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System Dynamics Modeling and Analysis of Fire Safety in High-Rise Buildings

Ying Wang*, Weili Wang
Renai College of Tianjin University, Tianjin, China
*Corresponding Author: Ying Wang

Abstract:

High-rise building is a complex system, which is characterized by complexity, systematicness and relevance. In the process of construction and occupancy of high-rise buildings, in case of fire, it will bring huge losses to people's lives and property. In this paper, the system dynamics method is used to analyze the fire safety system of high-rise buildings, to construct the system dynamics model of influence factors in fire safety of high-rise buildings. The simulation results show that the safety awareness factor has the greatest influence on the system, and the management level factor has the least influence on the system, which provides reference for the removal of fire safety hidden danger, the prevention and control of fire in high-rise buildings.

***Keywords**: High-rise buildings, Fire safety, System dynamics, Safe hidden trouble, Analogue simulation.*

I. INTRODUCTION

With the continuous acceleration of China's urban development process, the construction speed and scale of high-rise buildings have been significantly improved. High-rise buildings have become the main body to solve the problem of urban population living and improve land utilization. According to data released by the Fire department of the Ministry of Public Security, by 2018, there were 347,000 high-rise buildings with eight floors or more than 24 meters, and more than 6,000 super high-rise buildings with 100 meters or more. According to incomplete statistics, about 31,000 high-rise building fires occurred frequently in China in the past decade, resulting in 474 deaths and direct property losses of 1.56 billion yuan. Especially autumn and winter season, the weather is dry, a little careless, more likely to cause fire. On December 21, 2019, a fire broke out in the Tianzhu Complex building on Longshou North Road in Xi 'an, killing two residents on the 10th floor. On December 22, 2019, six people were found dead in the clearing of a fire at a high-rise residence in Jinnan Road, Guzhen Town, Zhongshan City. At 3am on December 23, 2019, a fire broke out in unit 1, Building 2, Jingjiang Yayuan Community, Dongdong Road, Changsha. Two members of a family were found on the 24th floor and later sent to the hospital to die. It can be seen that due to the characteristics of high-rise buildings, such as

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high floors, complex structure, large population and different functions, fire will inevitably bring huge losses to people's lives and property [1]. Therefore, it is very necessary to discuss the fire hazards in high-rise buildings and find out the reasons why high-rise buildings are more prone to fire.

High-rise buildings are more complex in structural design, fire protection design and construction technology than multi-storey buildings, and more uncertainty is caused by the intensive personnel. Each risk factor interacts with and influences the environment, forming a dynamic feedback system with multiple variables and nonlinear. If we want to make a scientific and effective assessment, we should consider from the perspective of system variability, find out the relationship between the factors accurately, so as to provide a basis for the fire prevention supervision of high-rise buildings.

II. INTRODUCTION TO SYSTEM DYNAMICS MODEL

System dynamics is a science that closely combines system science theory with computer simulation to study the structure and behaviour of system feedback [2]. It is based on cybernetics, system theory, decision theory and other related theories, from a dynamic perspective, the construction of the system model, display and control the system change and development law, and then feedback the system and optimize and control it [3]. The modeling process roughly has the following steps: First, carries on the investigation to the reality system, raises the question; Secondly, key variables are defined according to the assumptions of system behaviour. Thirdly, the causal diagram of the system is designed, equations are determined, parameters are defined and system flow diagram is drawn. Fourth, run the model, use Vensim software to simulate, analyze and observe the dynamic evolution results of the model, and compare it with the real system. Finally, the future development trend of the system is predicted and analyzed according to the simulation results.

III. RISK FACTOR ANALYSIS OF FIRE SAFETY SYSTEM IN HIGH-RISE BUILDINGS

3.1 Impact Factor Analysis

Liao has pointed out in the analysis of high-rise building fire safety characteristics, owners of fire safety awareness is weak, fire facilities configuration is not perfect, fire separation processing is not thorough and other problems are more prominent safety hazards [4]. Based on his working experience, Gao concluded that the main causes of fire disaster are many inflammable decoration materials of high-rise buildings, loopholes in fire safety management and weak business of management personnel [5]. Yang started from the design perspective of high-rise building patios, and believed that although patios could accelerate indoor air circulation, they were very adverse to fire prevention, and the most significant harm was the chimney effect [6]. According to the established fire risk evaluation index system of high-rise buildings, Yu pointed out that the effective design of fire prevention equipment, the reasonable allocation of fire fighting equipment and the implementation of fire control management system are of great help to the avoidance of fire [7]. By sorting out and summarizing relevant literature and combining with the statistical data

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of China Fire Protection Association, this paper concludes that there are four main sources of fire safety hazards in high-rise buildings in the past 10 years, including safety awareness, fire control configuration, design level and fire control management level.

