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A FIRE STATION LAYOUT OPTIMIZATION MODEL BASED ON SIMULATED ANNEALING

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Abstract: Fires pose a serious threat to life and property. A rational layout of fire stations is crucial for enhancing the fire - fighting emergency response capacity. This paper comprehensively applies the TOPSIS comprehensive evaluation model, the non - integer rank - sum ratio (RSR) model, the simulated annealing algorithm (SA), and the analytic hierarchy process (AHP) to study the optimization of urban fire station layouts. By using the first two models combined with the entropy weight method to evaluate the existing layout, problems such as insufficient coverage and long response times were identified. The SA was used to optimize the layout, which reduced the average response time by 4.7 minutes and balanced the jurisdiction scope. The AHP was used to clarify that factors such as fire risk levels are key factors affecting the layout. However, the simulated annealing algorithm has limitations such as slow convergence. Future research can introduce adaptive simulated annealing algorithms and strengthen the study of dynamic factors for improvement. This research provides a scientific basis and a feasible solution for the optimization of urban fire station layouts.
Keywords: Layout Optimization; TOPSIS; NIRSR model; SA algorithm; AHP

1 INTRODUCTION

Fires have always been a major threat to human life and property. In recent years, the fire situation in China has been severe, with approximately 100,000 fires occurring each year, causing huge losses to the country and the people [1]. The ability of firefighters to quickly reach the scene when a fire breaks out plays a decisive role in controlling the fire and reducing casualties, which largely depends on the rational layout of fire stations. A reasonable fire station layout can not only shorten the fire - fighting response time but also improve the utilization efficiency of fire - fighting resources and minimize fire losses. However, currently, urban fire station layouts generally suffer from problems such as irrational planning and unbalanced coverage, which seriously affect the fire - fighting emergency response capacity. Therefore, optimizing the fire station layout has become an urgent issue to be addressed.

In the field of urban fire station layout optimization, many scholars have conducted in - depth research and achieved a series of results. Wang Yarong et al.[2] used cluster analysis and genetic algorithms to optimize the location of fire stations. By dividing urban areas into different clusters and combining the global search ability of genetic algorithms, they found the best locations for fire stations, effectively improving the coverage efficiency of fire - fighting resources. Yao Yongfeng et al. [3] optimized the fire station layout based on the geographic information system (GIS) and multi - objective planning model, comprehensively considering factors such as population distribution, road networks, and fire risks. This not only improved the response speed but also reduced construction and operation costs. These studies have provided important theoretical and practical experience for urban fire station layout optimization[4-5]. However, existing research mostly focuses on the analysis of single or a few factors when considering the factors affecting the fire station layout, lacking a systematic and comprehensive consideration of multiple factors. At the same time, in the selection of optimization algorithms, some algorithms have problems such as slow convergence and being prone to getting trapped in local optima, which limit the effect of layout optimization[6].

In summary, this paper aims to comprehensively consider multiple factors, use the analytic hierarchy process (AHP) to assign weights to each factor, and construct a more scientific and reasonable fire station layout optimization model. At the same time, the simulated annealing algorithm (SA) is used to optimize the layout to overcome the limitations of traditional algorithms and improve the quality of layout optimization. This paper will evaluate the existing and optimized layouts through the TOPSIS comprehensive evaluation model and the non - integer rank - sum ratio (RSR) model, conduct a comparative analysis of their rationality, and provide more targeted and practical solutions for urban fire station layout optimization, thereby effectively enhancing the urban fire - fighting emergency response capacity and ensuring the safety of people's lives and property [7,8].

2 OPTIMIZATION AND ANALYSIS OF FIRE STATION LAYOUT BASED ON MULTIPLE MODELS

2.1 Construction of the Rationality Evaluation Model for the Existing Layout and Model Solution

In the research on urban fire station layout optimization, the TOPSIS comprehensive evaluation model can integrate multi - index information and evaluate the advantages and disadvantages of objects by comparing them with the ideal solution; the non - integer rank - sum ratio (RSR) model has a wide range of applications and strong anti - interference ability, which can stably and reliably handle various types of data; the simulated annealing algorithm (SA) can jump out of local optimal solutions and effectively solve large - scale combinatorial optimization problems; the analytic hierarchy process (AHP) can systematically analyze multiple factors, combine qualitative and quantitative factors, accurately determine the weights of factors, and provide quantitative basis for decision - making. First, in the TOPSIS - based multi - index evaluation model, the entropy weight method is used to obtain the weights of the number and distance of jurisdiction nodes and the average monthly number of cases, as shown in Table 1.

