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Analysis of fire rescue problems and fire station siting based on fitting algorithms

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Abstract: This paper provides an in-depth study of the fire rescue problem. Based on the number of calls to police at the site in previous years, monthly calls to police in 2022 were predicted through polynomial fitting, cubic spline interpolation, and a two-tone spline interpolation model to analyze and determine the best analytical model. The level of demand for fire stations at the site was measured by using the population density of the site and the number of emergencies per unit time, plus the distance to the nearest fire station at the site to measure its risk level, and finally the cost of building the fire station was considered to measure its composite index, and the site of the fire station was determined based on the composite index. And the grey prediction algorithm as well as the Topsis evaluation algorithm predicts the composite evaluation index for the next 9 years in order to determine where to build the fire station. This study will enable more efficient and uniform fire rescue and more rapid rescue operations to maximize the efficiency of rescue. The relevant data to reasonably predict the various types of emergencies that may occur in the future around the world is an important reference in the issue of fire station location.

Keywords: fire rescue, interpolation fitting, grey prediction algorithm, Topsis evaluation algorithm .

1. Background to the problem

With the rapid development of social and economic development, people's living standards are improving, and the urbanization rate is increasing year by year. However, with the development of urbanization, various safety hazards are also becoming more and more prominent, so fire rescue work becomes more and more important. At present, the frequent fire, earthquake, flood and other disasters in China have caused huge losses to the social and economic development of our country and seriously endangered the lives and property safety of the people. According to the United Nations World Fire Statistics Center. since the reform and opening up in 1979, there have been more than 5 million fires in China, causing 82,794 deaths, more than 10,000 injuries and economic losses of 52 billion yuan. Thus, fire hazards have had a catastrophic impact on China and the world. Raising fire awareness and promoting fire safety knowledge may require priority government investment. Once a fire breaks out, it develops rapidly and evacuation time is extremely short, resulting in considerable property damage and casualties.

Therefore, the state has placed higher demands on the emergency response capabilities of the fire rescue teams, especially for catastrophic accidents with property damage and a large scope of impact. Fire and rescue teams have a great responsibility, and they need to deal with a large number of safety incidents and draw lessons from them and keep a good record of their attendance.

In order to achieve an efficient, unified and responsive handling system and maximize rescue efficiency, the fire department has to compile statistics on the data of previous calls, including information on the time, location and type of incident, in order to better carry out future rescue work and also to provide a theoretical basis for the location of new fire stations. [1]

The geographical distribution of the 15 districts covered in this paper and the distances between the districts are shown in Figure 1.

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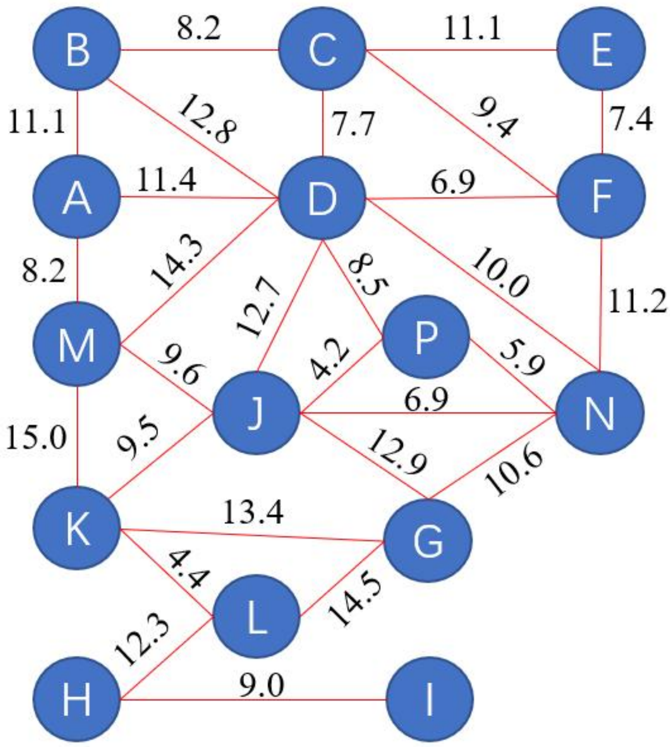

Figure 1 Map of adjacencies and distances between regions (distances in km in the figure)

2. Definition of symbols

PDi (population density) indicates the population density of region i.