3.2 Causal Loop Diagram

According to the risk factors determined above, the causal loop diagram of fire safety system in high-rise buildings can be constructed (Fig 1). It can be seen from the diagram that the system mainly has four feedback loops:

First, with the continuous improvement of fire education level, people's safety awareness will be constantly enhanced, and the level of fire safety will be continuously improved. After reaching a certain level, the investment in fire education can be reduced.

Secondly, with the continuous increase and improvement of fire control facilities, the level of fire control configuration will be continuously improved, and the level of fire control safety of high-rise buildings will be continuously improved. After reaching a certain degree, the input of fire control facilities can be reduced.

Thirdly, with the continuous improvement of fire designers' skills and level, the level of fire protection design will be continuously improved, and the level of fire protection safety of buildings will be continuously improved. After reaching a certain level, the design input can be reduced.

Fourthly, with the continuous enhancement of fire management measures, the management level of property and fire personnel will be continuously improved, and the fire safety level of buildings will be continuously improved. After reaching a certain degree, the management input can be reduced.

According to the above feedback loop, when the safety input of various factors is increased, the probability of affecting fire safety will be significantly reduced, and the fire safety level will be greatly improved. When the fire safety level reaches a high degree, the input value of various factors can be correspondingly reduced.

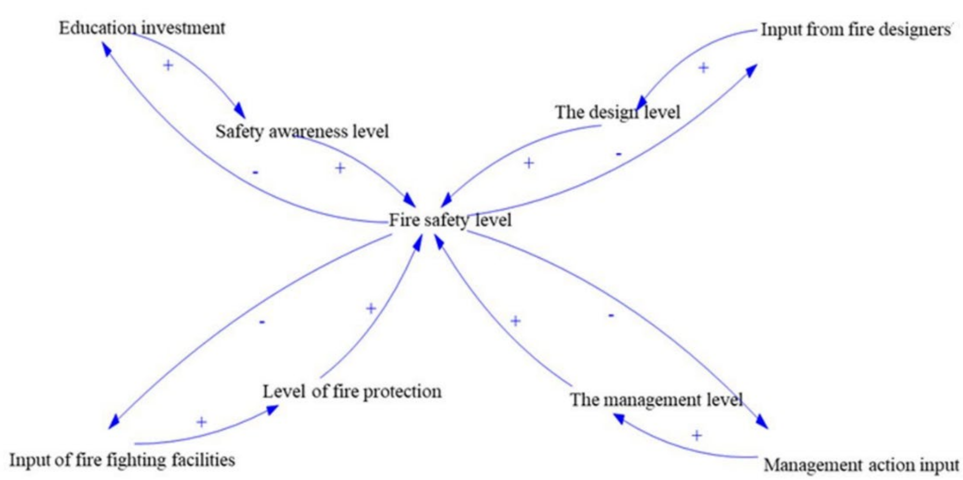

Fig 1: Causal cycle diagram of fire safety system in high-rise buildings

IV. SYSTEM DYNAMICS MODEL CONSTRUCTION

Causal feedback loop system diagram, at the beginning of the modeling can be used to understand the structure of the system, but when the need to quantify the high-rise building fire safety system and the simulation experiment, establish causality diagram is not enough, only then, will need to be in the high-rise building fire safety system factors, on the basis of cause and effect diagram, build a system dynamics model of fire safety.

4.1 Identify Variables

First, determine the boundary of the system, i.e. the key variables in the system. for example, for the first feedback loop, the key variables are: the level of safety consciousness, safety consciousness factors investment growth, safety consciousness into decrement factors influence coefficient, safety consciousness, safety consciousness factors ratio, safety awareness rate of the fire safety level of the system and the safety factor of safety input level 7 variables. Secondly, determine the nature of each variable. The safety awareness level is stock, the influence rate of safety awareness factors is flow rate, the fire safety level is auxiliary variable, the growth rate of fire education investment, the reduction rate of fire education investment, the influence coefficient of safety awareness factors and the influence rate of safety awareness on the system are constant. The set of variables for other feedback loops can be inferred in this way.

