A new method for personnel protection failure evaluation in metro fire with multiscenario coupled three dimensional model

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Abstract. With a closed environment and dense population, urban metros are difficult to evacuate quickly in the case of fire, which often leads to serious consequences such as stampedes. To deal with metro fires effectively, this paper presents a three-dimensional model for assessing the failure probability of personnel protection. First, scenario elements of metro fire evolution were selected based on typical cases and traditional performance-based evaluation methods, and a scenario element database was constructed. Second, based on this approach, a three-dimensional evolution model of the metro fire scenario was established to visually express the interaction relationship of each scenario element in plane dimensions. Finally, an evaluation model of the personnel protection failure risk index was constructed by coupling the metro fire, emergency management and trapped personnel, and the failure probability of personnel protection was calculated. This model can evaluate the real-time risk of death in the process of metro fire accidents and provide an important reference for emergency decisions and plan deployment.

1. Introduction

With the increasing pressure of transport on the ground, to meet the urban transportation demand, developing the metro is a strong trend, which not only saves the space on the ground greatly, but also serves more personnel by fast speed, accurate departure time, less energy consumption and less pollution. However, metro stations pose a significant challenge in the security of a large volume of personnel in a confined and complex space. In particular, the event of such instantaneous disasters as fire, trapped personnel tend to become the most threatened group, which often leads to serious consequences. According to statistics, 68 metro fire accidents occurred from August 1903 to February 2017, resulting in 1,262 deaths and 2,233 injuries.

Therefore, it is necessary to carry out personnel protection research to reduce casualties in fire. Personnel protection is generally understood as individual protection which mainly through wearing personal protective equipment to keep safe. This paper refers to a variety of macro emergency measures to avoid the danger of trapped personnel in metro fire.

These studies aim to explore the influence of the index system including the reaction of passenger when evacuation [1], social relations network under emergency situation, neighbors behavior, cooperation and competition behavior [2], familiarity degree and choices about exports [3], crowd attraction and repulsion behavior influencing factors in evacuation through statistics, simulation
experiment and other methods. Cellular automata, lattice gas theory and spatial grid theory are used for reasonably modeling according to different scale of evacuation simulation experiments [4]. To simulate personnel in evacuation, the undifferentiated model and social force model is adopted [5]. Resource deployment assess whether type and distribution of resource in multi-stage satisfied emergency demand. The consequences of injuries assessment is adopted the vulnerability model and entropy change principle. Other studies focus on injury to an individual as a victim exposed to fire [6].

There are abundant studies on the evolution of metro fires to determine the probabilities of different scenarios and key nodes, such as analytic hierarchy process-neural network, the knowledge element theory and Bayesian-neural network, hierarchical Petri net which object-oriented, probability rule reasoning method, fuzzy comprehensive evaluation method based on the "human-machine-environment-management" four aspects, fuzzy causality diagram [7]. There are also studies on game theory to assess the harm faced by personnel in the dynamic evolution of metro fire in order to obtain optimal emergency decisions for personnel evacuation and optimal allocation of resources.

There have been abundant research results on personnel evacuation and metro fire assessment, but there are few theoretical studies on the evaluation of the protection failure of trapped personnel in the complex system of metro fire, as well as the quantitative expression of the coupling relationship among metro fire, trapped personnel and emergency management. Therefore, this paper establishes a multifactor coupling-three-dimensional model of personnel protection failure in metro fires and makes a reasonable prediction and quantitative assessment of the possibility of casualties caused by trapped personnel to optimize emergency decisions and reduce the probability of personnel protection failure in metro fires.

The modeling ideas of this paper are shown in Figure 1. First, typical cases of metro fires are counted, and the emergency processes of metro fires are analyzed. The key scenario elements are obtained by screening the causes of accidents. Based on analysis of the evolution process of the Daegu metro fire by using a traditional performance-based evaluation method, scenario element events are obtained. Second, a plane dimension framework is constructed to reasonably express the interaction between two elements of the scenario. Then, a suitable mathematical model is selected to express the relationship of the interaction quantitatively, and the probability of personnel protection failure in the process of a metro fire is obtained by coupling the scenario elements in three dimensions. Finally, the results are applied to emergency decisions.

![Figure 1. Mind map of building a three-dimensional model of personnel protection in metro fire.](image)

2. Establishment of scenario elements and scenario events
In view of the protection failure of trapped personnel in metro fire, the main objects of concern are set as metro fire, emergency management (hereinafter referred to as emergency), and trapped personnel (hereinafter referred to as personnel). Complex systems are inherently uncertain and constantly evolve under the dynamic force of adaptability. Various elements of the system are coupled to each other in a non-linear way through the whole process of metro fire evolution.
2.1. Scenario elements
The key events or states that play an important role in the evolution of metro fires are called scenario elements and classified into metro fires, emergencies, personnel and others according to their characteristics. The key scenario elements influencing each of the other three objects change over time.