Table 1 Weights of Each Index Before Optimization Obtained by the Entropy Weight Method

Index	Number and Distance of Jurisdiction Nodes	Average Monthly Number of Cases
Weight	0.41249763	0.58750237

According to the TOPSIS - based multi - index evaluation model, the ranking results of fire stations according to the number and distance of jurisdiction nodes and the average monthly number of cases are shown in Table 2.

Table 2 Ranking under the TOPSIS Model

Fire Station Number	Score of Number and Distance of Jurisdiction Nodes	Rank of Number and Distance of Jurisdiction Nodes	Score of Average Monthly Number of Cases	Rank of Average Monthly Number of Cases
1	0.000	4	0.000	4
2	1.000	1	1.000	1
3	0.489	3	0.240	3
4	0.527	2	0.557	2

According to the RSR evaluation model, the ranking results of fire stations according to the number and distance of jurisdiction nodes and the average monthly number of cases are shown in Table 3.

Table 3 Ranking under the RSR Model

Fire Station Number	Score of Number and Distance of Jurisdiction Nodes	Rank of Number and Distance of Jurisdiction Nodes	Score of Average Monthly Number of Cases	Rank of Average Monthly Number of Cases
1	0.250	4	0.250	4
2	1.000	1	1.000	1
3	0.725	2	0.500	3
4	0.525	3	0.750	2

Combining the above two tables, it can be found that the scores and rankings of fire stations based on the number and distance of jurisdiction nodes are different under the two models, further indicating the irrationality of the fire station layout in City A.
Therefore, the simulated annealing algorithm (SA) model is used to optimize the fire station layout in City A.
First, the entropy values and weights of each index are obtained by the entropy weight method, as shown in Table 4.

Table 4 Entropy Values and Weights of Each Index in the TOPSIS Multi - Index Evaluation Model

Evaluation Index	Entropy Value	Weight
Total Distance	-1908782000000	0.528883
Average Monthly Number of Cases	-1700302000000	0.471117

After optimizing with the simulated annealing algorithm (SA) model, the jurisdiction scope of each fire station under the new layout is shown in Table 5, and the jurisdiction scope diagram is drawn as shown in Figure 1.

Table 5 Jurisdiction Scope of Each Fire Station in City A after Optimization

Node Number	Fire Station Number	Required Time/min	Distance/hm	Node Number	Fire Station Number	Required Time/min	Distance/hm
1	22	3.27	32.70	47	30	1.73	17.27
2	30	0.58	5.83	48	30	0.71	7.07
3	67	2.26	22.64	49	30	3.68	36.83
...	...	...	...	...	...	...	...
44	67	1.48	14.76	90	76	5.09	50.85