RPNi indicates the risk factor for the entire system when the fire station is constructed at Si.

Si indicates the region where the event occurred, S1 indicates region A, S2 indicates region B, ..., and S15 indicates region P.

CEi (comprehensive evaluation) indicates the comprehensive evaluation metric for the entire system when the fire station is constructed at Si.

3. Basic Assumptions

(1) The cost of building a fire station in an area can be measured by the PD of the area.
(2) The size of the damage caused by the accident can be measured by the PD of the area.
(3) A maximum of one fire station may be built in an area.
(4) An incident in an area is the responsibility of only the fire station nearest to it.
(5) A fire station will be built every three years starting in 2020.

4. Analysis and forecast of police presence

Plot a picture of the number of alarms as a function of month based on data from 2016 to 2019. Use multiple models to predict the data for 2020 and compare it to the true value to find the one with the best fit. This function was then used to predict the number of police calls per month in 2022.

A three-dimensional scatter plot based on data from 2016 to 2019, with year and month as independent variables and number of police calls as dependent variables and observing the approximate changes. The plotted image is Figure 2 shown. From the graph, it can be seen that May 2016 has the highest number of police calls at 275, which is much greater than other months.

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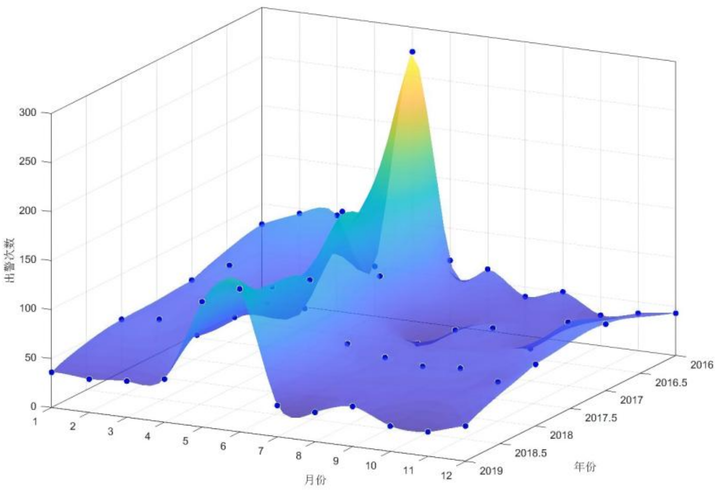

Figure 2 Images of the number of police calls as a function of year and month

Using these data, a polynomial fit, cubic spline interpolation, and a two-tone spline interpolation model were used to calculate the number of police calls for each month in 2020 and compare them to the true values.

The model constructed using a polynomial fit was first used and the results are shown in Figure 3. As can be seen in the figure the model is more evenly distributed and is unable to describe the more salient points such as the number of police calls in May 2016. The prediction of the number of police calls per month in 2020 using this model is thus

-22, -51, -23, 13, 30, 23, -1, -29, -44, -36, -3, 40

The goodness of fit is 0.6449. From the figure, we can see that the predictions of this model deviate greatly from the actual values and even show negative values. Therefore, we discarded this model .

