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Optimization Research on Fire Rescue based on Time Series Analysis

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Abstract

With the rapid development of Chinese economy, the complexity of urban space environment is rising sharply, various accidents and disasters occur frequently, and safety risks are increasing, so the fire rescue work is urgent. Based on the data of question B of the 18th May Day Mathematical Contest in Modeling in 2021, this research comprehensively uses the simple moving average method, weight assignment and other methods; builds an integer linear programming model for the arrangement of duty personnel, a time series model for predicting the number of fire rescue calls, and a multiple regression model for the number of occurrences of various events. This provides a feasible plan for the fire rescue work.

Keywords

Fire Rescue; Linear Programming; Time Series; CFTOOL; Toolbox; Data Analysis.

1. Introduction

In the 14th Five-Year Plan, the CENTRAL Committee of the Communist Party of China (CPC) explicitly calls for "balancing development and security to build a safer China of a higher level". On September 11, 2020, General Secretary Xi Jinping emphasized at a symposium of scientists that my country's economic and social development and people's livelihood improvement require scientific and technological solutions more than ever before [1]. With the rapid development of my country's economy, the complexity of the urban space environment has risen sharply, various accidents and disasters have occurred frequently, and safety risks have continued to increase. Fire rescue is urgent.

In recent years, the issue of fire rescue has received widespread attention from the society, and some scholars have also carried out corresponding research in a timely manner. Jiang [2] designed a GIS spatial data structure based on urban fire protection according to the characteristics of MapInfo, used object-oriented technology and MAPX components, combined with open data interface and GPS satellite positioning technology and map matching technology, finally realized the functions of zoom-in, zoom-out, roaming, graphic element flashing and eagle-eye diagram display of the electronic map, as well as the optimal path analysis and buffer analysis for fire rescue. Yin [3] carried out the development and formation of the dual main body of Chinese fire forces in emergency rescue, discussed the characteristics of fire forces as national armed forces and national public security organs in emergency rescue respectively, thus, expounded the rights, obligations and legal responsibilities of the two main identities in emergency rescue respectively, to reflect the characteristics of their dual main status, and found the unity of the two main status in emergency rescue. Chen [4] studied the path optimization of the rescue plan in the underground shopping mall under the condition of emergency, drew the conclusion that the best straight-line distance between the evacuation door and the nearest safety exit is 20 to 30 meters, and classified the obstacles according to the moving state for the first time; through studying the theoretical formula, got the speed of flame spreading and the safe distance between pedestrians and the flame spreading area, which has guiding significance for personnel rescue.

It is not difficult to find that the existing research mainly focuses on the technology used in fire rescue, and lacks quantitative analysis and corresponding empirical analysis of fire rescue, which provides further research space for this project.

2. Data Sources and Assumptions

The data in this article comes from question B of the 18th May Day Mathematical Contest in Modeling in 2021. In order to facilitate the problem research, the following assumptions are put forward:

(i) The fire brigade duty personnel can be on duty for up to 24 hours a day.

(ii) In each fire rescue, the number of fire brigade staff is fixed at 5 people.

(iii) Each fire rescue is completed within the specified time period and will not affect the next duty.

(iv) When a fire alarm is received, the fire brigade will go to the fire. The number of fire alarms received is equal to the number of fires fought by the fire brigade.

3. Analysis of Duty Personnel Arrangement based on Linear Programming Model

3.1. Research Ideas

Divide the day into three time periods, and the number of people on duty in each time period is not less than 5. The fire brigade has 30 people on duty every day, and we want to determine the number of people on duty that should be scheduled for the first day of February, May, August, and November each year. Firstly, the data was extracted by EXCEL and analyzed by pre-processing method. Secondly, the maximum method was used to select the data and establish the integer linear programming model. Finally, through LINGO software programming, we get the number of on-duty workers on February 1, May 1, August 1 and November 1 every year.

3.2. Research Methods

3.2.1. Data Preprocessing

Table 1. The number of fire alarm calls in different time periods.

Year		2016	2017	2018	2019	2020
Feb 1	Ⅰ	0	0	0	0	0
	Ⅱ	4	1	1	1	1
	Ⅲ	1	0	1	2	3
May 1	Ⅰ	1	0	0	1	0
	Ⅱ	5	0	0	2	0
	Ⅲ	5	1	1	0	1
Aug 1	Ⅰ	0	1	0	0	0
	Ⅱ	0	1	1	0	1
	Ⅲ	0	1	1	0	2
Dec 1	Ⅰ	0	0	0	0	0
	Ⅱ	0	1	1	1	1
	Ⅲ	0	1	0	1	0

Note: “Ⅰ” refers to the time period 0:00-8:00; “Ⅱ” refers to the time period 8:00-16:00; “Ⅲ” refers to the time period 16:00-24:00.