45	30	4.59	45.87	91	76	5.56	55.60
46	30	3.99	39.91	92	76	7.56	75.62

Note: Time and distance are uniformly rounded to two decimal places

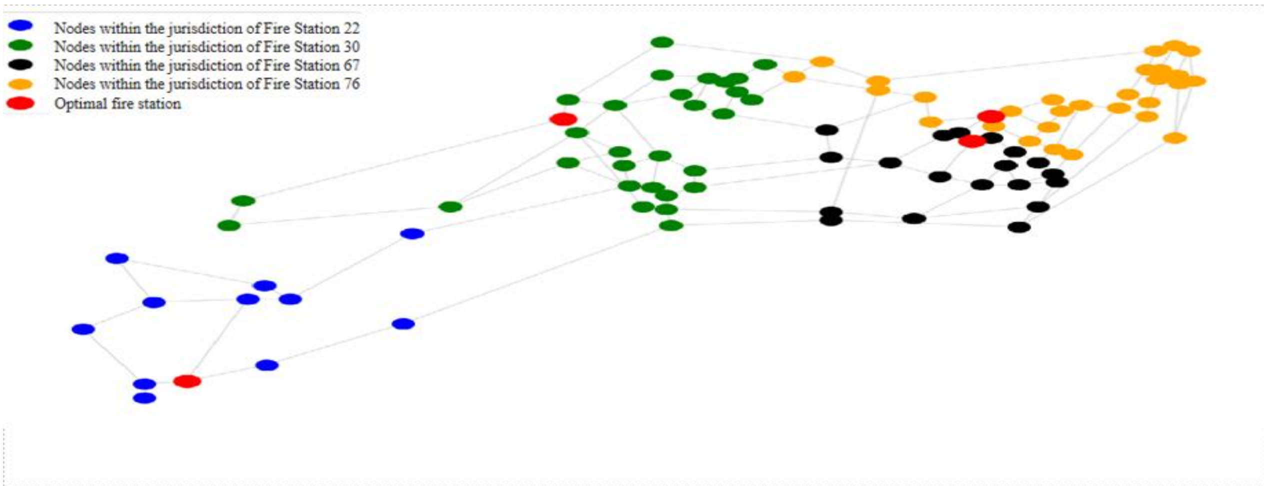

Figure 1 Layout and Jurisdiction Scope of Each Fire Station after Optimization

Analyzing Table 5 shows that after the fire station layout is optimized, firefighters can reach all nodes except Node 28 within 8 minutes after the fire occurs, which meets the time requirements of the fire station layout. At the same time, the number of nodes, distance, time, and case - occurrence frequency within the jurisdiction scope of each fire station after optimization are summarized as shown in Table 6. The number of jurisdiction nodes of Fire Stations 22, 30, 67, and 76 is (12, 30, 20, 30) respectively, and the jurisdiction scope distribution and fire - fighting resource allocation are more balanced than before optimization.

Table 6 Jurisdiction Scope, Distance, Time, and Case - Occurrence Frequency of Each Fire Station after Optimization

Fire Station Number	Number of Jurisdiction Nodes	Total Distance/hm	Total Time/min	Average Monthly Total Number of Cases
22	12	445.0862213	44.50862213	21.2
30	30	1114.030147	111.4030147	43.6
67	20	543.7649218	54.37649218	25.7
76	30	1050.610701	105.0610701	34

According to the TOPSIS -based multi-index evaluation model, the ranking results of fire stations after optimization according to the number and distance of jurisdiction nodes and the average monthly number of cases are shown in Table 7.

Table 7 Ranking of the Optimized Layout under the TOPSIS Model

Fire Station Number	Score of Number and Distance of Jurisdiction Nodes	Rank of Number and Distance of Jurisdiction Nodes	Score of Average Monthly Number of Cases	Rank of Average Monthly Number of Cases
22	0.000000	4	0.000000	4
30	1.000000	1	1.000000	1
67	0.270593	3	0.200893	3
76	0.923881	2	0.571429	2

According to the RSR evaluation model, the ranking results of fire stations after optimization according to the number and distance of jurisdiction nodes and the average monthly number of cases are shown in Table 8.

Table 8 Ranking of the Optimized Layout under the RSR Model

Fire Station Number	Score of Number and Distance of Jurisdiction Nodes	Rank of Number and Distance of Jurisdiction Nodes	Score of Average Monthly Number of Cases	Rank of Average Monthly Number of Cases
22	0.250	4	0.250	4
30	0.950	1	1.000	1

67	0.500	3	0.500	3
76	0.800	2	0.750	2

Combining the above two tables, it can be found that the rankings of fire stations based on the number and distance of jurisdiction nodes and the average monthly number of cases are the same under the two models, indicating that the optimized layout is more reasonable than the original layout.