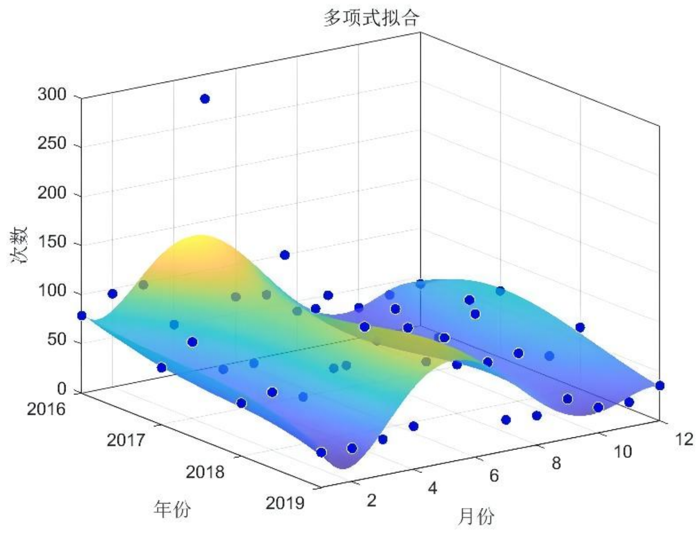

Figure 3 Polynomial fit constructed model

Secondly, the fit is performed using bi-tuning and spline interpolation, and the bi-tuning technique works similarly to the derivatives in two or multi-dimensional space as the derivatives in one-dimensional space. In the m-dimensional space of this paper, the surface solving problem using N data points is

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$$\Delta^4\omega(x) = \sum_{j=1}^{N} \alpha_j \delta(x - x_j)$$

$$\omega(x_j) = \omega_j$$

where Δ^4 is the biharmonic sum operator and x is a position in the m-dimensional space. In this problem m = 2 and N = 48. Its general solution is as follows.

$$\omega(x) = \sum_{j=1}^{N} \alpha_j \phi_m(x - x_j)$$

Solving for the linear system yields α_j

$$w_i = \sum_{j=1}^{N} \alpha_j \phi_m(x - x_j)$$

The following table gives the bimodal and Green's functions in one and two dimensions $\phi_m(x)$.

Table 1 Bi-tone and Green's functions in one and two dimensions

dimensionality	Green's function (math.)$\phi_m(x)$	The gradient of the Green's function$\Delta\ \phi_m(x)$
1	$\|x\|^3$	$x\|x\|$
2	$\|x\|^2(\ln\|x\| - 1)$	$2x(\ln x - 1)$

Figure 4 shows the data for 2016 to 2019 fitted with a two-tone and spline interpolation model. Due to the interpolation method used, the model predicted the data for 2016 to 2019 with 100% accuracy. In addition, the model's prediction for the number of police calls per month in 2020 is

23, 28, 36, 48, 57, 57, 47, 35, 28, 24, 23, 26

The goodness of fit is 0.8271, which is a good fit to reality, so the model is considered for use as a predictive model for the number of fire rescue calls.[2]

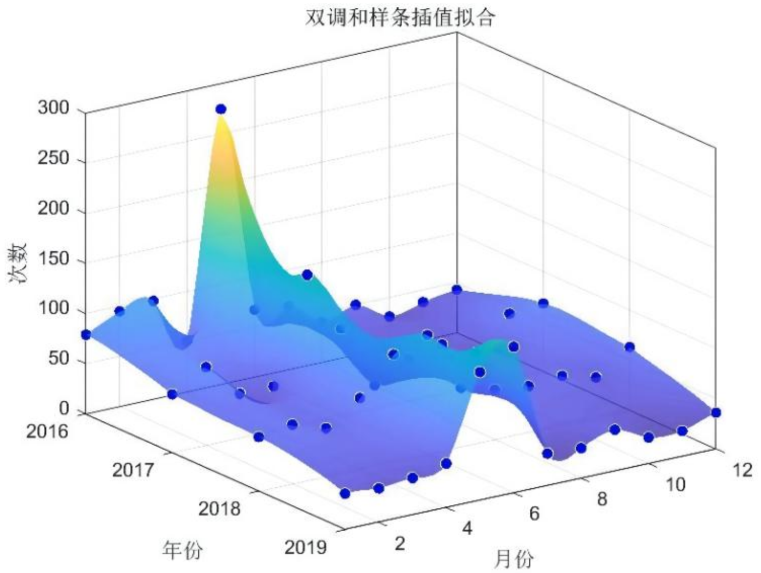

Figure 4 Two-tone and difference model fitting results

Figure 5 shows a comparison of the predicted as well as the true values of the monthly number of police calls from 2016 to 2019 made using the cubic spline interpolation method.[3] It can be seen that the model captures the more volatile data compared to the polynomial fit model. The predictions of the number of police calls per month for 2020 using this model are

24, 29, 45, 71, 111, 110, 68, 33, 28, 26, 30, 5

The goodness of fit is 0.7963. it can be seen that the predictions of this model are more reliable than those of the polynomial fit model, but the errors are still large.

