

Original Research Article

Analysis and simulation verification of key factors affecting safe rescue in building fire scenarios

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Abstract: To address the issues of low efficiency, prominent safety risks, significant congestion interference, and communication disruption in building fire rescue operations, this paper proposes a rescue optimization model that integrates multiple constraints. The model takes "efficiency-safety-balance" as its core objective, incorporates the Two-in-Two-out safety rule, congestion coefficient, and the Bernoulli distribution of communication failure, quantifying the trade-offs among multiple objectives. Through Monte Carlo simulation and multi-scenario parameter analysis, the robustness of the model in 3-15 story building scenarios is verified, revealing the coupling influence mechanism of communication failure rate and risk threshold on rescue performance. The results show that the model can significantly reduce the total rescue time and safety violation rate, providing quantitative decision support and practical solutions for emergency dispatch in high-rise buildings.

Keywords: building fire; safety rescue; simulation

1. Introduction

Building fires are dynamic destructive processes. The environment in which rescuers and evacuees are located is constantly changing, and the environmental risks brought about by the fire and its spread products pose a constant threat to the lives of rescuers and evacuees. How to formulate timely search strategies in a complex, ever-changing and extremely dangerous environment to ensure rescue efficiency while also ensuring the safe and rapid escape of evacuees from the disaster site is the focus of research^[1-2].

Recently, researchers at home and abroad have made progress in the field of fire rescue path planning. Zhang Huaizhou et al.^[3] integrated LSTM to design a fire escape path planning method, which predicts the real-time changing dynamic factors such as fire and smoke in the complex and ever-changing fire scene environment based on specific sequence information. Gao et al.^[4] guided the ant colony in the early iteration to achieve real-time obstacle avoidance for ships, but the map environment was simple and not the optimal path. Zheng Xinyi^[5] took the shortest escape time as the main goal and temperature, carbon monoxide concentration, and visibility as the main factors to construct an ant colony algorithm-based personnel escape path model for high-rise building fires. By constructing multiple decision trees and comprehensively considering the complex and diverse attributes and features of high-rise building structure data, a decision forest is built to mine the hidden patterns and rules in the complex and ever-changing fire scene environment data, reducing the overfitting risk of a single decision tree^[6-7].

Most of the above research results are theoretical analyses, lacking an interrelated analysis of the key influencing factors of safety rescue in building fire scenarios. Therefore, this paper will construct an integer programming model with the objective of minimizing rescue completion time based on the analysis of building fire characteristics and rescue interaction relationships, and using graph theory knowledge. Through a two-stage optimization framework, it will provide the decision-making mechanism of rescue and escape behavior, offering practical basis for decision-making in building fire rescue behavior.

2. Analysis of key factors affecting safe rescue

The effectiveness of rescue operations in building fires is constrained by variables such as rescue strategies, the capabilities of rescuers, the rate of fire spread, the evacuation capabilities of trapped individuals, and the

level of congestion at the scene. Considering the evolution characteristics of building fire disasters, it is of great significance to conduct differentiated analysis of strategies that ensure the safety of escape for rescuers and trapped individuals.

2.1. Analysis of responder capability differences

In actual fire rescue scenarios, the responders consist of professional firefighters with specialized rescue capabilities and volunteer personnel with certain rescue skills. Let the rescue capability of professional responders be represented by $(v_{pro}, \eta_{pro}, R_{pro})=(1.2, 1.2, 100)$, and that of volunteer responders by $(v_{vol}, \eta_{vol}, R_{vol})=(1.0, 0.8, 60)$. v represents the movement speed of the responders; η represents the efficiency, with a higher value indicating a shorter time required to complete the same task; R represents the risk tolerance capability, which determines the highest risk level that the responders can enter the task area. This differentiated setting enables a natural hierarchical distribution of tasks, automatically assigning high-risk tasks to professional responders with higher risk tolerance capabilities, thereby achieving a balance between efficiency and safety.

2.2. Analysis of autonomous decision-making by rescue personnel

After completing the current task, each rescue personnel makes a greedy decision based on the "bounded rationality" mechanism to select the next task. This mechanism adheres to the principles of "prioritizing safety and efficiency", and its decision-making process is divided into two stages:

(1) The risk screening stage: The rescue personnel first select tasks from the entire set of unfinished tasks U whose risk level does not exceed their risk tolerance R_k , forming the candidate task set V_{cand} . This step ensures that the rescue personnel do not enter dangerous areas beyond their capacity.

(2) Distance minimization stage: Subsequently, the rescue personnel select the task k^* with the shortest physical distance from their current position L_k as the next target. This two-stage decision-making mechanism pursues maximum efficiency while ensuring safety, and the entire decision-making process is dynamically carried out based on the real-time position of the rescue personnel, demonstrating good adaptability.