2.2 Analysis of the Influencing Factors of Fire Station Layout Based on the Analytic Hierarchy Process

2.2.1 Construction of the evaluation index system

For the location selection of fire stations, each location selection plan of fire stations is regarded as a decision - making unit. Through investigations of fire protection planning and fire station construction, based on the "Regulations on the Construction and Management of Urban Fire Protection Planning" and the "Construction Standards for Urban Fire Stations", and combined with the influencing factors of fire station location selection, a fire station location selection evaluation index system is established (as shown in Table 9). It should be noted that the system is divided into two categories of qualitative and quantitative indicators as secondary indicators. The tertiary indicators are 5 indicators including the aforementioned hot - spot factors, which reflect the advantages and disadvantages of fire station location selection from aspects such as hot - spot factors, society, geographical environment, rescue time, and fire - fighting economic construction. The fire risk level within the jurisdiction can reflect the importance of the fire station. The higher the risk, the more important the fire station is, the more meaningful the location selection is, and the higher the score will be. The accident hot - spot and time situation can reflect the frequency and time of fire accidents within the jurisdiction of the fire station. This indicator is related to road factors and the impact on residents, but these two indicators do not overlap. The overall goal of constructing this index system is to determine the main factors affecting the fire station layout to ensure that the fire station layout can effectively respond to fires in the shortest possible time.

Table 9 Fire Station Location Selection Evaluation Index System

Secondary Indicators	Tertiary Indicators	Quaternary Indicators
A1 Qualitative Indicators	B1 Hot - Spot Factors	C1 Fire Risk Level within the Jurisdiction C2 Accident Hot - Spot Time Situation C3 Traffic Conditions
	B2 Social Factors	C4 Urban Population Density C5 Fire - Fighting Facility Construction Situation
	B3 Geographical Factors	C6 Terrain Conditions C7 Meteorological Conditions
A2 Quantitative Indicators	B4 Time Factors	C8 Maximum Time for Fire Trucks to Reach the Accident Site/min C9 Minimum Time for Fire Trucks to Reach the Accident Site/min
	B5 Economic Factors	C10 Fixed Cost of Fire - Fighting Facility Construction/10,000 yuan C11 Annual Total Operating Cost of the Fire Station/10,000 yuan

2.3 Construction of the Analytic Hierarchy Process (AHP) Model

2.3.1 Establishing the hierarchical structure model of the system

First, the decision - making problem is decomposed into different hierarchical structures, usually divided into the target layer, criterion layer, and alternative layer. The target layer is the ultimate goal of decision - making, the criterion layer contains the criteria affecting the decision - making, and the alternative layer is the specific decision - making options. There is a certain relationship between the elements of each layer and the elements of adjacent layers. Upper - layer elements are usually the synthesis or influencing factors of lower - layer elements, and lower - layer elements are the specific implementation or refinement of upper - layer elements. For example, in decision - making analysis, the upper - layer goal is ultimately decomposed into specific alternatives through the criteria and sub - criteria of the middle layer. Through the understanding and research of fire station construction location selection, the hierarchical structure established is shown in Figure 2.

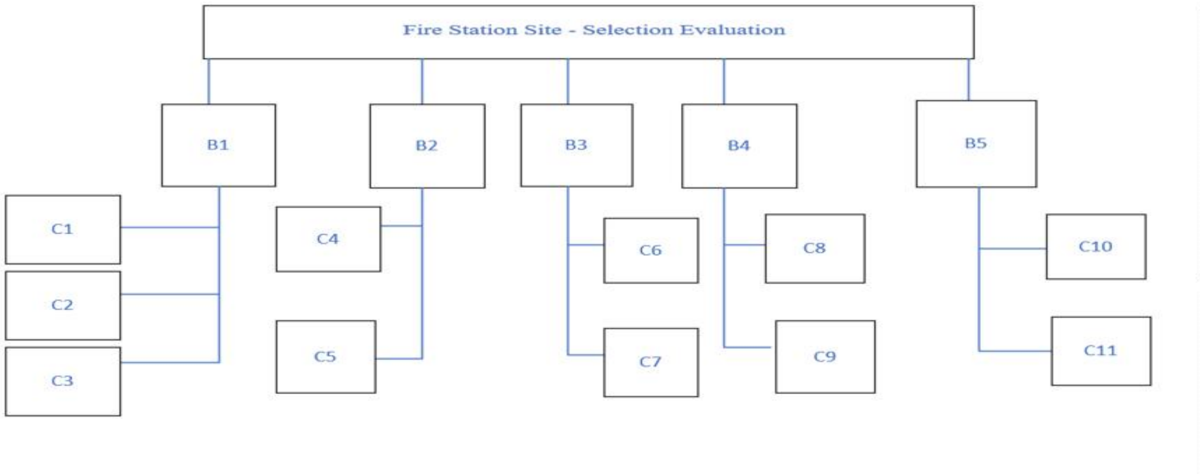

Figure 2 Hierarchical Structure

The scaling method is shown in Table 10:

