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Site Selection of Fire Stations in Cities Based on Geographic Information System and Fuzzy Analytic Hierarchy Process

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ABSTRACT

The site selection and layout planning of fire stations in cities is a key content of fire safety, and it provides an important support for the emergency rescue and fire control. However, the fire station construction and the division of their jurisdictions in most cities of China is random, lacking in scientificity and rationality. As the size of the city grows, fire hazards and fire loads increase continuously as well, which has brought great challenges to the fire emergency response and the safe operation of the cities. This paper adopts a multi-criterion decision-making method that is called the Fuzzy Analytic Hierarchy Process (FAHP), and the Geographic Information System (GIS) to decide the reasonable locations of fire stations in a county in China. First, it obtained a candidate set of fire station locations based on GIS; then four main criteria of transit time, scale cost, social service and environmental geography were decided, and each criterion was subdivided into several sub-criteria to make the site selection more specific; after that, these criteria and sub-criteria were compared by the pairwise importance judgment matrices and the multi-objective fuzzy optimization, and at last, a comprehensive evaluation was conducted according to the suitability and importance of the alternative locations of the fire stations. The research results in this paper can assist policy makers in determining the most suitable locations and layout of fire stations in cities, so as to improve the overall fire control situation of the cities.

1. INTRODUCTION

As a result of the rapid economic development in the past three decades, China has become the world's second largest economy. However, as the size and diversity of the cities are gradually increasing, the planning and construction of the fire forces have failed to keep up with the pace of the times. The lagging fire forces and the increasing fire hazards have led to frequent fire incidents in cities, bringing major challenges to the cities' abilities in fire warning and emergency response. Since cities have the characteristic of complex natural spaces, how to scientifically select the locations and plan the layout of fire stations have become an important requirement for the construction of fire forces. Whereas, in terms of the site selection of fire stations and the division of their jurisdictions, China still adopts the empirical approach and the simple "circle-drawing" method, which lacks reasonable and scientific theoretical research and spatial analysis, and cannot comprehensively consider the various factors that affect the fire safety [1-5]. In order to improve public safety and eliminate the hidden hazards brought by the rapid development of the cities, it is urgent to adopt a method similar to the multi-objective decision-making optimization to select the locations of fire stations, so as to improve the efficiency of fire emergency response, and reduce the economic losses and emergency costs.

A system called the Geographic Information System (GIS) has been developed by researchers to help extract the physical characteristics of the earth's surface so as to manage, analyze and display the geographic data [6-10]. Based on fire risk assessment, Dong et al. [11] introduced GIS to the problem of new fire station site selection and old fire station layout planning. AHP is often adopted for site selection and layout planning problems, it is a method that uses multi-criterion variables for decision-making, and it simplifies complex decision-making problems into a set of binary comparison and its consistency check [12-14]. Neissi et al. [15] adopted GIS-based AHP to evaluate areas along the Izeh Plain (Iran) that are suitable for different pressure and gravity irrigation systems. Yavaşoğlu et al. [16] applied GIS and AHP to detect the optimal possible locations for Antarctic expedition stations. Koc et al. [17] adopted AHP, GIS and other multi-indicator decision-making methods to study the solar energy site selection in the four counties of Igdir, including Tuzluca, Igdir Central, Karakoyunlu and Aralik. Based on GIS, Karakuş et al. [18] adopted AHP, Simple Additive Weighting (SAW) and other multi-index decision-making methods to analyze the seven indicators of solid wastes and land use (Geological structure, land-use grades, transportation, underground water, surface water, residential areas, and utilization of existing land). To solve the fire station site selection problem, Lili Yang et al. [19] proposed a method combining fuzzy multi-objective planning and Genetic Algorithm (GA), which appropriately transforms the original fuzzy multiple objectives into several single uniform "minimum-maximum" objectives, so that GA can be easily applied to the problem solving. Although the research on the site selection problem has achieved some results in recent years, there is still a lack of optimization methods for the site selection and layout planning of fire stations in cities. The site selection and layout planning of fire stations should comprehensively consider relevant influencing factors, so as to improve the comprehensive optimization model of site selection and layout planning of fire stations.