To reasonably express the relationships at different times in the whole process of a metro fire, three scenario elements were taken as the x, y and z axes. These axes were developed in the order of time. Key scenario elements were analyzed and selected based on the statistics of 68 metro fires from August 1903 to February 2017 [8].

2.2. Scenario events
The specific representation of scenario elements in an accident is called scenario events. The key scenario events can be abstracted as functions of time whose initial states not only affect the subsequent states but also interact with the states of other scenario events.

*Table 1. Scenario element and scenario event database of metro fire.*

| Scenario element | Scenario event a |
|------------------|------------------|
| Metro fire       | Vehicle risk     |
|                  | Vehicle combustion characteristics, vehicle fault, metro piston wind, parking position |
|                  | Facility risk    |
|                  | Fireproof and refractory material, platform doors, platform depth, metro complexity, tunnel length |
|                  | Bearing capacity |
|                  | Metro fire design and management, structural protection, early warning, smoke control and water-based fire extinguishing systems, engine systems, emergency lighting systems |
|                  | Disaster risk reduction capacity |
|                  | Evacuation sequence, route guarantee, emergency linkage, traffic control, medical treatment, scenario cleaning, investigation, prevention and recovery capacity |
| Emergency management | Emergency response capacity |
|                  | The speed of reconnaissance and search, the effective of internal attack (using the phenomenon of the inlet and outlet of the fire), the operable of fire-fighting |
|                  | Communication support capacity |
|                  | Communication security, real time broadcast system |
|                  | Resource allocation capacity |
|                  | Material and personnel distribution, emergency equipment (mobile smoke extractor, internal attack life line, guide rope, thermal imager, resource transport vehicles, oil and gas supply vehicles, emergency rescue vehicles, catering vehicles) |
| Trapped personnel | Personnel factor |
|                  | Baggage, safety education, similar disaster experience, awareness and ability of drivers and personnel of fire prevention, awareness and ability of tunnel managers of fire prevention, ability of escape |
|                  | Crowd factor |
|                  | Psychological impact, age distribution, gender differences, redistribution of limited rational behaviour, population density, changes of social relations in emergency, reactive and initiative behaviour, centrality of evacuation, team cohesion |
| Others           | Environment factor |
|                  | Toxic gases, hot smoke diffusion, readability of paths within buildings, exit conditions |
|                  | Other factor |
|                  | Fire resistance of buildings, weather factors, social periods, other emergencies |

*a. Key scenario events are selected for application.*

The key scenario events are selected by analyzing the evolution process of historical accidents [9]. Such as key scenario elements in the evolution process of the metro fire accident in Daegu on February 18, 2003 include watchman ignored the fire and did not report, the dispatching did not prevent the subsequent vehicles from coming into the station, and the personnel could not open the
doors and were stuck in the carriages through mainly analyzed. The scenario factor database is shown in Table 1 by referring the selected scenario events and existing performance-based assessment methods of metro fire.

3. Construction of three dimensional model

The main relationships among metro fires, emergencies and personnel in different dimensions are as follows to develop a simple quantitative expression of the interactive influence.

3.1. Objects and interactive influence relationships

1) Personnel and metro fire.

The protection ability of personnel decreases and they are vulnerable to injury in emergency situations of high heat, toxic smoke, crowded personnel and psychological panic in the limited space of a metro fire environment.

2) Metro fire and emergency.

Metro fires and emergencies are confrontational, as the more severe a fire is, the more difficult the emergency; in contrast, the more limited an emergency is, the less likely the fire is to grow.

3) Personnel and emergency.

Figure 2. Failure probability evaluation process of personnel protection in metro fire.
The worse the ability of personnel to save themselves in fire, the more urgent need for emergency, the greater pressure and the more difficulties on rescue. Emergency measures have a compensation effect on this need. An assessment process model that reflects this relationship is shown in Figure 2.

3.2. Interaction of multiscenario elements expression

The "points" representing scenario events in the chain evolution on the timeline are extended as "lines" and "bars" to better express the interactive influence relationship of scenario elements in metro fires. The interaction relationships of scenario elements on the plane dimensions are named the vulnerability of personnel in fire, the correlation between metro fires and emergencies, and the compensation of emergencies for personnel needs. The interaction of scenario elements is visualized by putting them in the three plane dimensions of the three-dimensional model.

Key scenario events in corresponding time $t$ or time period $\Delta t$ are selected depending on the accident and are interacted within the grid divided by "bar" of key scenario events in each dimension. Select the key scenario events of three types of objects in Table 1 for an example, as shown in Figure 3.