Table 10 Scaling Method

Scaling Value	Importance Degree of One Element to Another
1	Equally important
3	Slightly important
5	Obviously important
7	Strongly important
9	Strongly important
2,4,6,8	Mid - values of the above - mentioned adjacent judgments

The elements in the judgment matrix represent the relative importance of factors with respect to the factors in the upper - level.

A judgment matrix system is established. According to the 11 evaluation indicators for fire station site - selection, the judgment matrix is constructed as shown in Figure 3 below:

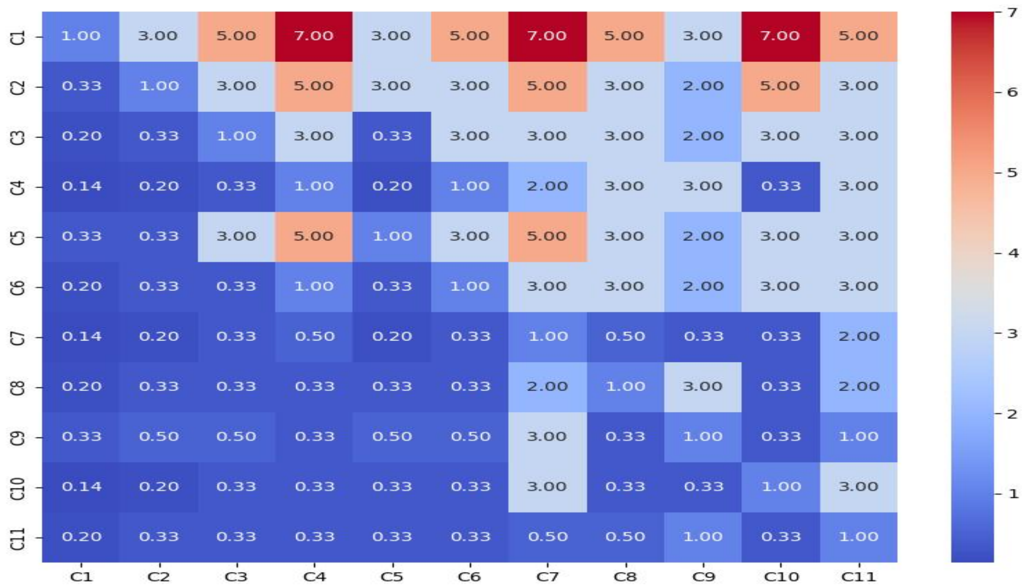

Figure 3 Heat Map of the Judgment Matrix

1. Calculation of Index Weights: Calculate the maximum eigenvalue $\lambda_{\max}$ of each judgment matrix U and obtain the normalized eigenvector w. That is: $Uw = \lambda_{\max} w$

Here, the specific formula for calculating the eigenvector is not clearly given in the original text, so it is not translated in detail. The components of it are the weights we need $(w_1, w_2, \ldots, w_n)$. Under normal circumstances, it is rather troublesome to obtain the eigenvector, so the root - method is used for approximate calculation:

$$w_i = \left[\prod_{j=1}^{n} a_{ij} \right]^{\frac{1}{n}}, n = 1, 2, ..., n \tag{1}$$

The weight is the result of normalization processing, that is:

$$w_i^* = \frac{w_i}{\sum_{i=1}^{n} w_i}, s.t. \sum_{i=1}^{n} w_i^* = 1, w_i^* \geq 0, i = 1, 2, ..., n \tag{2}$$

2. Consistency Test of the Judgment Matrix:

Make a questionnaire and invite experts to score and judge. After calculating the weights according to the formula, it is also necessary to conduct a consistency test on the pairwise - comparison judgment matrix to reduce the inaccuracy and arbitrariness of subjective judgment. The consistency test adopts the following formula:

$$CR = \frac{CI}{RI} \tag{3}$$

In the formula:

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

CI is the consistency index.