In view of the above problems, this paper first gives the relevant construction standards of fire stations, and selects a county in China as the research area; and then the influencing factors of fire station site selection are analyzed; after that, based on GIS gird analysis, a candidate set of fire station locations is obtained; and at last, the AHP is adopted to optimize the locations of fire stations in the city to overcome problems such as long drive time of fire trucks, unreasonable jurisdiction radius, and uneven layout, etc. The contributions of this paper can be summarized into three aspects as follows:

1) The study establishes a fire station location model for the target county based on GIS and obtains the candidate set of locations.

2) The study combines AHP and fuzzy inference to construct the multi-objective fuzzy optimization model, and this combined method can consider more influencing factors comprehensively.

3) The proposed method can be improved easily to provide a scientific decision-making basis for the layout planning of other cities.

The rest of this paper is organized as follows: Section 2 introduces the fire station construction standards; Section 3 selects candidate sites for fire stations in the target city; Section 4 optimizes the locations of fire stations based on FAHP; Section 5 gives conclusions.

2. FIRE STATION CONSTRUCTION STANDARDS

The construction of urban fire stations is generally implemented by governments at all levels; according to the latest laws and regulations, it has been included into the local economic and social development plans and the special fire protection plans. In order to adapt to the requirements of social development, the construction of fire stations should take factors of various aspects into consideration, such as the local transportation and economy, time, fire risks, climate and environment, geographical conditions, local policies, and the actual fire-fighting capabilities of the fire stations, etc. The diversity of the involved aspects and the interconnected factors have decided that this job will be extremely complicated. In this regard, targeted research should be conducted from the aspects of economics, sociality, safety, rationality, and feasibility, so as to formulate the optimal fire station construction standards.

In accordance with the *Standards for the Construction of Urban Fire Stations (2017)* and the development situations of domestic and foreign cities, the standards for the construction of fire stations can be summarized as follows: 1. Fire stations should be set up in accordance with the social development situation in each region; normal mission fire stations, special mission fire stations and material and technical support fire stations should be set up accordingly; in terms of normal mission fire stations, primary, secondary and small ordinary fire stations should be set up according to the actual situations. 2. The number of fire stations can be obtained by dividing the area of the urban planning area by the fire jurisdiction area and taking the round number of the calculation result. 3. The area needs to be covered by the fire stations is determined by the outline of the urban planning area, and overlap should be avoided as much as possible. 4. The layout of the fire stations should take into account the actual coverage of the fire stations and their fire rescue capabilities during emergencies. 5. The site selection of fire stations should follow the principle that fire fighters should be able to reach the margin of their jurisdictions within five minutes after receiving the set off instructions (the drive time of fire trucks should be within four minutes). 6. Combining fire hazard sources and key fire control units, possible questions should be analyzed in a targeted manner and the actual fire risks within the jurisdiction should be evaluated. 7. For areas with high fire risks, the site selection should follow the principles of shortest response time and fastest arrival, so as to minimize the damage caused by the fire as much as possible. 8. The distance between the on-duty vehicles and the main evacuation exits of public buildings should be equal to or more than 50 meters, and corresponding transportation facilities such as signs, markings and signal lights should be set on both sides of the main entrance and exit of the on-duty fire trucks. 9. The garage doors of the fire stations should face the urban roads, except for the jointly-built small stations, the set-back boundary lines of the fire stations should not be shorter than 15 meters. 10. The fire station configuration and equipment should be optimized, and the number of fire stations should be reasonably controlled; the equipment of fire trucks and the fire protection suits of fire fighters should match with the actual situations.

