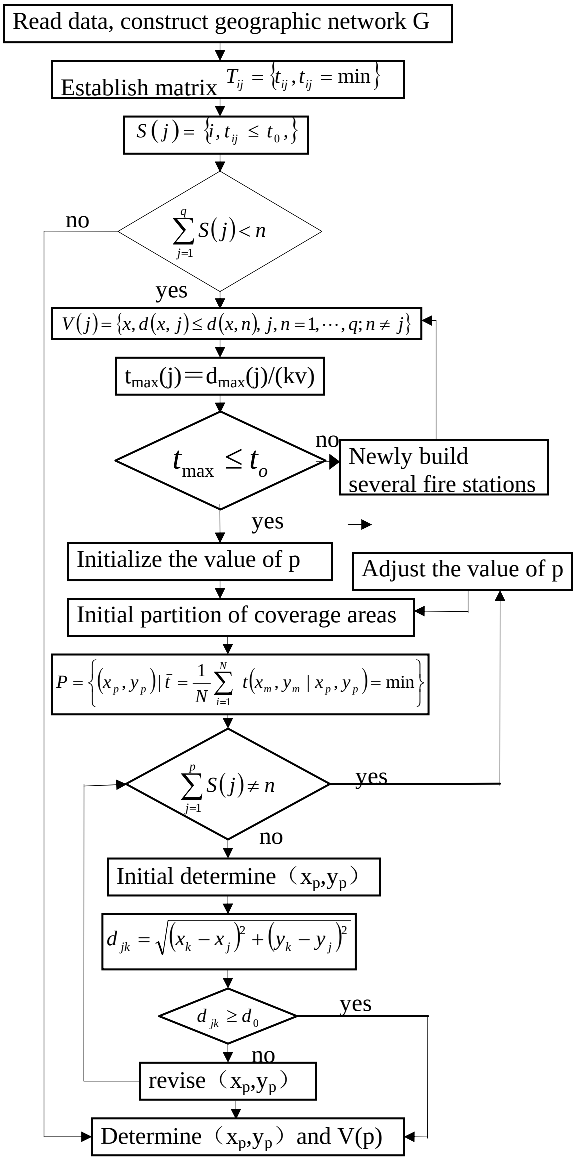

Fig.2 Flow Chart of Urban Fire Station Location Optimization

3.3 Key techniques and theirs resolutions

3.3.1 Initial value of new fire stations

The initial value of p can be determined by gradual method on the basis of Voronoi diagram. For each constructed fire station to construct its Voronoi diagram as $V(j) = \{x, d(x, j) \le d(x, n), i, n = 1, \cdots, q; n \ne j\}$, here d (x, y) is the beeline distance of the two points. The formula of $t_{max}(j) = d_{max}(j) / (k\,v)$ can be used to Calculate the longest service time of each fire station's coverage area, where d_{max} is the longest distance from every fire station to the boundaries of its Voronoi diagram, and k is the road's curvature coefficient of Voronoi diagram; v is the average drive speed of the fire engine in the Voronoi diagram. According to each t_{max} of Voronoi diagram, several new fire stations can be added to the region of Voronoi diagram with t_{max}. Then to rebuild Voronoi graph for all fire stations and calculate t_{max}. If $t_{max} > t_0$ still, new fire station should be added again until $t_{max} \leqslant t_0$. The result value of p is just the number of new fire stations, and these Voronoi diagrams are the result of coverage areas of fire stations.

3.3.2 Calculation the center of every part

Calculation of the center of every part after partitioning the urban area to several parts should be done along the actual road network. To every part, supposing the coordinate of its outside boundary is (x_m, y_m), the fire station located at(x_p, y_p), and along the road network, the minimum drive time from fire station to this point is, $t(x_m, y_m \mid x_p, y_p)$, $\bar{t} = \frac{1}{N}\sum_{i=1}^{N} t(x_m, y_m \mid x_p, y_p)$, the node where the value of $\bar{t}$ is minimum is the center of this part.

3.3.3 Optimization of fire station locations

This optimized method select the following principle as revising condition: the distance from its coverage area boundary to populous public buildings and places, such as primary schools, hospitals, kindergartens, nurseries, cinemas, bazaars etc, should no less than 50 m. According to related stipulations, that 50 m is Euclidean distance. So we can use buffering analysis of GIS tools to revise the fire station locations. First of all, build a new layer of point for above-mentioned populous places and public buildings (select its center location point), and to establish buffer areas by 50 m for all points in the layer, then to overlay the buffer areas layer to geographical network layer. If there is any new fire station in the buffer areas, we should select the site nearby but not in the buffer areas to replace the location, which need to satisfy the location conditions.