**Figure 3.** Schematic diagram of three-dimensional evolution and interaction of scenario events within $\Delta t$ in metro fire.

4. Quantitative calculation of personnel protection failure probability coupled with multiple scenario factors

The evolution of a metro fire and the interaction of key temporal scenario events that need to be considered in the fire over time in their respective plane dimensions are visualized through the three-dimensional model. The plane dimension has been segmented into grids by intersecting "bars" of key scenario events.

4.1. Quantitative expression of interaction

1) Analysis of the interaction between personnel and metro fire -- vulnerability.

The relationship between personnel and a metro fire is quantitatively represented by the vulnerability method [10]. The vulnerability probability $R_i$ of personnel protection is calculated as one of sub factors of personnel protection failure. The probability value range of the vulnerability of personnel protection is $0 \leq R_i \leq 1$, which varies with time. Refer to Figure 4 for indicator selection.

2) Interaction analysis of metro fire and emergency -- confrontation.
The guarantee rate of personnel protection $x_i$ is calculated quantitatively by the game theory used to express confrontation between metro fire and emergency.

Player: "metro fire" $s_1$; "emergency decision-maker" $s_2$.

Strategy space: the state space of "metro fire" $s_1$ is $S_1 = \{\alpha_1, \alpha_2\}$, and degree of hazard $\alpha_2$ is lower than $\alpha_1$. It is assumed that only one resource is needed for each emergency stage in process of metro fire in the rescue although fire-fighting resources include fire extinguishing chemical, foam loading, etc. in application.

![Vulnerability diagram](image)

**Figure 4.** Selection of personnel vulnerability index in metro fire.

Emergency process involves the amount of resources owned $x_1$, transported $x_2$, used $x_3$, used effectively $x_4$. There is the minimum $x^2$ to be chosen in calculation considering the limit of the emergency situation existing $x_1 \geq x_2$ and hard to determine $x_3$ and $x_4$ quickly in the emergency decision. Fire will be controlled if only a sufficient number of fire-fighting resources carried to the fire point within a certain time and certain crisis condition and fire will be partly controlled when $x^2$ is unsatisfied. The rate of degree of control range from 0 ~ 100%. The aim is to fully control the fire after $n$-phase of confrontation, so that degree of control reach 100%. There still have compensation measures if it cannot be reached but cost a lot. Prevention cost: response cost: compensation cost = 1:10:100 according to the emergency historical data.

![Resource distribution diagram](image)

**Figure 5.** Resource distribution diagram.
Distance between fire-fighting resources and the fire station (A, B, C, D, E in Figure 5.) is represented by the time length of resources transfer (0.8r, r, 1.5r, 2r in Figure 5.). The strategy space in n-phase $S_{2l} = \{\beta_{1l}, \beta_{12}, ..., \beta_{1n}\}$. The drawing method is shown in Figure 5.

Win function: The payment function of $s_2$ includes guarantee rate and cost. Constraint conditions can be added and the strategy space can be simplified according to different purposes of emergency decision-making. For clarity and specify statistics, as shown in Table 2.

**Table 2. Fire resources transportation method and cost.**

| Method          | Method 1 | Method 2 | Method 3 |
|-----------------|----------|----------|----------|
| The quantity    | $N_1$    | $N_2$    | $N_3$    |
| Transport costs per unit | $P_1$    | $P_2$    | $P_3$    |
| Total           | $T_1$    | $T_2$    | $T_3$    |

State transfer function: The first stage of confrontation in metro fire is with a certain probability value of crisis state, and the state transfer function $p_{ij}(i, j = 1, 2)$ in the subsequent stage is determined by the fire situation and resource guarantee rate. Evolutionary tree diagram will be drawn to make the confrontation situation of each stage clearer. Figure 6 shows the confrontation evolution of two stages of a metro fire.

![Figure 6. Evolution of two-stage confrontation in metro fire.](image)

$x_t$ Personnel protection guarantee rate.

$T_n$ Cost to control fire 100%.
Probability value of evolution to the fire situation.
The emergency decisions made for different metro fire situations at different stages are optimized according to the evolution results. A mixed solution is the optimal solution when an emergency decision maker chooses emergency measures based on probability, and it is difficult to make a detailed decision.

3) Interaction analysis of emergency and personnel—compensation coefficient.
The relationship between an emergency and personnel is represented by the compensation coefficient $\mu_i$, representing a complement to the failure of personnel protection. The level of the compensation coefficient is divided according to a comparison between the effect caused by emergency measures and the effect expected by emergency plans. The probability value range of compensation coefficient is $0 \leq \mu_i \leq 1$, which varies with time.