3. SELECTION OF CANDIDATE SITES FOR FIRE STATIONS IN CITIES

3.1 Study area

The target county is located in the east of the economic zone of Jiangsu, Zhejiang, Shanghai and Anhui, on the north bank of the lower Yangtze River. Its latitude is between 31°04′~31°45′ north latitude, and the longitude is between 117°05′~117°43′ east longitude. The target county has an area of 1473.43km^2 and it is a typical small city. The landform of the county is quite complicated, the terrain is higher in the north and lower in the south, the city faces the Yangtze River and surrounded by lakes. The low and flat land in the central area accounts for 18.54% of the county's total area. The climate of the county is northern subtropical mild monsoon climate, with sufficient sunshine, abundant rainfall, and four distinct seasons. The geology of the county is a volcanic basin, which is characterized by the Mesozoic volcanic rocks. In 2018, the GDP of the county was 25.84 billion yuan, with a year-on-year growth of 6.1%. Based on the registered population, its per capita GDP was 26,541 yuan, and the economy of the city is rising steadily.

(a) A sketch map of the target county

(b) A satellite image of the county

Figure 1. Study area of the target county

The study area of this paper is the downtown of the target county. The planned area of the city is about 32.1km^2, as shown in Figure 1 above. Limited by geographical conditions, the county's downtown area is composed of 5 scattered small regions, which has largely increased the transit time of fire trucks, and current conditions can hardly meet the requirements of the fire station construction standards.

3.2 Influencing factors of site selection

The influencing factors of site selection of fire stations in the target county is quite complex, this paper mainly takes four points into consideration:

3.2.1 Transit time

China's fire station construction standards stipulate that fire trucks should be able to reach the fire site within 5 minutes. However, due to objective reasons such as traffic congestion, fragmented regions, driving speed, and ambiguous address, the transit time of fire trucks often cannot meet the 5-minute requirement. When selecting the sites for fire stations, only by comprehensively considering the geographical conditions of the region, the road traffic conditions, and the key fire control units within the jurisdiction, can we effectively shorten the transit time and improve the execution of firefighting.

3.2.2 Scale cost

The target county has continuously increased its investment in the construction of fire forces, but how to maximize the utilization of the investment is also one of the core problems for the site selection of fire stations. The scale cost of fire stations includes the one-time construction cost and the annual maintenance cost. Only by comprehensively considering the economic factors can we optimize the scale, location and construction sequence of the fire stations.

3.2.3 Social services

The purpose of fire station construction is to serve the society, so the site selection must take into account the social factors, such as the whether the site is a planned site; which usage has a more important significance; and whether the setup of the fire station in the site has an impact on the surrounding residents. All these questions are of practical significance.

3.2.4 Environmental geography

Environmental geography has a significant impact on the operation of the fire station once the construction is completed, therefore, the location of the fire station should be on flat ground, and natural barriers such as rivers or mountains should be avoided, and severely polluted area must be excluded as well; moreover, priorities should be given to street areas that are adjacent to the main roads within the study area.

3.3 Generation of GIS-based candidate locations

GIS has now become a powerful tool for processing spatial data and digital maps. GIS was defined earlier as an information system that processes geographic coordinate data and morphological feature spatial data. GIS data is complex and its volume is extremely large, so it needs a platform for visualization output. ArcGIS software not only provides access to attributes and spatial information, but also has the functions of map drawing, and visualization display and analysis. This software is a GIS software released by the American Environmental Systems Research Institute (ESRI) in 1982. After many years of upgrading, this software has been widely recognized and applied in the field of geography. In ArcGIS 10.2 version, digital maps can be re-rasterized in the module "converter tools" and the performance of the tools has been improved. Therefore, this paper adopts the ArcGIS 10.2 version for the relevant research.

3.3.1 Data information extraction

Data information extraction includes trimming, segmentation, and filtering, etc. Based on the attributes and spatial information, extracting given data from the given features is the first step of GIS modeling. For example, screening the data of land for special use from the land use data of the county includes the land use type vector data set, current fire station distribution data set, linear road data set, residential area distribution data set, mountains, lakes, and other layers.