The values of the consistency index RI for different orders are shown in the following table 11:

Table 11 Values of the Consistency Index RI

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.90	1.12	1.24	1.32	1.41	1.45	1.49

If $CR < 0.1$, the consistency of the judgment matrix meets the requirements, that is, the judgment result is reliable; otherwise, the judgment matrix needs to be reconstructed.

The result of the model solution CR is 0.0626, which meets the consistency requirement, indicating that the judgment result in Table 11 is reliable. As can be seen from Table 12 below, according to the data, the fire risk level within the jurisdiction (C1) has the highest weight, indicating that it is a key factor in evaluating fire safety. The accident hot - spot situation (C2) and the fire - fighting facility situation (C5) are also very important, but to a lesser extent. The weights show that operational and response capabilities such as traffic conditions (C3), terrain (C6), and population density (C4) play an important role, but they are not as crucial as direct risk factors. The fastest and slowest arrival times of fire trucks at the accident site (C8 and C9), as well as the fire - fighting facilities and their operating costs (C10 and C11) are relatively less important but still relevant. The impact of weather conditions (C7) is the smallest. This may be because although weather affects fire risks and responses, compared with other factors in the model, it is uncontrollable and has a lower impact level. This fire station site - selection evaluation system emphasizes the multi - aspect nature of fire safety assessment, giving priority to direct risk factors while also considering operational conditions and costs. This comprehensive approach ensures that the developed fire safety strategies are both robust and take into account various key factors that may affect the effectiveness of fire prevention and emergency response measures.

Table 12 Corresponding Weights of Each Index

Index Meaning	Corresponding Weight	Weight Ranking
Fire Risk Level within the Jurisdiction (C1)	0.28	1
Accident Hot - Spot Time Situation (C2)	0.17	2
Fire - Fighting Facility Construction Situation (C5)	0.14	3
Traffic Conditions (C3)	0.10	4
Terrain Conditions (C6)	0.07	5
Urban Population Density (C4)	0.06	6
Maximum Time for Fire Trucks to Reach the Accident Site per Minute (C8)	0.05	7
Minimum Time for Fire Trucks to Reach the Accident Site per Minute (C9)	0.04	8
Fixed Cost of Fire - Fighting Facility Construction (in 10,000 yuan) (C10)	0.04	9
Annual Total Operating Cost of the Fire Station (in 10,000 yuan) (C11)	0.03	10
Meteorological Conditions (C7)	0.03	11

2.3 Sensitivity Analysis of the Model

In the problem of finding the optimal layout of fire stations, the initial average speed is set at 60 km/h and assumed to be constant. At the same time, it is set that all fire stations should reach the nodes within their jurisdiction as quickly as possible within 8 minutes. The goal of sensitivity analysis is to evaluate the impact of changes in different variables on the layout and jurisdiction scope of fire stations to ensure the robustness of the layout plan and its effectiveness in practical applications. This paper selects the average speed variable for sensitivity analysis. Keeping other relevant variables unchanged, the average speed is allowed to fluctuate by 5% up and down. The simulated annealing algorithm is used to calculate the optimal layout, and the Dijkstra algorithm is used to calculate the jurisdiction scope of each fire station. The Pycharm software is used to draw the graph of the number of nodes within the jurisdiction scope of each fire station changing with the speed under different speeds.