4. CASE STUDY

Based on the proposed method, we make a real city's fire station plan as an example to test the capability of the gradually optimization method and the rationality of the results by using ArcGIS software as tools.

4.1 Data preparation

The city already has four fire stations, and it is requested that the planning result of fire stations must meet the national stipulations. There is no other request on the number and location of new fire station.
Firstly, a point layer of populous places and public buildings is created with the distribution of primary schools, hospitals, kindergartens, cinemas, bazaars etc, and to create coverage file of urban road network, in which set the resistance value of network arcs by synthesis considering driving speed on all ranks of roads as well as the man-made or natural barriers, such

as roads engineer constructing, river etc. Then to establish the network swerve table and set the time of vehicle turning, create resource center table and set those nodes of existed fire stations locations as centers, while all the other nodes of network are considered as candidate centers (In this experiment, we think that all the nodes in network can build fire stations); subsequently set all the nodes of network as demand points. The experiment data has been prepared as figure 3, where 1181 arcs and 1123 nodes compose of the road network.

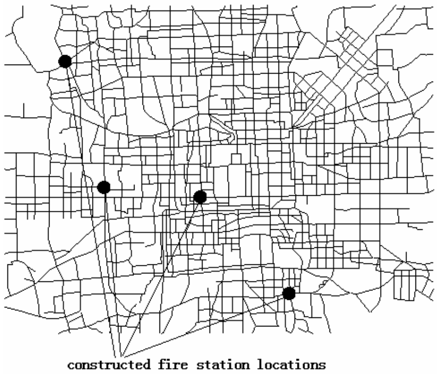

Fig.3 City Road Network Model

4.2 Case study

Firstly the Voronoi diagram of the 4 existed fire stations are constructed, and the initial value of P is predefined with 16. The procedure of fire station location plan is performed with the AML of the secondary development language of ArcGIS. The result shows that 16 fire stations could satisfy the requirement of the whole city zone's fire control. So we try to reduce the number of fire stations one by one, and redo the planning of fire station location until the number could not satisfy the demands of the whole city zone's fire control. The iterative experiments show that coverage area could not cover the whole city until the number reduces to 11. Thus, we can plan to build 8 new fire stations for the primary results.

In this case, to conform with the principle that the distance of fire station from populous public buildings and spaces is no less than 50m, we establish corresponding buffer of point layer and relocate the position of fire stations which are in any of buffers. Finally we get the ultimate result shown as Fig. 4, where every fire station location is the center of a radial network and the service area of each fire station is a set of all the other end points of line segment eradiation from the center.

So we can conclude from the above case as following:①The method could perfectly fulfil optimized station location plan, and its procedure is practicable. ②This optimization method can ensure all demand points can get service of fire control within the regulated time, and each fire station coverage area is divided on the basis of actual road network with GIS software, which avoids the subjectivity of division manually. ③The initialization value of p and the division of fire station coverage areas are based on Voronoi diagram and gradual optimization method is use to revise them, which help to increase the planning speed.

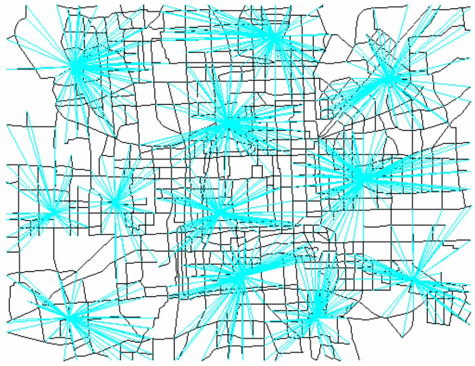

Fig.4 Ultimate Result of Fire Station Location Selection and Coverage Area Boundary Partition

5. CONCLUSIONS AND SUGGESTIONS

This paper proposed a method of gradual optimization of urban fire station plan based on geographical network model, and a case of city fire station plan is given as an example to test its capability and scientificity. The study shows that the method can implement based on the software platform of ArcGIS with its secondary development technology AML and existing spatial analytical functions, which not only can get scientific and reasonable result to satisfy requirements, but also is easily to extend to the other fields, such as police patrol, gas station and so forth. This model has high precision and efficiency, and can satisfy the many related applications.

Since fire station plan is a synthetic problem of spatial decision-making, there are many subjective factors must be consider beside the limited service time, such as land-price, wind direction etc. ,which will result in that the coverage areas can not cover the whole city zone and require to revise the planning layout many times, in addition the precise of the result will be decreased. So our succeeded study is to development a synthetic optimization model and to work out high efficiency computation method to integrated the subjective factors into it.

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