3.3.2 Buffer analysis

Buffer analysis is a type of domain analysis that solves the proximity problems. For research object A, the buffer can be defined as:

$$Q = \{x \mid d(x, A) \le r\} \tag{1}$$

where, d is the Euclidean distance and r is the radius of the domain.

In ArcToolbox, click to create a multiple ring buffer, and set related parameters according to the actual situation; then select the vector features in the layer and set the range of the buffer; after that, select the obstacles between the fusion buffers, the buffer fusion method and the output position of the results, and then the corresponding buffers for different features could be established.

3.3.3 Surface analysis

Surface analysis is to extract the spatial feature information data contained in the given data, such as slope direction, contour, fill and cut, mountain shadow, slope, curvature, and visibility analysis, etc. Surface analysis mainly analyzes the geological information data, and raster data is the main data type for surface analysis.

3.3.4 Overlaying analysis

Overlaying analysis is the most important analysis tool in site selection model construction, and it is one of the most commonly used tools for extracting the implicit spatial information. Under a unified reference coordinate system, it conducts set operations on two or more different data to generate new data and new attribute features. Overlaying analysis includes erase, intersect, union, identify, update, intersect and invert, spatial connection, and other analysis tools.

After buffer analysis, under a unified reference coordinate system, the buffer layers and the impact factor layers were superimposed on each other in pairs, and set operation was performed to obtain new data and attribute characteristics; then obtain and retain the layer that was affected by all impact factors, and all the data for suitability analysis were on this layer, which met the scope of urban fire station location requirements. Since there were many candidate regions, after the proper threshold was selected, the candidate locations were calculated by the model, and the number of candidate fire stations at this time was 201, as shown in Figure 2.

Based on the above analysis, referring to the fire force construction investment planned by the county government, the number of new fire stations was set to 4.

Figure 2. Candidate locations for fire station construction

4. OPTIMAL LOCATIONS OF FIRE STATIONS BASED ON FAHP

4.1 Analytic Hierarchy Process (AHP)

AHP is one of the multi-criterion decision-making methods. It decomposes the complex problems associated with the alternative schemes layer by layer according to the decision makers' perception and understanding of these alternatives. With AHP, decision makers compare each factor at the same level in pairs to determine the best choice.

The numerical scale of AHP consists of 17 numerical values, which can be described as follows:

$$\left\{\frac{1}{f}, f_1, f_i\right\}, i = 2, 3, \ldots, 9$$

where, $f_1 = 1, f_{i+1} > f_i > 1$. The values of $f_i(i = 1,2,\ldots,9)$ correspond to the language scale of the i-th layer of AHP. By selecting different values of $f_i(i = 1,2,\ldots,9)$, different numerical scales could be obtained.

Order A=$(a_{ij})_{n\times n}$ to be a pairwise comparison matrix of mutually inverse numbers, where $a_{ij}>0$, $a_{ij} \times a_{ji}=1$. The weight vector can be derived from matrix A.

The AHP language scale has 9 grades, as shown in Table 1. Linguistic Scale

Table 1. Linguistic scale

Grade	AHP linguistic scale
1	equally important
2	weakly more important
3	moderately more important
4	moderately plus more important
5	strongly more important
6	strongly plus more important
7	demonstratedly more important
8	very, very strongly more important
9	extremely more important

Additive normalization method is an optimization method and can be expressed as:

$$\omega_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}},\ i = 1, 2, \ldots, n \tag{2}$$

Order the eigenvector of matrix A to be W (also called the weight vector). It can be obtained by solving the following linear system.

$$A\mathbf{W} = \lambda\mathbf{W},\ e^T\mathbf{W} = 1 \tag{3}$$

where, λ is the main eigenvalue of matrix A. λ_{max} is the largest eigenvalue. To prevent subjective and one-sided judgment, the weights must be subject to the consistency check, and the calculation standard of consistency is as follows:

$$\eta_\lambda = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

where, n is the number of influencing factors.

