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Study and implementation of fire sites planning based on GIS and AHP

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Abstract

Urban fire is a hidden danger for city safety. Therefore, the overall layout of fire fighting facilities is an important part of fire control planning in cities. This study combines the method of GIS and AHP together. The paper, which fully considers the complicated data and their mutual influence, makes full use of spatial analysis, data processing and query. Planning and analysis will be more flexible and universal by utilizing this method, and the complexity of spatial location selection can be decreased considerably, which consequently may overcome the casualness and uncertainty of subjective site selection. And finally, the approach satisfies the planning requests of some related fire fighting department to a certain degree.

Key words: GIS(Geographic information system); AHP(Analytic Hierarchy Process); fire station planning© 2011 Published by Elsevier Ltd.

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1. Introduction

Urban fire is a hidden danger for city safety. Therefore, the overall layout of fire fighting facilities is an important part of fire control planning in cities.

Reasonable construction of fire facilities and layout of fire stations can improve governments' ability to reduce or prevent fire disasters in cities considerably. What's more, safeguarding urban infrastructure and protecting the lives of local residents are all possible results. Accordingly, a safe environment can be created there.

Recently, with the rapid development of national economy and urban construction, city scale is much larger than before, but fire fighting facilities are relatively lagging. The incoordination between comprehensive ability to resist fire in city and its development reveals gradually. At present, the most prominent issue related to domestic fire stations planning is the insufficiency of fire sites. The principle of fire sites planning is to reach the edges of your areas of responsibility within 5 minutes after alarming. Moreover, proper area of responsible regions may be 4 to 7 square kilometers.

However, most of our cities can not reach that standard. As cities continue to expand, number of fire stations has not increased accordingly. In addition, when it comes to the finished fire sites, problems may be the uneven spatial distribution, inappropriate planning and so on. For example, traffic congestion around fire sites and narrow roads can definitely contribute to the delay of prime time for rescue, because fire engines can not get to the fire scenes in time. Consequently, our safety can not be guaranteed effectively. In contrast, the layout of fire sites in western countries is relatively complete. They are denser, more reasonable. Thus, it will cost less time for the firemen to reach the scenes. Then, fire can be controlled and damage can decrease to a lowest level. Furthermore, the construction mechanism of fire sites in our country is not so smooth and cycle of building is too long. Therefore, we should give priority to those that are in urgent and the most useful when pondering which should be built first.

2. Research Status

Currently, there are two major methods to plan the layout of fire stations, that are Abstract Mathematical Models and GIS combined with AHP. What should be done first when you use Abstract Mathematical Models is to choose the elements that need to be researched into according to the requirement of fire sites selection (identify the problems). Then a series of mathematical equations or geometric symbolic can be used to express every element related to site selection (build models). And finally, the problem can be solved under the previous steps (solve the models). The features of this method can be concluded in the following passage.

We are able to solve the location issue that has just one factor. But, some factors, for instance, density data, is hard to express by mathematics equation. In addition, establishment of models is so complex that it needs sufficient mathematics skills to solve the problem and it is difficult to transform mathematical models to computer models. What's more, some abstract models are easy to divorce from reality, and it is not easy to consider all the complex essential factors and their mutual influence. The versatility of this traditional method is not so good. Therefore, it is hard to provide intuitionistic interactive analysis-tools to policy-making people. Specifically, as to fire station planning and constructing in a city, the traditional analytical method for location selecting cannot be used if considering immense amount of data of transportation, population, economy and so on.

But GIS combined with AHP can make full use of GIS functions such as space analysis, data processing and inquiry. It has following characteristics. In the process of location selection, the complex data and their mutual influence can be considered well. And it is not necessary to use massive complex mathematical equations to describe space position of each factor. Moreover, the analysis is more flexible and it is easy for data renewal. Location selective models are easier to understand. In addition to that, there is a variety of GIS software to utilize, so it is not necessary to realize foundational analysis function from the very bottom. Secondary development functions of GIS can also be used to develop excellent man-machine interactive interface. As a result, GIS combined with AHP is a tendency to planning recently, and many efforts have been made to conduct planning problems using GIS. However, mature planning and experiments are relatively few towards the selection of fire station location.