According to the data given in Annex 2, the data from February 1, May 1, August 1 and November 1 from 2016 to 2020 are extracted and sorted out, and each day is divided into three time periods. The number of firefighter receiving alarm in different time periods is shown in Table 1.

3.2.2. Establish Linear Programming Model

The establishment of linear programming mathematical model is to find out the optimal solution under certain constraints and objective functions [5]. In this analysis, the constraints are that the number of people on duty is at least 5 in three time periods per day, and only 30 firefighters can be assigned to be on duty each day. In order to ensure the timeliness of firefighters calling out to the police, we select the maximum number of alarm reception times corresponding to each alarm time period as the number of alarm calls in this time period on that day of the month. Accordingly, the following integer linear programming model is established:

$$\begin{cases} \min (z) = x_1 + x_2 + x_3 \\ x_1 \gg 5a \\ x_2 \gg 5b \\ x_3 \gg 5c \\ 5 \ll x_1, x_2, x_3, \leq 30 \end{cases}$$

where min (z) is the number of people on duty in a certain time period. x_1, x_2, x_3 respectively represent the number of people on duty in three time periods in a certain day; a represents the number of fire alarms received in the first time period; b represents the number of fire alarms received in the second time period; c represents the number of fire alarms received in the third time period.

3.3. Result Analysis

When the number of alarm receptions in a certain time period is 0, in order to meet the condition that the number of people on duty in each time period is not less than 5, we stipulate that in this case, a, b and c are taken as 1 respectively.

It can be seen from the data in Table 1 that the values of a, b, and c in the three time periods on February 1 each year are 1, 4, and 3, respectively. Using the LINGO software to bring the data into the model, we get a value of 5 for a, 20 for b, and 15 for c. This means that in the three time periods of the day on February 1, the maximum number of fire alarms received in the first time period (0:00-8:00) is 1, and 5 people should be arranged on duty; the maximum number of fire alarms received in the second time period (8:00-16:00) is 4, and 20 people should be arranged on duty; the maximum number of fire alarms received in the third time period (16:00-24:00) is 3, and 15 people should be arranged on duty.

Similarly, the maximum number of fire alarms received in each time period on May 1 each year is 1, 5, and 5, respectively. Using the LINGO software, we can obtain that the number of people on duty corresponding to each time period should be 5, 25, and 25. The maximum number of fire alarms received in each time period on August 1 each year is 1, 1, and 2, respectively. Using the LINGO software, we can obtain that the number of people on duty corresponding to each time period should be 5, 5, and 10. The maximum number of fire alarms received in each time period on December 1 each year is 1, 1, and 1, respectively. Using the LINGO software, we can obtain that the number of people on duty corresponding to each time period should be 5, 5, and 5.

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4. Prediction of the Number of Fire Brigade Rescues based on Time Series

4.1. Research Ideas

Sort out and analyze the known data, and establish the prediction model of fire rescue alarm times based on time series. Use MATLAB software to solve the model, and evaluate the model by substituting PSI index with relevant data, finally, forecast the number of fire rescue calls for each month in 2021.

4.2. Research Methods

4.2.1. Data Preprocessing and Visualization

Using the data of the four years of 2016 and 2019 and processing them by month, we obtain the data on the number of fires handled by the fire brigade every month from 2016 to 2019. They are shown in Table 2.

Table 2. Statistics on fire rescue times from 2016 to 2019 on a monthly basis.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Times(2016)	79	95	98	51	275	67	63	40	50	31	38	43
Times (2017)	58	28	44	14	148	87	23	42	49	33	65	68
Times (2018)	54	129	68	71	107	119	59	50	46	44	40	63
Times(2019)	67	76	73	44	138	146	72	30	41	26	25	36