R is the average random consistency indicator value, then η_R can be calculated as follows:

$$\eta_R = \frac{\eta_\lambda}{R} \tag{5}$$

If $\eta_R < 0.1$, the pairwise comparison matrix A has satisfactory consistency; otherwise, the comparison matrix needs to be readjusted until it passes the consistency check.

4.2 Fuzzy comprehensive evaluation

1) Establish the index set $\boldsymbol{U} = \{u_1, u_2, \cdots, u_n\}$. $\boldsymbol{U}$ is divided into k first-grade indices, that is $\boldsymbol{U} = \{U_1, U_2, \cdots, U_k\}$. Wherein $\boldsymbol{U} = \bigcup_{i=1}^{k} U_i, U_i \cap U_j = \emptyset (i \neq j)$. Similarly, the first-grade index $\boldsymbol{U_i}$ can be divided into several second-grade indices $\boldsymbol{U_i} = \{u_{i1}, u_{i2}, \cdots, u_{in_i}\}(i = 1,2,\cdots,k)$; wherein $n_1 + n_2 + \cdots + n_k = \sum_{i=1}^{k} n_i = n$.

2) Establish weight vector according to the improved AHP, and the corresponding weight vector of $\boldsymbol{U}$ can be written as follows:

$$\bar{\mathbf{W}} = (a_1, a_2, \cdots, a_n)\, i = 1, 2, \cdots, n \tag{6}$$

The corresponding weight vector of U_i can be written as:

$$\bar{\mathbf{W}}_i = (a_{i1}, a_{i2}, \cdots, a_{ij}, \cdots, a_{im})\, i = 1, 2, \cdots, m \tag{7}$$

3) Establish fuzzy evaluation set $\boldsymbol{V} = (v_1, v_2, \cdots, v_n)$.

4) Use the evaluation set for the fuzzy evaluation of single factors. The single-factor evaluation matrix R can be obtained by the following formula:

$$\mathbf{R} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{mm} \end{pmatrix}, 0 \le r_{ij} \le 1 \tag{8}$$

5) Order the fuzzy comprehensive decision model to be $(\boldsymbol{U}, \boldsymbol{V}, \boldsymbol{R})$, the weight vector is $\bar{\boldsymbol{W}}$, and the corresponding comprehensive evaluation is $\boldsymbol{B} = \bar{\boldsymbol{W}} \circ \boldsymbol{R}$. According to the complexity of the model, a multi-level fuzzy evaluation model can be designed.

4.3 Index set of fire station locations

From the four aspects of transit time, scale cost, social service and environmental geography, the locations of fire stations were evaluated. The transit time includes the maximum transit time and average transit time from the fire station to the scene of the fire. The scale cost includes the construction cost and annual operating cost of the fire station; the social service includes the compliance of site plan and the impact on surrounding residents; the environmental geography includes the transit convenience, the meteorological conditions and the geographical conditions.

The first-grade indices of the evaluation indices are the transit time, scale cost, social service and environmental geography. The second-grade indices are maximum transit time, average transit time, construction cost, annual operating cost, compliance of site plan, impact on surrounding residents, transit convenience, meteorological condition and geographical condition; that is, four first-grade indices and nine second-grade indices, as shown in Figure 3.

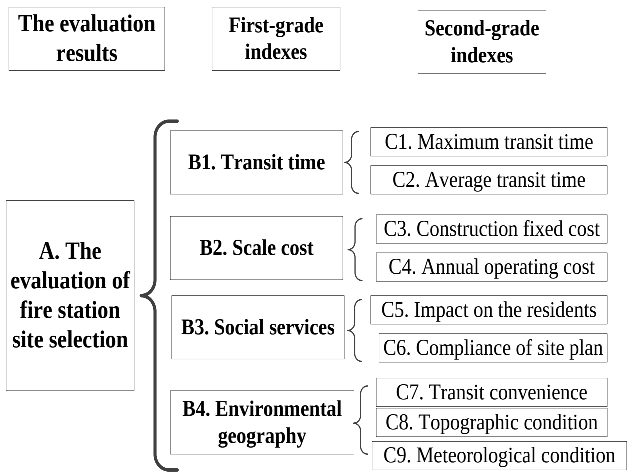

Figure 3. Evaluation indices of fire station locations

4.4 Determination of weights

First, a hierarchy of indices of the locations of fire stations in cities is established as shown in Figure 4 below.