On the basis of the foundation concluded by predecessors, this research has analyzed basic principles of fire station planning and proposed a technical solution of fire station planning based on GIS and AHP. Take data of BeiJing within 3rd Ring Road for example, location selection AHP models are designed by using GIS network analytic method, buffer analytic method and superimposition analytic method. Then we realize the selection of influencing factors of location selection objectively as well as synthesis weights assignment. Feasibility of technical plan has been confirmed by experiments. Although factors considered in the paper are not so sufficient, it may provide technical mentality and method for the future planning.

3. selection of fire station location based on AHP

3.1. technical route

This research plans the layout of fire stations within Beijing 3rd ring road by combining GIS and AHP together. Through analysis and city's characteristics within the Beijing 3rd ring roads we take three main factors into account, which are population density, building loss after catching fire and distance to the nearest fire station. A model can be established using AHP. Then we calculate the comprehensive weight that each factor accounts for, and figure out which area needs to be built with fire stations according to different weights. The entire researching process needs to use ArcGIS 9.3 system as depending platform, and takes full use of ArcGIS functions such as spatial analysis module, network analysis module, superimposition analysis module, data management module and so on. Thus, data acquiring, data processing and data analysing can be carried on by using those modules. Its overall route can be divided into the following three parts approximately:

1. View the goal of fire site selection as the analytical territory of location selection problem. Take factors such as path, distance, time, loss into consideration. Extract the influencing factors for location selection.
2. View ArcGIS as a platform to process the data. Establish AHP analysis models by using spatial analysis, superimposition analysis and network analysis. Carry on spatial analysis for models.
3. Calculate the weight of each factor by using AHP. Realize the combination between quality and quota.

3.2. characteristic of AHP

Nowadays people bump into many policy-making problems in their daily life. For example, if you want to buy a shirt, you must make the choices like whether to buy shirts made of cotton, silk or polyester fiber. If you invite friends to have a dinner, you must make choices like holding the dinner at home or going to a restaurant. When people handle with these policy-making problems, they have to consider different kinds of factors, but they have commons in features such as relating to economy, society, humanity and so forth. When making comparison, judgment, appraisal and decision, we find that it is always difficult to quantify the importance, influence or priority of those factors. We often solve problems subjectively (according to objective reality).Therefore, It will bring difficulties to general mathematics methods when solving problems. T.L.Saaty et al. proposed a practical method that can deal with this kind of issue effectively in 20th century 70's, which is called Analytic Hierarchy Process (short for AHP). This is a systematized and hierarchical analysis method which is qualitative and quantificational. That is, we can get rid of deviation caused by subjective qualitative evaluation before, and incorporate objective into reality.

3.3. realization flow

3.3.1. selection of factors

We carry this research based on ***Urban planning Fixed quantity Target Temporary Provisions*** issued by National Construction Committee and ***Fire station Architectural design Standard*** issued by Ministry of Public Security. We establish a lot of factors related to humanity, nature and society such as population, transportation, road distance between existing fire stations and so on. According to the above standard, factors determined finally are population density, road distance to the nearest fire station and loss if buildings catch fire. These three factors are taken into consideration in this research as the influence factors.

(1) population density

An area where population is more crowded has a higher possibility to catch fire. And once this happens, economic loss will be higher and its influence will be deeper. Therefore, such areas need more fire stations.

(2) building loss after catching fire

According to the prices of existing houses in Beijing, the buildings nearer to streets have higher construction cost. Then once catching fire, it will create more economic loss. So it needs firemen to reach the fire scenes in a shortest time, for preventing the fire from spreading. Thus, more fire stations should be established around these buildings to reduce economic loss caused by fire to the greatest degree.