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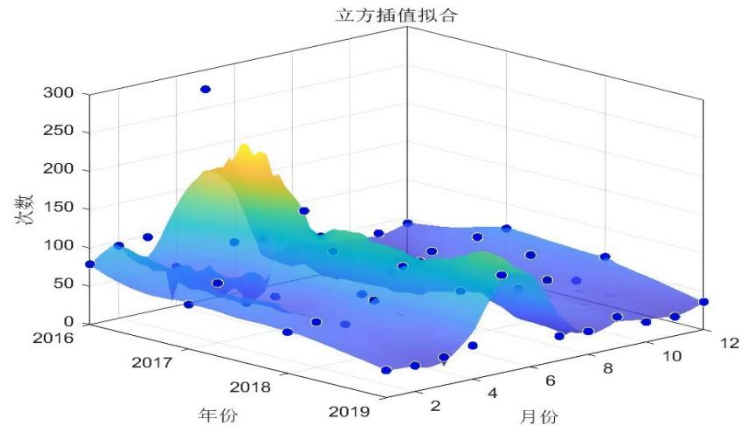

Figure 5 Results of the 4 cubic difference fitted model

In summary, the two-tone and spline interpolation method was used as the prediction model. The results of the prediction of the number of police calls from January to December 2020 using this model are as follows.

23, 28, 36, 48, 57, 57, 47, 35, 28, 24, 23, 26

The accuracy and stability analysis of the prediction results is done next. Accuracy: Using the squared loss function after eliminating the magnitudes.

$$l(Y, F(X)) = \frac{1}{2m}\sum_{i=1}^{m}\left(\frac{f(x_i) - y_i}{y_i}\right)^2$$

The calculated value is 0.0698, which is small and in good agreement with the actual and has a high accuracy.

The stability of the model is analyzed below, and we perform a sensitivity analysis. A schematic plot of the system variables year versus month versus the number of outgoing police events (Figure 6).

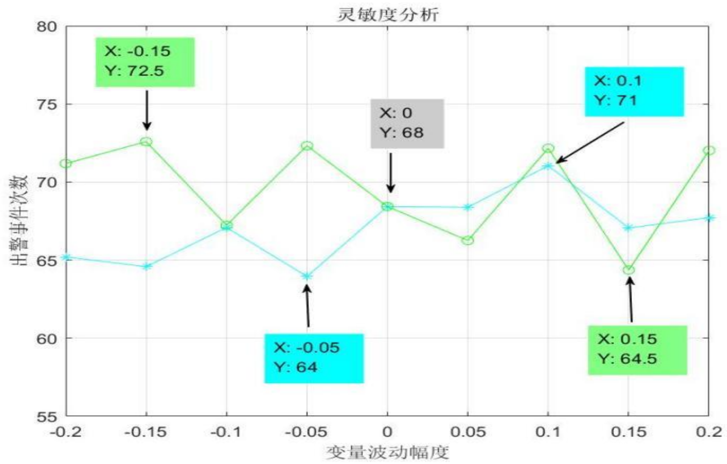

Figure 6 Schematic of system variables vs. number of outgoing alarm events

Using July 2020 as an example, the graph corresponds to the intersection of the green dash and the blue dash. The meaning of this point is that when the variable fluctuation amplitude is 0, the number of outgoing events is 68. The green dash indicates that the control year is constant, so that the month fluctuates up and down continuously by 20%, and the maximum fluctuation amplitude of the corresponding number of events can be observed to be about 6.618%, which is less than 10%; the blue dash indicates that the control month is constant, so that the year fluctuates up and down continuously by 20%, and the maximum fluctuation of the corresponding number of events can be observed to be amplitude is about 5.882%, which is also less than 10%. Similarly, the volatility of the number of events corresponding to a change in the year or month at the rest of the time points is

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also smaller. In summary, the degree of change in the model output after changing any one of the system parameters with uncertainty is small and therefore the sensitivity is low and the stability of the model is high.