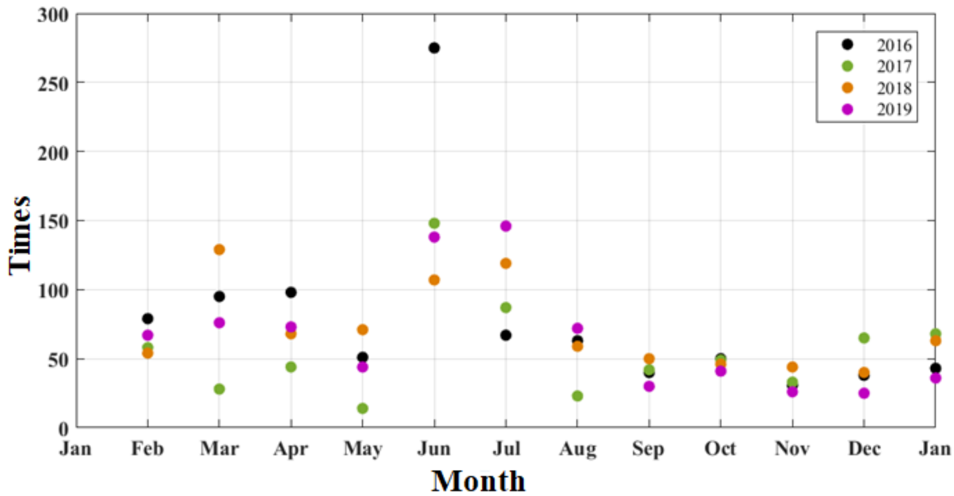

Figure 1. Distribution of fire rescue times from 2016 to 2019 on a monthly basis.

The data in Table 2 is visualized, and the distribution map of the number of police calls in each month from 2016 to 2019 is shown in Figure 1.

It can be seen from Figure 1 that the number of police calls in May 2016 is significantly different from other data, which is regarded as an outlier and corrected. After the data is corrected, the number of police calls in May 2016 is 134. Firefighters responded most frequently during the spring and summer seasons of the year, with relatively little fluctuation in other months.

4.2.2. Establish a Time Series Model to Study the Number of Fire Brigade Rescues

The moving average method is used to calculate the time series average of a certain number of terms over time series, which is usually used to reflect the long-term trend of the development of things. When periodic and irregular changes affect the value of time series and the fluctuation is large and it is difficult to show the development trend, the influence of these factors can be eliminated by moving average method, so as to achieve the purpose of analyzing and predicting the long-term trend of the series. One of the most commonly used moving average methods is simple moving average method [6]. The following is the calculation formula of simple moving average method.

Assuming that the observation series is $y_1, y_2, \ldots, y_T$, the number of terms in the moving average is $N < T$. The calculation formula of a simple moving average is as follows:

$$M_t^{(1)} = \frac{1}{N}(y_t + y_{t-1} + \cdots + y_{t-N+1})$$
$$= \frac{1}{N}(y_{t-1} + \cdots + y_{t-N}) + \frac{1}{N}(y_t - y_{t-N}) = M_{t-1}^{(1)} + \frac{1}{N}(y_t - y_{t-N}).$$

When the basic trend of the forecast target fluctuates up and down at a certain level, a simple moving average method can be used to establish a forecast model:

$$\hat{y}_{t+1} = M_t^{(1)} = \frac{1}{N}(y_t + y_{t-1} + \cdots + y_{t-N+1}), t = N, N+1, \cdots, T.$$

The standard error of its prediction is:

$$S = \sqrt{\frac{\sum_{t=N+1}^{T}(\hat{y}_t - y_t)^2}{T-N}}.$$

The average value of the series values of the most recent N periods is used as the forecast result of each future period. Generally, the value range of N is: $5 \leq N \leq 200$. When the basic trend of the historical sequence does not change much and there are many random components in the sequence, the value of N is bigger, otherwise the value of N is smaller. In the data with a definite seasonal variation period, the number of items of the moving average is taken as the period length. An effective way to choose the best N value is to compare the prediction errors of several models, and the one with the smallest prediction error gets the best N value.

4.3. Result Analysis

Assuming that the date is t, the number of alarms is y_t, take the prediction formula of $N = 4$, we get

$$\hat{y}_{t+1}^{(1)} = \frac{(y_t + y_{t-1} + y_{t-2} + y_{t-3})}{4}, t = 4.$$

The monthly fire rescue data from 2016 to 2019 was programmed with MATLAB software and substituted into the model to obtain the predicted number of police calls per month in 2020. Compare the predicted results with the actual data in 2020, as shown in Table 3.