(3) road distance to the nearest fire station

When there are many fire stations located at the same area, scope of responsibility of these fire stations must be considered. If there are many fire stations at the same area, the area of responsibility of every fire station may be overlapped. Therefore, new fire stations must be established at the area where there is no fire station or few fire stations.

3.3.2. factors processing

(1) raw data

The research is conducted at an area within 3rd ring road in BeiJing. Raw data includes road network data within Beijing 3rd ring roads, construction areas of buildings in Beijing and location of fire stations within Beijing 3rd ring roads. Road network data is the linear data. Building area data is surface data. Fire station position information is point data.

(2) Derivation data

In the dense area, it is more likely to catch fire. Scope affected by fire is broad and fire spreads quickly. Therefore, more fire stations need to be built there. Then we need to study population density distribution map in that region. Because we have not gotten population data in that area, we have to replace the population data by building area. That is, bigger building area, denser population.

Because in the raw data, building areas are polygon surface data, in order to facilitate us to make population density map later, we should first transform the building area data to point data in ArcGIS. We may obtain population density distribution map in the study region by processing the point data. The referring field is area. (Fig 1)

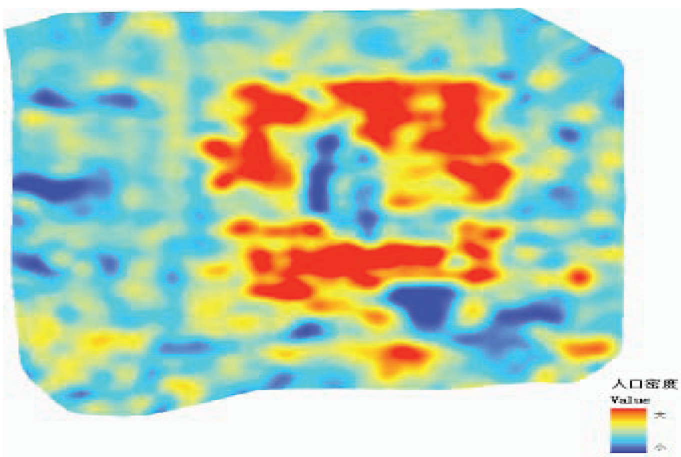

Fig 1 Population density distribution map

population density
Value
High
Low

Moreover, new fire stations must be far from the existing fire stations, making sure that newly built fire stations situated in an area where there is no fire station or few fire stations at present. Therefore, we must establish road distance data to the nearest fire stations by using Network Analyst functions in ArcGIS. (Fig 2)