In summary, the two-tone and spline interpolation model has good accuracy and stability, and the prediction results of the number of fire rescue calls for each month in 2022 have a high degree of confidence. The predicted results of the number of police calls for January to December 2022 using this model are shown in the following table.

Table 2 Projected results of the number of police trips in 2022

month	Projections (times)
January 2022	11
February 2022	15
March 2022	20
April 2022	24
May 2022	26
June 2022	27
July 2022	25
August 2022	23
September 2022	21
October 2022	20
November 2022	20
December 2022	21

5. Fire station siting analysis

The composite evaluation indicator CE was used to measure the "risk level" of the entire system. CE includes the population density of the area, the number of emergencies per unit time, the distance to the nearest fire station in the area, and the cost of building a fire station. A total of 15 areas from A to P were analyzed, of which two areas, J and N, had fire stations in place.

The shortest distance matrix for the 15 locations is first obtained by Dijkstra's algorithm.

The "risk factor RPNi " for the entire system when the fire station is built at Si is obtained from the regional population density and the number of emergencies per unit time. Considering the large differences in PDi and the number of emergencies per unit time in different regions, the data were smoothed using the logarithmic function. From the formula

$$y1 = e^{\log_{10} x}, y2 = e^{\log_{100} x}$$

The results after smoothing the PDi and the number of events per unit time can be obtained, as shown in Table 3.

The corresponding RPNi is obtained by weighting the smoothed data to the shortest distance.

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Table 3 Smoothed results for 2020 PDi and event counts

2020	Number of emergency incidents	Data smoothing results	PDi	Data smoothing results
A	22	3.828307046	0.0735744	0.567430709
B	16	3.333823964	0.0730142	0.566489726
C	15	3.241678525	0.0631489	0.54891202
D	18	3.508794408	0.0809533	0.57933017
E	32	4.504829206	0.0832505	0.582860982
F	17	3.422765744	0.0775029	0.573876523
G	43	5.121608017	0.0684071	0.558528624
H	18	3.508794408	0.065443	0.553181899
I	9	2.59670286	0.0620432	0.546810536
J	24	3.975741381	0.072973	0.566420298
K	25	4.046854888	0.0665591	0.555216984
L	13	3.046347562	0.0457977	0.511924479
M	17	3.422765744	0.0823613	0.581503433
N	7	2.328206061	0.0841751	0.58426059
P	157	8.988083572	1.6060606	1.108359467

Next, the CE is calculated using the Topsis algorithm, which proceeds as follows.

(1) Find the canonical decision matrix by vector normalization. Let the decision matrix A = (aij)m* n for the multi-attribute decision problem and the normalized decision matrix B = (bij)m* n.

$$b_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}}, i = 1,2,...,m; j = 1,2,...,n$$

where given A is a matrix of 2 rows and 15 columns, namely i=2 and j=15. where the first row is the RPNi when building fire stations in each area and the second row is the corresponding PDi (i.e., construction cost).

(2) Construct the weighted norm matrix C = (cij)m*n. The weight vector of each attribute is given by the decision maker as $\omega = [\omega_1, \omega_2, \omega_3, ..., \omega_n]^T$, then cij =wj *bij, i=1, 2..., m; j=1, 2..., n.