Table 3. Comparison of actual fire rescue data and forecast data in 2020.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Actual times	57	49.5	53	45	100	100.5	48.5	29.5	38.5	25.5	42	57
Predicted times	28	23	28	46	62	55	25	29	36	25	51	62

Check the accuracy and stability of the model. When $N = 4$, the average standard error of prediction is:

$$\overline{S} = \frac{1}{12}\sum_{i=1}^{12}\sqrt{\frac{\sum_{t=3}^{4}(\hat{y}_t^{(1)} - y_t)^2}{4-3}} = 29.3,$$

because the standard error value is small, indicating that the model is more accurate. An intuitive comparison of the predicted data and the actual data is shown in Figure 2. From the comparison chart, we can see that our predicted data curve fits the actual data curve very well.

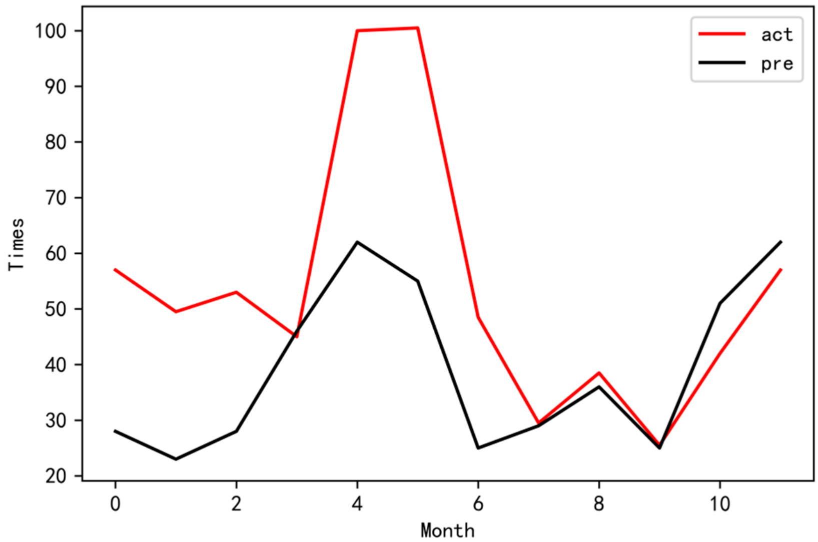

Figure 2. Comparison chart of actual fire rescue data and forecast data in 2020.

In practice, the PSI index is commonly used to measure the stability of the model. The PSI index refers to the Population Stability Index. PSI reflects the stability of the distribution of different samples in each fractional segment. The formula is:

$$\text{PSI} = \text{sum}(\text{actual proportion} - \text{expected proportion}) \times \ln(\text{actual proportion} \div \text{expected proportion})$$

the calculated PSI value is 0.25. That means that the stability of the model is within the reliable range.

As the stability and accuracy of the established model are within the reliable range, the model is used to predict the number of fire brigade rescues in each month of 2021, and the prediction results are shown in Table 4.

Table 4. Forecast of the number of fire brigade rescues every month in 2021.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Predicted times	33	30	24	44	70	87	28	19	32	16	45	49

5. Analysis of Occurrence Times of Various Fire Events based on CFTOOL Toolbox

5.1. Research Ideas

Divide the emergency incidents that the fire brigade needs to deal with into 7 categories, namely ①, ②, ..., ⑦. According to the occurrence time of 7 types of events, explore the relationship between the number of occurrences of various events and the month. First, preprocess the data, organize the data into the number of occurrences of various events per month. Then, use the CFTOOL toolbox of MATLAB to fit the curve, and use the linear fitting, rational, sum of sine three methods to establish the mathematical model. Finally, use the fitting degree as the evaluation standard to determine the optimal model of the occurrence times of each type of events.

5.2. Research Methods and Result Analysis

Taking event ① as an example, sort the data from 2016 to 2020 by month, and the average is obtained to obtain the data of the number of occurrences and the month of the event, as shown in Table 5.

Table 5. Average number of occurrences of event ① per month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Times	10.6	9.2	7.4	5.8	8.8	8.6	5	3.4	4.2	2.8	6.4	9.6

Firstly, through linear fitting of MATLAB's CFTOOL toolbox, establish a linear model:

$$f(x) = a \times \left(sin(x - p_i)\right) + b(x - 10)^2 + c.$$

Under the condition of 95% confidence interval, the coefficient a = 1.133 (-0.8379, 3.103), b = 0.07271 (0.01861, 0.1268), c = 5.084 (3.186, 6.909), and the goodness of fit $R^2_{(1)}$ is 0.5073. The fitted image is shown in Figure 3.