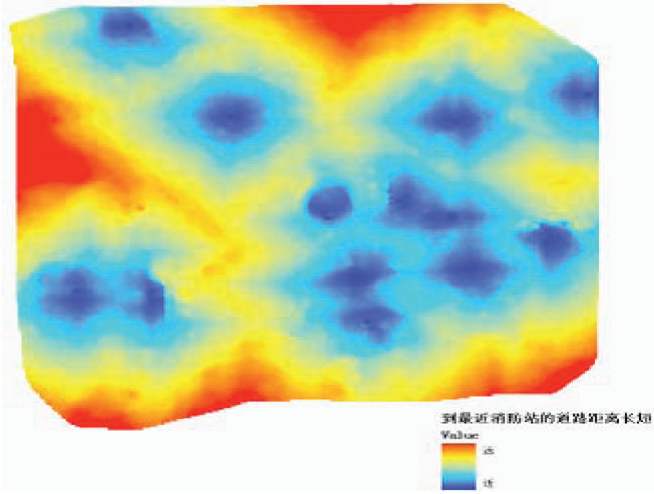

Fig2 road distance to the nearest fire station

Besides, as to building loss data, building value will be highe[illegible]o streets. Therefore, the loss caused by fire will be bigger. Because the loss will be differen[illegible]ling to the distance between roads and buildings, buildings near first level streets will lose much more than buildings near third level if they are caused by fire. Thus we work out straight distance data to the first level stre[illegible]econd level street and third level street separately by using distance module in ArcGIS. Then we give each derived data a certain weight separately, and calculate fire loss synthetically in different areas. Our road will be classified based on 2010 Beijing transportation tourist map. AHP can be used to calculate the weight of each factor. Value of each weight can be seen in table 1. Raw data which involves in AHP needs an evaluation made by expert or populace. Because of our limited condition, our origin data is determined by investigation to 100 stochastic populace finally. (results in Fig 3) Investigative data is evaluated according to 1-9 criterion proposed by Saaty et al.. That is, the value scope is 1,2,…,9 and the reciprocal is 1,1/2,…,1/9. When carrying on qualitative comparison in pairs, people usually have 5 obvious ranks in their brains. That rank may be described conveniently with 1-9. (Table 2)

Table 1 Weights of different levels of road

Weight decided by distance to different level of roads	First level road	second level road	third level road	weight
First level road	1	4	3	0.6196
second level road	1/4	1	2	0.2243
third level road	1/3	1/2	1	0.1561
λ =3.1092739 CI=0.054637 CR=0.0942017 CR<0.1，pass the Consistency test				

Table 2 meanings of scale 1-9

scale	meanings
1	This row of factor and this column of factor have the same influence.
3	This row of factor influences slightly more than this column of factor.
5	This row of factor influences more than this column of factor.
7	This row of factor influences much more than this column of factor.
9	This row of factor influences absolutely more than this column of factor.
2,4,6,8	The influence will be between two levels above.
1, 1/2, …, 1/9	The influence will be opposite to the list above.

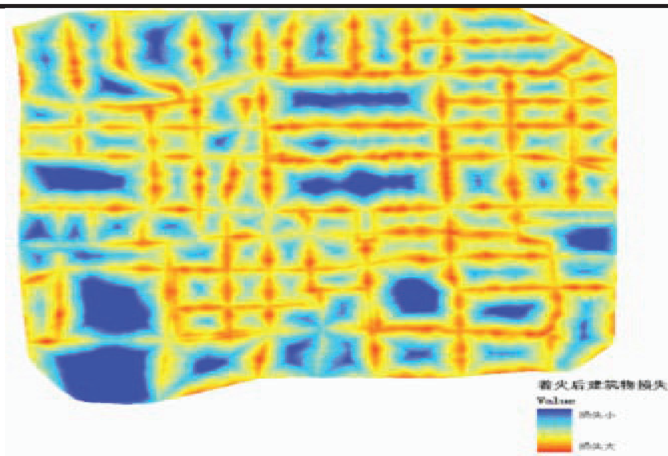

Fig 3 distribution map to loss of buildings after catching fire

(3) Reclassification of data

Before carrying on superimposition analysis to each influencing fa rious factors must be normalized first, which can make the data stay in the same rankin ystem. Only then can we conduct superimposition analysis. This research divides the data into 10 levels while making classification. As for the data of population density, after classifying, the value will be higher if it is denser whi wer if it is sparser. And as for the data of road distance to the nearest fire station, after classifying, the value will be higher if it is further from roads. Finally as to the data of losses of buildings catching fire, after classifying, the value will be higher if it lost more. For each factor, bigger value means more necessary to build new fire stations.

3.3.3. Weight

If all the data have the same importance, we only need to carry on merging all the data together. But in fact the importance of each factor which affected fire station location selection is different. And here, we calculate the weight through AHP once more. Finally, we figure out the weight of each factor (each classified data). (table 3)

Table 3

Selection of location	Population density	Road distance	Loss of buildings	weight
Population density	1	4	3	0.6196
Road distance	1/4	1	2	0.2243
Loss of buildings	1/3	1/2	1	0.1561
λ =3.1092739 CI=0.054637 CR=0.0942017 CR<0.1，pass the Consistency test				