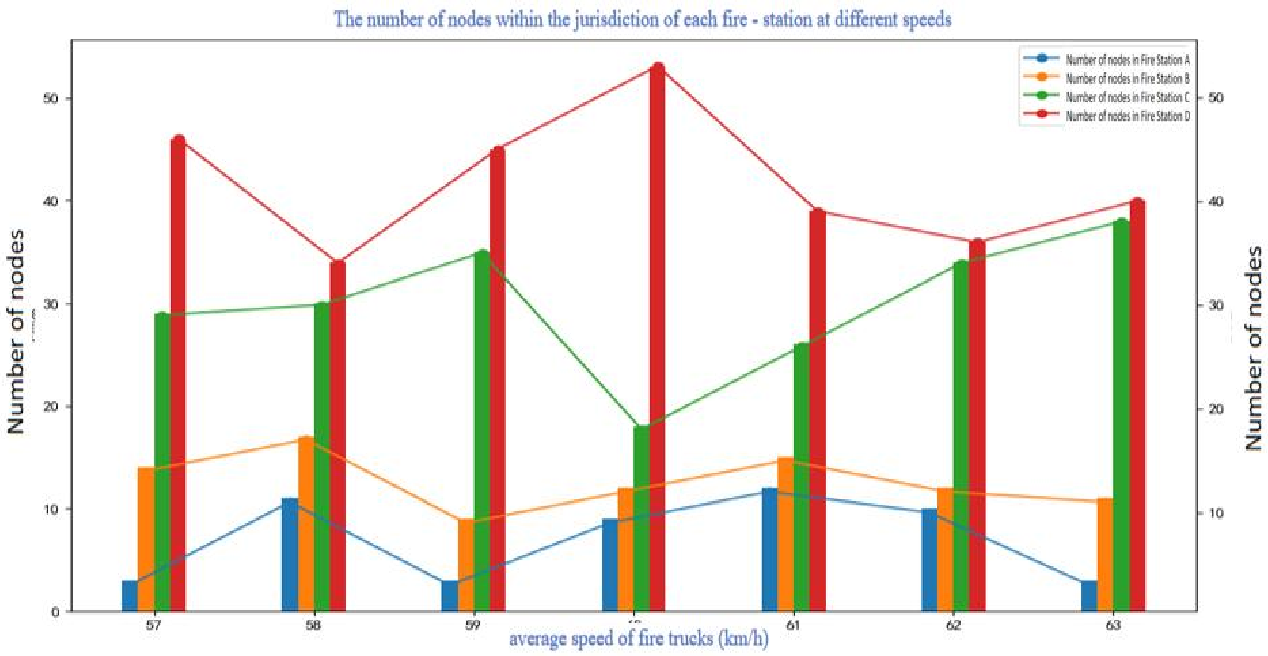

Figure 4 Number of Nodes within the Jurisdiction Scope of Each Fire Station under Different Speeds

As can be seen from Figure 4, assuming that the speed of fire trucks is constant at different speeds within the fluctuating range, the number of nodes within the jurisdiction scope of each fire station changes greatly, indicating that the layout and jurisdiction scope division of fire stations are relatively sensitive. This should be paid special attention to in the practical problem of fire station layout and jurisdiction scope division. Through sensitivity analysis, we can identify the key factors affecting the fire station layout and adjust the layout strategy according to the analysis results to ensure that fire stations can effectively respond to fire accidents in the shortest possible time under various possible circumstances.

3 CONCLUSION

This research focuses on the optimization of urban fire station layouts and conducts in - depth exploration by comprehensively applying multiple models and algorithms. Through the TOPSIS comprehensive evaluation model, the non - integer rank - sum ratio (RSR) model, and the entropy weight method, the defects of the existing fire station layout in City A in terms of node coverage and emergency response time are accurately identified. The layout is optimized by using the simulated annealing algorithm (SA), which significantly improves the emergency response speed and balances the jurisdiction scope of fire stations, verifying the effectiveness of this algorithm. The analytic hierarchy process (AHP) is used to clarify the key factors affecting the layout, providing theoretical support for optimization. The research results have high feasibility in practical applications. The optimized layout has obvious advantages in emergency response, node coverage, and resource allocation, effectively guaranteeing urban fire safety.

However, the simulated annealing algorithm has a slow convergence speed and high computational cost when dealing with large - scale problems. This problem will become more prominent with the growth of urban scale and data volume. Moreover, the model does not fully consider dynamic factors such as real - time traffic flow changes and dynamic adjustments of urban functional areas. Future research can introduce optimized algorithms such as the adaptive simulated annealing algorithm (ASA) to improve algorithm performance; strengthen the research on dynamic factors and integrate real - time data to construct dynamic models; expand the research scope to consider the coordinated operations of fire stations and the dynamic allocation of fire - fighting resources, and improve the urban fire safety guarantee system.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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