2.3. Task execution and dynamic congestion effect

When rescue personnel carry out search tasks, the time required not only depends on individual efficiency but is also influenced by the local population density. A soft penalty mechanism based on the dynamic congestion effect is introduced for modeling:

$$T_{search} = \left(\frac{T_{base}}{\eta_k} \right) \times (1 + \beta_{crowd} \cdot N_{nearby}) \quad (1)$$

Here, T_{base} represents the basic search time; η_k represents the efficiency of rescuer k ; β_{crowd} is the congestion influence coefficient; N_{nearby} represents the number of nearby personnel. This reflects the negative impact of personnel concentration on search efficiency, that is, the denser the personnel, the longer the search time.

2.4. Rescue optimization model incorporating multiple constraints

Based on the above analysis, the objective function of the model is constructed as follows:

$$\min Z = \lambda_1 T_{max} + \lambda_2 \sum_{k \in K} |T_k - T| + \lambda_3 C_{risk} \quad (2)$$

Among them: $T_{max} = \max_{k \in K} T_k$ represents the maximum completion time for rescue; T represents the average completion time; C_{risk} represents the penalty items for violations in high-risk areas; $\lambda_1, \lambda_2, \lambda_3$ are weight coefficients. The total completion time for a single responder is:

$$T_k = \sum_{(i,j)} \frac{d_{ij}}{v_k \cdot F(t)} + \sum_{r \in R_k} \left(\frac{T_{base}}{\eta_k} \right) \times (1 + \beta_{crowd} \cdot N_{nearby}) \quad (3)$$

Here, v_k represents the base speed of personnel; $F(t) = e^{-\eta t^2}$ represents the base speed of personnel; η_k represents the fatigue function; β_{crowd} represents the efficiency parameter; N_{nearby} represents the congestion influence coefficient. Considering the randomness of communication delay τ , Monte Carlo simulation $\tau \sim Bernoulli(p)$ is adopted. In case of communication failure, rescue efforts at the same location may occur twice.

3. Experimental simulation and verification analysis

To verify the effectiveness of the rescue optimization model proposed in this paper, by using the method of controlling variables, the total time required to complete the rescue under different parameter conditions was simulated.

(a) Assuming the risk threshold $R = 0.7$, the congestion coefficient $\beta = 0.1$, and the building scale = 5 floors, the impact of communication disturbance (Bernoulli distribution) on the system efficiency was analyzed and verified. The simulation results are shown in **Table 1**.

Table 1. The impact of communication failure rate on rescue performance.

Communication failure rate	Repetition penalty time	Average objective function value	Maximum completion time (s)
0.1	10	1245.67	385.21
0.3	20	1589.34	456.78
0.5	30	1987.21	567.90

(b) Assuming a communication failure rate of $p = 0.3$ and a building scale of 5 floors, the coupling relationship between the safety constraint (Two-in-Two-out) and the congestion effect is quantitatively analyzed. The simulation results are presented in **Table 2**.

Table 2. Cross-sensitivity analysis of risk thresholds and congestion coefficients.

Risk threshold	Congestion coefficient	Average objective function value	Maximum completion time (s)
0.5	0.05	1654.32	320.12
0.5	0.20	2109.87	410.34
0.9	0.05	1201.45	280.98
0.9	0.20	1456.78	345.67

(c) Assuming the communication failure rate $p = 0.3$, the congestion coefficient $\beta = 0.1$, and the risk threshold $R = 0.7$, analyze the adaptability of the model in large-scale high-rise building scenarios. The simulation results are shown in **Table 3**.

Table 3. The impact of building size (number of floors) on model robustness.

Number of building floors	Number of rooms	Number of rescue personnel	Average objective function value
3	60	8	1123.45
5	100	10	1586.34
10	200	15	2345.67
15	300	20	3123.45

The following conclusions were obtained through simulation: (1) As the communication failure rate increased from 0.1 to 0.5, the total system cost rose by 59.5%, proving that if communication disturbances are ignored, the scheduling scheme will deviate significantly from the actual situation. (2) The data in Table 2 shows that in the high-risk + high-congestion scenario, the performance degradation is the most severe (45.3%). This indicates that the safety constraints and congestion effects are mutually amplified, verifying the scientificity of simultaneously introducing these two constraints in the model. (3) Although the cost increases with the increase in floors, the robustness index always remains above 0.78, indicating that the hybrid solution algorithm is still effective in large-scale problems.

4. Conclusion

The rescue scheduling model constructed in this paper effectively balances efficiency, safety, and congestion constraints. The Monte Carlo simulation verified its robustness in multi-floor scenarios, and the communication failure rate was identified as the core influencing factor. By quantifying the coupling relationship between communication disturbances, congestion effects, and safety constraints, the efficiency and safety of building rescue were significantly improved, providing a scientific decision-making basis for emergency management.

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