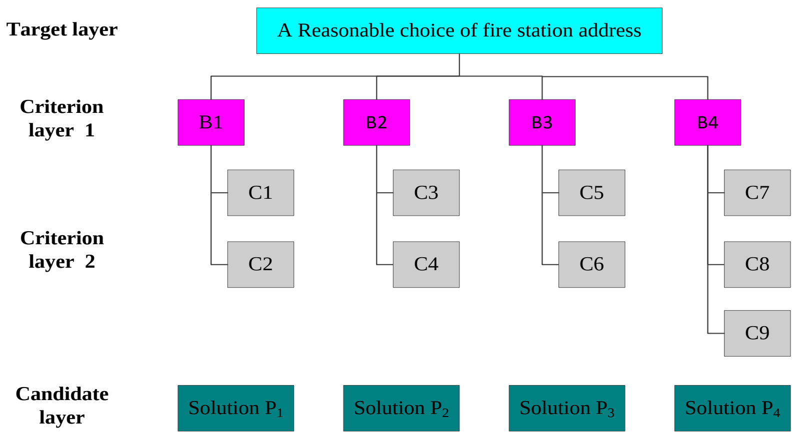

Figure 4. Hierarchical structure of fire station locations

Second, construct judgment matrices for the locations of fire stations in the city.

According to the pairwise comparison of the importance of each factor in the same layer relative to a certain factor in the previous layer, the judgment matrices are obtained as follows:

1) The importance judgment matrix of criterion layer 1 relative to the target layer is:

According to Table 1 and expert experience, the importance judgment matrix of $\mathbf{B_1}$, $\mathbf{B_2}$, $\mathbf{B_3}$ and $\mathbf{B_4}$ relative to A is

$$\mathbf{P} = \begin{bmatrix} 1 & 4 & 5 & 6 \\ 1/4 & 1 & 3 & 2 \\ 1/5 & 1/3 & 1 & 2 \\ 1/6 & 1/2 & 1/2 & 1 \end{bmatrix}.$$

2) The importance judgment matrices of criterion layer 2 relative to criterion layer 1: respectively, the importance judgment matrix of C_1 and C_2 relative to B_1, the importance judgment matrix of C_3 and C_4 relative to B_2, the importance judgment matrix of C_5 and C_6 relative to B_3, and the importance judgment matrix of C_7, C_8 and C_9 relative to B_4 are:

$$\boldsymbol{P}_1 = \begin{bmatrix} 1 & 1/3 \\ 3 & 1 \end{bmatrix}$$

$$\boldsymbol{P}_2 = \begin{bmatrix} 1 & 4 \\ 1/4 & 1 \end{bmatrix}$$

$$\boldsymbol{P}_3 = \begin{bmatrix} 1 & 5 \\ 1/5 & 1 \end{bmatrix}$$

$$\boldsymbol{P}_4 = \begin{bmatrix} 1 & 6 & 5 \\ 1/6 & 1 & 2 \\ 1/5 & 1/2 & 1 \end{bmatrix}$$

Third, calculate the weights of each layer and check the consistency of the weights. Since the calculation method of each importance judgment matrix is the same, here we only expand one matrix **P** in detail.

$$\mathbf{P}=\begin{bmatrix}1 & 4 & 5 & 6\\ 1/4 & 1 & 3 & 2\\ 1/5 & 1/3 & 1 & 2\\ 1/6 & 1/2 & 1/2 & 1\end{bmatrix}\xrightarrow{\text{Column normalize}}$$

$$\begin{bmatrix}0.618 & 0.686 & 0.526 & 0.546\\ 0.154 & 0.171 & 0.316 & 0.181\\ 0.124 & 0.057 & 0.105 & 0.181\\ 0.103 & 0.086 & 0.053 & 0.091\end{bmatrix}$$

$$\xrightarrow{\text{row sum}}\begin{bmatrix}2.376\\ 0.822\\ 0.467\\ 0.333\end{bmatrix}\xrightarrow{\text{normalized}}\begin{bmatrix}0.594\\ 0.206\\ 0.117\\ 0.083\end{bmatrix}$$

Then, the eigenvector is $\boldsymbol{W} = [0.594 \quad 0.206 \quad 0.117 \quad 0.083]^T$.