(3) Determine the positive ideal solution C* and the negative ideal solution C0. let the jth attribute value of the positive ideal solution C* be c_j^* , and the jth attribute value of the negative ideal solution C0 is C_{ij}^0 then.

$$\text{positive ideal solution} c_j^* = \begin{cases} \max\limits_i c_{ij}, & \text{j for benefit attribute} \\ \min\limits_i c_{ij}, & \text{j for cost attribute} \end{cases}, \quad j = 1,2,...,n$$

$$\text{negative ideal solution} c_j^0 = \begin{cases} \max\limits_i c_{ij}, & \text{j for benefit attribute} \\ \min\limits_i c_{ij}, & \text{j for cost attribute} \end{cases}, \quad j = 1,2,...,n$$

(4) Calculate the distance from the alternative to the positive ideal solution and the negative ideal solution. The distance of alternative di to the positive ideal solution is

$$s_i^* = \sqrt{\sum_{j=1}^{n} (c_{ij} - c_j^*)^2}, i = 1,2,...,m;$$

Alternative di The distance to the negative ideal solution is

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$$s_i^0 = \sqrt{\sum_{j=1}^{n} (c_{ij} - c_j^0)^2}, i = 1,2, \ldots, m。$$

(5) Calculate the value of the ranking indicator for pairs of options (i.e.: composite evaluation indicator), namely.

$$f_i^* = \frac{s_i^0}{s_i^0 + s_i^*}, i = 1,2, \ldots, m$$

(6) Rank the programs inf_i^* the order of merit of the options from largest to smallest.

The "composite evaluation indicators" obtained according to the Topsis evaluation algorithm are shown in the first column of Table 5. According to the principle of lowest CE, the fire station should be selected in the L area.

The next step is to predict the number of emergencies in each region for the next 9 years by using the grey prediction algorithm to determine which region the fire station should be built in. The steps of the grey prediction algorithm are as follows.

(1) Testing and processing of data

In order to ensure the feasibility of the GM(1, 1) modeling approach, the necessary test processing of the known data is required.

Let the original data series $x^{(0)} = (x^{(0)}(1), x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n))$, compute the series ratio of the series

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 2,3, \ldots, n$$

If all the level ratios fall within the tolerable coverage interval$X = (e^{\frac{-2}{n+1}}, e^{\frac{2}{n+1}})$ within the interval, then the data column$x^{(0)}$ can be modeled as GM(1,1) and gray predictions can be made. Otherwise, the data is transformed appropriately, such as a translation transformation, to take C so that the data columns $y^{(0)}(k) = x^{(0)}(k) + c, k = 1,2, \ldots, n$ of the data fall within the tolerable coverage.

(2) Building the GM(1,1) model

It is not advisable to set $x^{(0)} = (x^{(0)}(1), x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n))$ satisfy the above requirements and model GM(1,1) with it as data

$$x^{(0)}(k) + az^{(1)}(k) = b$$

The estimates of a,b were obtained using regression analysis, so the corresponding whitening model was

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b$$

solve

$$x^{(1)}(t) = \left(x^{(0)}(1) - \frac{b}{a}\right) e^{-a(t-1)} + \frac{b}{a}$$

Thus, the predicted value is obtained

$$\hat{x}^{(1)}(k+1) = (x^{(0)}(1) - \frac{b}{a})e^{-ak} + \frac{b}{a}, k = 1,2, \ldots, n-1$$

From this, the predicted values are obtained accordingly.

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k),\ k = 1,2, \ldots, n-1$$

(3) Testing the predicted values

①Residual test: calculate relative residuals

$$\epsilon(k) = \frac{x^{(0)}(k) - \hat{x}^0(k)}{x^{(0)}(k)}, k = 1,2, \ldots, n$$

If for all $|\epsilon(k)| < 0.1$ the higher requirements are considered to be met; otherwise, if for all $|\epsilon(k)| < 0.2$, then the general requirements are considered to be met.

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②Stage ratio deviation value test: Calculation

$$\rho(k) = 1 - \frac{1 - 0.5a}{1 + 0.5a}\lambda(k)$$

If for all the $|\rho(k)| < 0.1$, then the higher requirement is considered to be met; otherwise, if for all $|\rho(k)| < 0.2$, then the general requirements are considered to be met.