4.2. Failure probability of personnel protection through multiscenario event coupling
The plane dimensional grid, which represents the interaction of key scenario events at different times, is coupled in three dimensions, and the spatial volume coupled by the grid changes the relationship of scenario elements from qualitative analysis to quantitative calculation. As shown in Figure 7.

The spatial volume shown in Figure 7 is used to represent the probability of personnel protection failure $F_i$ and needs the length, width and height of the key scenario events "bar" in three dimensions in the calculation, which are the result values obtained by calculating the vulnerability, confrontation and compensation described above.

$$F_i = R_i \times (1 - x_i) \times (1 - \mu_i)$$

Where,

- $R_i$ — Vulnerability probability of personnel protection in each time period;
- $x_i$ — Personnel protection guarantee rate in each time period;
- $\mu_i$ — Compensation probability of personnel protection failure in each time period.

The differences between (2) and (3) in Figure 8 are as follows: (2) it is mainly reflected in the aspect of emergency planning. The purpose is to prevent avoidable injuries to personnel, which is a kind of prevention against the failure of personnel protection. And (3) it is to take measures to prevent the complete failure of personnel protection when the personnel is facing extreme danger, which is a kind of compensation for the failure of personnel protection.

Figure 7. Real-time probability value of personnel protection failure through scenario event coupling.
Figure 8. Calculation method of spatial volume value of personnel protection failure probability in emergency decision-making.

5. Application of three dimensional model

The failure probability represented by the spatial volume at a time \((t \pm dt)\) or time period \((t \pm \Delta t)\) is used to determine the risk of death. In this period, when the probability exceeds a certain threshold, this means the complete failure of personnel protection under the combined action of factors such as uncontrollable fire, emergency failure and inappropriate, or excessive vulnerability of personnel protection. The efficiency of personnel rescue is 0, and isolation measures are considered to be established in this situation. Personnel shall be rescued actively when the failure probability is below a certain threshold. Emergency decisions are determined according to obtained result classification, as shown in Table 3.

| Corresponding measures |
|------------------------|
| 0~\(F_1\) | There is no need to consider the optimization of emergency decision-making. |
| \(F_1\sim F_2\) | To optimize emergency decision. |
| \(F_2\sim1\) | To prevent the station fire from worsening and to take quarantine measures to surrounding dangerous areas. |

Table 3. Personnel protection failure probability and subsequent measures classification.

The mathematical model parameters or simulation preconditions on each plane dimension will be adjusted in real time if an emergency occurs that affects the accident due to environmental factors, and then the probability of personnel protection failure will be re-judged. The spatial volume representing the real-time personnel protection failure probability obtained through the above methods is used to visualize the risk of death of personnel in the emergency process of a metro fire.

If there is obvious transfer of disaster sites over time, multiple models should be used in series and if the disaster occurs in different areas at the same time or can be used in parallel because this three dimensional model defines the scope of a specific location.

Through the above calculation and classification approaches, relevant policies can be given for metro fire emergencies. Different fire events have different acceptable degrees of casualties, and \(F_1\) are also different, such as \(F_1 = 0.3, F_2 = 0.7\). Rescue measures must be taken and optimized when the failure probability \(F_1\) is in the range of acceptable loss. Outside this range, personnel rescue is unlikely, there is no need to drain emergency resources, and measures should be taken to avoid further losses.
6. Conclusions
This paper presents a new theoretical modeling method for personnel protection failure evaluation of complex metro fire emergency system with multiscenario coupling. It solves the problem that it is difficult to determine the research objects and find the interactive influence relationships of the metro fire system. And focus on quantitatively assessment of real-time risk of death which has not been calculated before because lacking of method to apply limited data.

First, this paper obtains the influencing factors in the complex metro fire emergency system through historical cases. Multiscenario factors include the metro fire, trapped personnel and emergency management and are embodied as scenario events at specific times. Second, this paper simplifies and defines the relations among the three kinds of scenario elements and constructs a physical model to express them. Third, the three kinds of scenario elements are used as three coordinate axes over time to form a stereo model. Each face is divided into grids by the lines generated by specific scenario events at different time nodes on the axes. The grids are coupled into the spatial volume of the physical model through the interaction of various scenario elements. Finally, this volume represents the probability of personnel protection failure in the complex subway fire emergency system caused by the interaction of scenario events, which is obtained by calculating the length, width and height represented by the probability values of the three dimensions it contains. Furthermore, this method can also be used as a reference for other complicated systems with unclear development mechanisms, such as explosions and poison gas. Further, it can also be used for reference to other complicated systems with unclear development mechanism, such as explosion and poison gas.

In this paper, a data flow has not been constructed, and a quantitative computing model has not been built. A more detailed model can be built by computer to transform this method into a data flow with the assistance of big data and cloud computing to realize the application value of the model in rapid calculation and emergency decision optimization for metro fires.

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