3.3.4. Uniform examination

Comparison matrix in pairs is usually not line array. But in order to use its eigenvectors which correspond to eigenvalue λ as weight vector of factors to be compared, its inconsistent degree should be within a permission scope. Then how do we determine this scope? According to this theorem and the fact that λ relies on aij continuously, if λ is much larger than n, inconsistency of A is more serious. Thus, error caused by taking eigenvectors as weight vectors is bigger. Therefore, we may use the value of λ-n to weigh the inconsistency of comparison matrix in pairs. Saaty et al. call CI=λ-n/n-1 consistency index. Towards our research, Reciprocal matrix of order 3 or coupled comparison matrix A is:

$$\begin{Bmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{Bmatrix}$$

In order to determine the permissible range of inconsistency of comparison matrix, we need to find the standard to weigh consistency index CI of comparison matrix in pairs. Saaty et al. introduce a so-called random consistent index RI. RI is shown in table 4.

Table4 Value of stochastic consistency index RI

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

As to the comparison matrix that n⩾3, the ratio of its consistency index CI and random consistent index RI of the same rank(it means the same n) is called consistency ratio CR. When CR⩽0.1, we may use eigenvectors of eigenvalue λ which correspond to comparison matrix in pairs as weight vector of factors to be compared. Here, only one comparison matrix in pairs is being used: We calculate the value of λ using root law (λ =3.1092739). Then we work out that CI=0.064637 and CR=0.0942017⩽0.1. Therefore, it can pass consistency test. That is to say, 0.6196, 0.2243 and 0.156 can be used as weight vectors.

4. analysis of fire station

Through Raster Calculator tool in ArcGIS, we carry on combination computation for three factors based on the weight which solved above. And we conduct classification of its result. Still, it can be divided into 10 ranks. The location which needs construction of fire stations most is 10 and least is 1. We believe that the areas where score is 8, 9 or 10 are suitable for constructing new fire stations. Like Figure 4, existing fire stations can be represented as green flags, while fire stations which plan newly can be represented as purple flags. Red region is the region where score is 10. Green region is the region where score is 9. Blue region is the region where score is 8. And pink region is the region where score is smaller than 8.

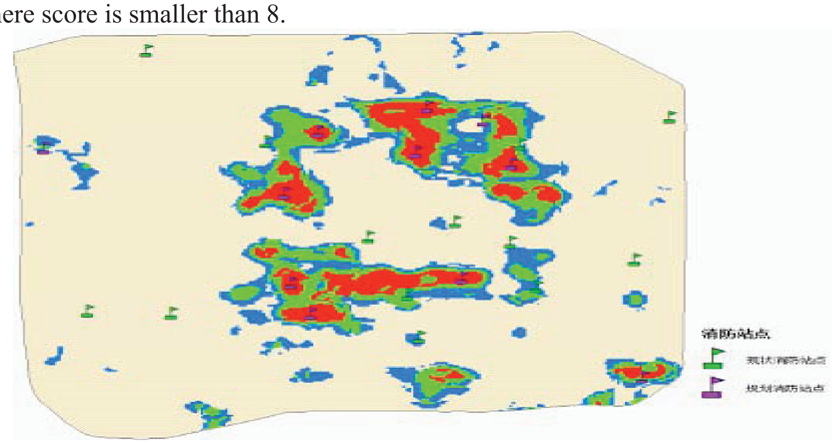

Fig4 fire station distribution map

fire stations

fire stations existng

5. Analysis of plan result

Figures below show regions where present fire stations can arrive in a certain tifire stations planned regions where fire stations in planning can arrive in a certain time. Fig5 is regions where fire stations can arrive within 4 minutes before planning; Fig 6 is regions where fire stations can arrive within 4 minutes after planning. Fig 7 is regions where fire stations can arrive within 3 minutes before planning; Fig 8 is regions where fire stations can arrive within 3 minutes after planning. Fig 9 is regions where fire stations can arrive within 2 minutes before planning; Fig 10 is regions where fire stations can arrive within 2 minutes after planning. By contrast, it can find out that cover areas of fire stations are broader after planning. And firemen can arrive at larger regions in a shorter time. Thus, it will reduce the loss to a maximum extent.