The number of incidents predicted by the above grayscale prediction algorithm for each region from 2021 to 2029 is shown in Table 4.

Table 4 Number of accidents predicted for each region from 2021 to 2029 based on grey time series prediction algorithm

	inaccuracies	2021	2022	2023	2024	2025	2026	2027	2028	2029
A	8.2527%	29	29	28	28	28	27	27	27	26
B	5.5202%	22	21	20	19	18	18	17	16	15
C	2.5%	8	16	16	16	16	16	16	16	8
D	8.9081%	23	20	18	16	15	13	12	11	9
E	6.4416%	31	26	23	19	17	14	12	11	19
F	4.6175%	16	13	17	9	7	13	5	4	11
G	3.8467%	47	52	57	63	70	48	86	75	40
H	4.5262%	23	24	13	27	28	22	31	33	19
I	4.9028%	12	11	9	8	7	6	5	5	4
J	4.3374%	25	23	22	20	18	17	20	15	23
K	8.2101%	28	25	22	20	18	16	14	16	18
L	6.7514%	20	21	21	21	21	22	22	22	22
M	11.803%	23	19	15	12	9	7	6	5	4
N	6.1594%	14	12	11	9	8	7	6	5	5
P	56.5176%	256	241	227	213	201	189	178	167	157

The data were smoothed in the same way and the "composite evaluation indicators" were derived at three-year intervals according to the Topsis evaluation algorithm, resulting in the data shown in Table 5.

Table 5 Fire station locations derived from Topsis evaluation algorithm and corresponding evaluation metrics

RPNi	One projection (2020 data)	2023	2026	2029
A	0.5536	0.5513	0.5457	0.549
B	0.5447	0.5403	0.5262	0.5677
C	0.5263	0.5248	0.5053	0
D	0.5376	0.5355	0.5144	0.574
E	0.5526	0.558	0.5482	0.5811
F	0.542	0.544	0.5277	0.5796
G	0.5715	0.5742	0.5832	0.5662
H	0.5252	0.5206	0.5554	0.5553
I	0.5284	0.5217	0.5528	0.5656
J	0	0	0	0
K	0.5444	0.5421	0.5914	0.5887
L	0.5162	0.5112	0	0
M	0.5724	0.5705	0.5702	0.5627
N	0	0	0	0
P	0.9623	0.9797	0.9521	0.8904
Fire station siting	L	L	C	A

In summary, according to the CEi minimum principle, fire stations should be built in 2023, 2026 and 2029 in areas L,C, A respectively.

6. Conclusion

Three prediction models for the number of fire rescue calls were developed based on data from 2016 to 2019 for the site, in terms of months. Among them, the two-tone and interpolation model predicted the 2020 data better and had high correlation, so the two-tone and difference model was used as the prediction model for the number of fire rescue calls. This model predicts the number of calls from January to December 2021 in the order of 11, 15, 20, 24, 26, 27, 25, 23, 21, 20, 20, 21. In determining where to build the fire station, the "comprehensive evaluation index" is used to measure the overall system performance when building the fire station at that location. RPNi, where the composite evaluation indicator includes PDi and the weighted sum of the number of emergencies per unit time and its distance to the shortest fire station, is used to calculate by the Topsis algorithm that the fire station should be built in area L. If a new fire station is built every 3 years from 2020-2029, it should be built in region L,C,A in that order. By predicting the number of fire station calls in 2021 and the study of the fire station siting problem, this thesis is important for the improvement of fire rescue efficiency in real life. The results obtained from the prediction can effectively enable the firefighting authorities to avoid some low-level mistakes, and at the same time enable the firefighting staff to have a pre-awareness and precautions for better and faster police attendance. Simulation of siting issues, combined with the actual situation, can maximize the use of limited land resources to achieve the best rescue benefits, so that all areas are best located within the effective protection. This is the best guarantee to improve the safety of people's lives and is also the key to the smooth development of society.

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