From $\boldsymbol{PW} = [2.376 \quad 0.822 \quad 0.467 \quad 0.333]^T$, we can get the maximum eigenvalue as:

$$\lambda_{\max}=\sum_{i=1}^{4}\frac{(\mathbf{PW})_i}{4W_i}=4.012$$

The consistency indicator is:

$$\eta_\lambda=(\lambda_{\max}-n)/(n-1)=0.004$$

The random consistency ratio is:

$\eta_R = \eta_\lambda / R = 0.0044 < 0.1$, so, the weights of **B1**, **B2**, **B3** and **B4** is $\bar{\boldsymbol{W}}_1 = [0.594 \quad 0.206 \quad 0.117 \quad 0.083]^T$.

The same method can be applied to obtain other weight matrices, which will not be repeated here.

4.5 Fuzzy comprehensive analysis results

The candidate set $\boldsymbol{D} = \{D_1, D_2, D_3, \cdots D \ \}$ composed of candidate addresses was subject to the comprehensive evaluation, and the optimal target set was obtained as $\boldsymbol{T} = \{T_1, T_2, T_3, T_4\}$; to perform fuzzy comprehensive evaluation on the locations of the fire stations, a membership function between the second-grade indices and the evaluation set was determined. In order to express the fuzzy mapping from the factor set **D** to the judgement set **V**, "good" or "poor" judgements were used to evaluate the set.

The fuzzy complementary judgment matrix of the fire station locations can be obtained as:

$$\mathbf{R}=\begin{bmatrix}r_{11} & \cdots & r_{1j} & \cdots & r_{1n}\\ \vdots & & \vdots & & \vdots\\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in}\\ \vdots & & \vdots & & \vdots\\ r_{m1} & \cdots & r_{mj} & \cdots & r_{mn}\end{bmatrix}$$

where, r_{ij} is the scale value of the candidate set element D_j to the target set element T_i, n=201, m=4.

The membership function evaluated as "good" is defined as:

$$B_{ij}=\frac{r_{ij}-\underset{j}{\wedge} r_{ij}}{\underset{j}{\vee} r_{ij}-\underset{j}{\wedge} r_{ij}} \tag{9}$$

The membership function evaluated as "poor" is defined as:

$$B_{ij}=\frac{\underset{j}{\vee} r_{ij}-r_{ij}}{\underset{j}{\vee} r_{ij}-\underset{j}{\wedge} r_{ij}} \tag{10}$$

where, B_{ij} is the membership value in the fuzzy inference; $\underset{j}{\wedge} r_{ij}$ represents that the candidate set $j = 1,2,\cdots,n$ takes the minimum of the eigenvalues of target i; $\underset{j}{\vee} r_{ij}$ represents that the candidate set $j = 1,2,\cdots,n$ takes the maximum of the eigenvalues of target i.

Using formula (9), the eigenvalue matrix of the candidate set can be transformed into a relatively "good" membership matrix of the candidate set:

$$\mathbf{B}=\begin{bmatrix}B_{11} & \cdots & B_{1j} & \cdots & B_{1n}\\ \vdots & & \vdots & & \vdots\\ B_{i1} & \cdots & B_{ij} & \cdots & B_{in}\\ \vdots & & \vdots & & \vdots\\ B_{m1} & \cdots & B_{mj} & \cdots & B_{mn}\end{bmatrix}$$