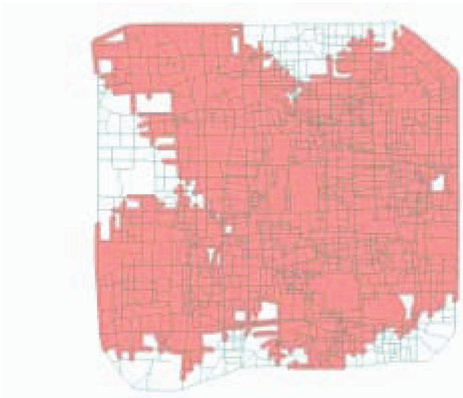

Fig5 coverage 82.1%

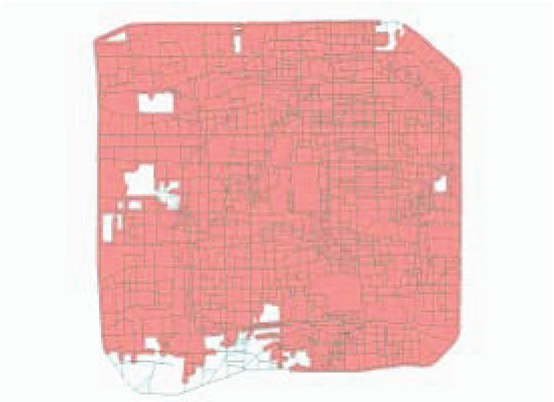

Fig6 coverage 95.2%

Fig7 coverage 56.3%

Fig8 coverage 75.8%

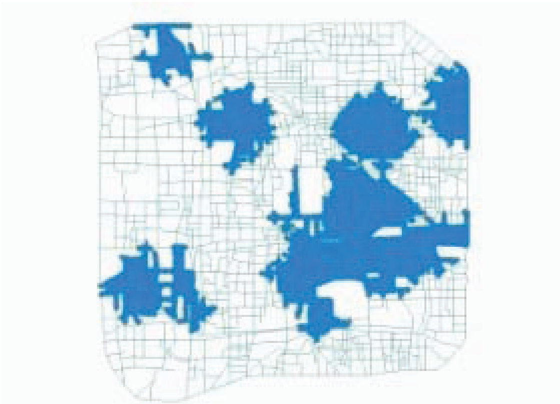

Fig9 coverage 28.8%

Fig10 coverage 44.8%

Fig 11 is the contrastive map of responsibility areas of fire stations, in which green regions are responsibility areas of fire stations before planning and red regions are additional responsibility areas of fire stations after planning. It can be find out that in urban centers, responsibility areas of fire stations are nearly covered the whole city after planning.

The data used is within 3rd ring road at this time and no data outside 3rd ring road has been used. However, in reality, some areas outside 3rd ring roads still have important influence to some areas within 3rd ring road. Therefore, we can find out from the result that in the place near 3rd ring roads and within 3rd ring road, there still exist areas where there is no fire station that is responsible for them. If we add data outside 3rd ring road, the result will be more accurate.

Fig 11 contrast map of fire station responsibility before and after planning

6. Conclusion

This research utilizes network analytic method, buffer analytic method, superimposition analytic method as well as AHP (mainly consider weight of each factor). We use such method to the selection of fire station location, solve the problem of fire station location selection successfully and give the location where establishment of fire stations is suitable. Compared with traditional location selection method, using GIS to car[illegible] a bigger flexibility. And it can reduce the complexity of spatial location selection to the greatest degree. Moreover it may overcome the capriciousness and uncertainty of subjective location selection. Furthermore the precision of location selection can be enhanced. This experimental method can satisfy location selection request of fire department to a certain extent.

responsible areas of fire stations before planning

responsible areas of fire stations after planning

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