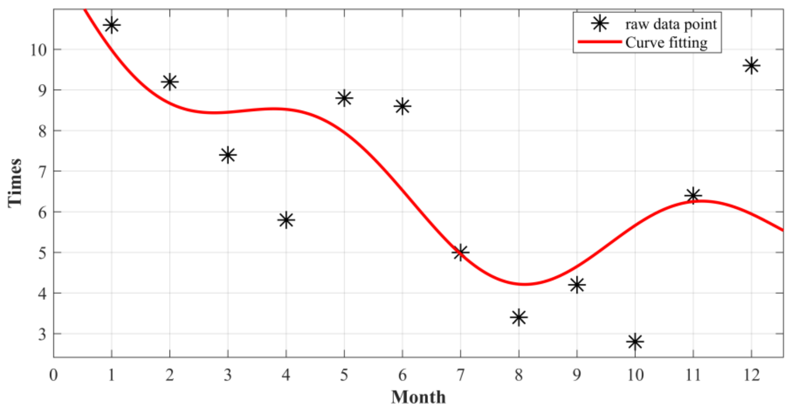

Figure 3. Linear model curve fitting diagram of event ①.

Next, through the rational in MATLAB's CFTOOL toolbox, build a general Rat 43 model:

$$f(x) = (p_1 \times x^4 + p_2 \times x^3 + p_3 \times x^2 + p_4 \times x)/(x^3 + q_1 \times x^2 + q_2 \times x^3 + q_3).$$

With a 95% confidence interval, p_1 = 1637 (-2.825e+06, 2.828e+06), p_2 = 4.072e+04 (-7.039e+07, 7.03e+07), p_3 = 3.853e+05 (-6.653e+08, 6.66e+08), p_4 = -1.647e+06 (-2.847e+09, 2.844e+09), p_5 = 2.797e+06 (-4.83e+09, 4.835e+09), q_1 = 5453 (-9.443e+06, 9.454e+06), q_2 = -6.235e+04 (-1.079e+08, 1.078e+08), q_3 = 1.902e+05 (-3.286e+08, 3.289e+08). The goodness of fit $R^2_{(2)}$ is 0.9228.

Then, through sum of sine in MATLAB's CFTOOL toolbox, we established a general Sin 4 model:

$$f(x) = a_1 \times sin(b_1 \times x + c_1) + a_2 \times sin(b_2 \times x + c_2) + \cdots a_4 \times sin(b_4 \times x + c_4).$$

With a 95% confidence interval, a_1 =19.76, b_1 = 0.3394, c_1 = -0.1591, a_2 = 60.47, b_2 = 0.6098, c_2 = 1.273, a_3 =49.21, b_3 =0.6687, c_3 =4.061, a_4 =1.387, b_4 =1.974, c_4 = -3.215. The goodness of fit $R^2_{(3)}$ is 0.9951.

Finally, since the $R^2_{(3)}$ of third model is the largest among the three models constructed, we choose this model as the optimal model for the occurrence of event ①. The rest of the events can be done in this way, too.

6. Conclusion

Based on LINGO, EXCEL and other software, this paper selects the data of question B of the 18th May Day Mathematical Contest in Modeling in 2021 as the research data. According to the common problems and data characteristics in fire rescue, the research content is divided into three parts: one is to study how to arrange personnel on duty, and the other is to study the regularity of the number of fire rescue calls, the third is to study the relationship between the number of fire incidents and the month.

Aiming at the problem of on-duty personnel arrangement, we established a linear programming model, screened out the number of fire alarm calls that could represent each research period by the maximum method, and put them into the model. It comes to the conclusion that the number of people on duty in the three periods on February 1 is 5, 20 and 15 respectively; the number of people on duty in the three periods on May 1 is 5, 25, 25; the number of people on duty for the three periods of August 1 is 5, 5, 10; the number of people on duty on November 1 is 5, 5, 5.

According to the rule of fire rescue times, remove the outliers, use the data from 2016 to 2019 to establish a time series model, and use the data from 2020 to verify the model. It gets that the accuracy and stability of the model are good. We predict that the times of fire rescue for each month in 2021 is 33, 30, 24, 44, 70, 87, 28, 19, 32, 16, 45 and 49 respectively.

For the relationship between the number of fire incidents and the month, use MATLAB's CFTOOL toolbox to fit the preprocessed data. We first use linear fitting, rational, and sum of sine three methods to establish mathematical models, then use the degree of fit as the criterion for evaluating the model, finally select the model with the largest value of the degree of fit as the optimal model for the occurrence of each type of event.

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