According to the definition of "good" membership, for two successive level membership functions the relative maximum membership is $g_i = 1$ or $\boldsymbol{g} = (g_1, g_2, \cdots, g_m)^T = (1,1,\cdots,1)^T$; similarly, for the "poor" membership, the relative minimum membership is $g_i^{'} = 0$ or $\boldsymbol{g}^{'} = (g_1^{'}, g_2^{'}, \cdots, g_m^{'})^T = (0,0,\cdots,0)^T$, we can use D_{jg} to describe its difference from the "good" evaluation, and D_{jg} is defined as:

$$D_{jg}=u_j\sqrt[p]{\sum_{i=1}^{m}\left[\omega_i(g_i-r_{ij})\right]^p}.$$

D_{jb} is used to describe its difference from the "bad" evaluation, and D_{jb} is defined as:

$$D_{jb}=(1-u_j)g'_{jb}=(1-u_j)\sqrt[p]{\sum_{i=1}^{m}\left[\omega_i(r_{ij}-g'_i)\right]^p}$$

where: p is the distance parameter, ω_i is the weight of the optimal set,

$$u_j=\frac{1}{1+\left\{\dfrac{\sum_{i=1}^{m}\left[\omega_i(g_i-r_{ij})\right]^p}{\sum_{i=1}^{m}\left[\omega_i(r_{ij}-g'_i)\right]^p}\right\}^{\frac{2}{p}}}$$

The judgement score vector is defined as: $S = (s_1, s_2) =$

$(90{,}40)$; the score of fuzzy comprehensive evaluation is: $F_{ij} = (D_{jg}, D_{jb}) * S^T$. The elements in the candidate set were subjected to comprehensive fuzzy evaluation, and the final scores were ranked from high to low. The higher the ranking, the more suitable the location of fire stations in cities. Currently, there is 1 fire station in this city, and it plans to build 4 more fire stations. According to the ranking, the most suitable location is **A**, whose comprehensive evaluation score is $F_A = 82.12$; in addition, for the followed three more suitable candidate locations B, C and D, their comprehensive evaluation scores are $F_B = 80.32$, $F_C = 75.14$, and $F_D = 71.56$, respectively, as shown in Figure 5.

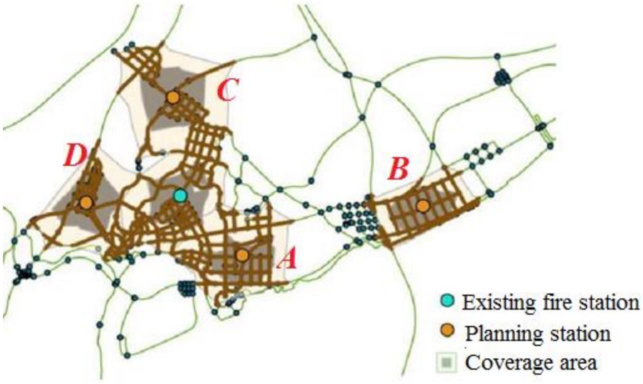

Figure 5. Comprehensive evaluation results

5. CONCLUSION

It has been concluded that there are many external factors affecting the site selection and layout planning of fire stations in the cities. To ensure the scientificity of fire station locations, factors such as the transit time of fire trucks, and scale cost of fire stations, social services, environment and climate should be taken into consideration comprehensively. This paper first identified potential fire station locations based on GIS, and then it introduced the preliminary knowledge about AHP and the fuzzy comprehensive evaluation approach. This paper regarded the site selection and layout planning of fire stations in a certain county as a multi-criterion decision-making process considering different influencing factors. In this way, four first-grade indices (transit time, scale cost, social service, and environmental geography) and nine second-grade indices were selected for the study area. After that, the fuzzy optimization was integrated into the AHP, and the suitability of candidate locations was comprehensively evaluated and scored to obtain the fire station layout that is most suitable for the study area. Follow-up studies in the future will focus on the numerical scale selection rules and optimization of this method so as to facilitate the modification of the proposed method and apply it to the site selection and layout planning of other municipal buildings.

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