4.2 Construct the System Dynamic Flow Diagram

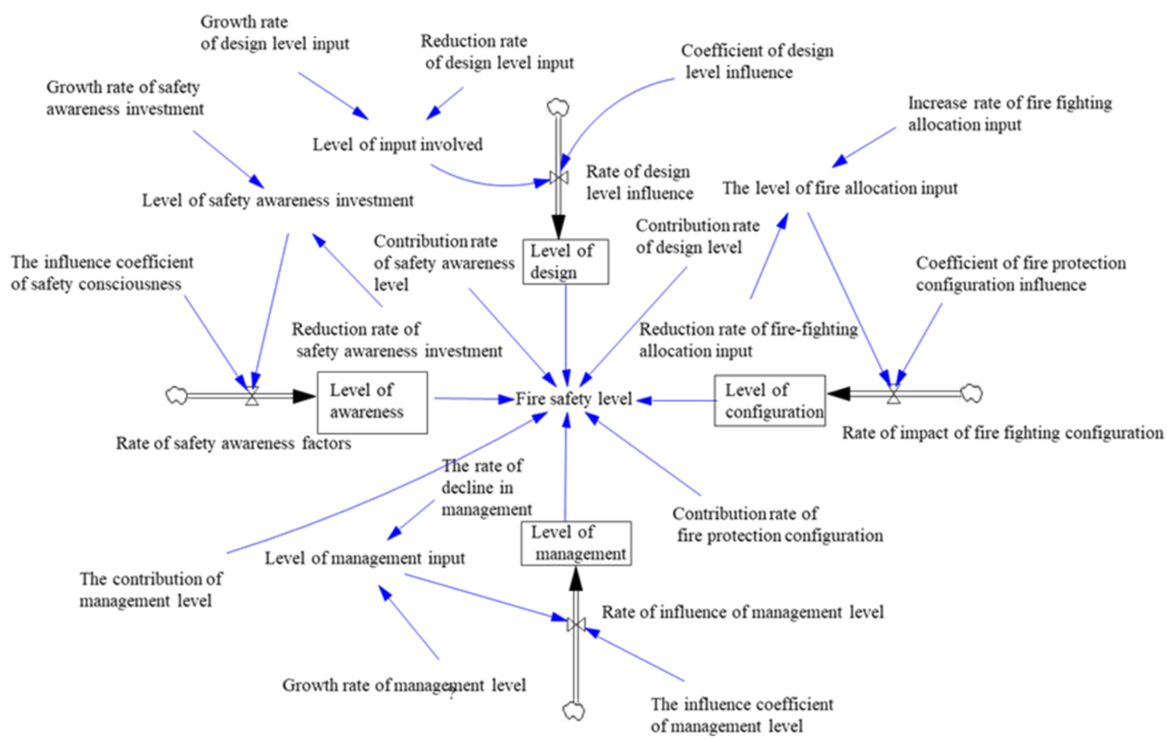

Fig 2: Flow diagram of fire safety system in high-rise buildings

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According to the causal feedback loop, the dynamic flow diagram of fire safety system in high-rise buildings is constructed by using the mechanism principle of flow rate and stock change (Fig 2). It can be seen from the figure that the fire safety target level of the system is the final output end, which is directly affected by the four subsystems such as safety awareness, fire protection configuration and design level. Based on the nature of each variable mentioned above and the research of relevant scholars, the model is constructed. For the fire safety system of high-rise buildings, the level of safety awareness is the stock, and its flow rate is the influence rate of safety awareness factors. Then, the influence coefficient of safety awareness factors and the safety investment level of safety awareness factors that affect safety awareness factors are determined. The investment level of safety awareness is related to the level of fire safety system and the growth rate of safety investment. When it changes, the level of safety investment will change accordingly, thus affecting the influence rate of safety awareness factors.

4.3 Set up the System Dynamics Equation

System dynamics equation is A set of mathematical equations that quantitatively describes the relationship between system elements on the basis of flow diagram, mainly including horizontal equation (L), rate equation (R), auxiliary equation (A), constant equation (C) and initial value equation (N). According to the flow diagram of fire safety system in high-rise buildings, the following equation can be established:

$$\mathrm{L:}\ \mathrm{L} \cdot \mathrm{K} = \mathrm{L} \cdot \mathrm{J} + \left(\sum \mathrm{R} \cdot \mathrm{JK}_{\mathrm{in}} - \sum \mathrm{R} \cdot \mathrm{JK}_{\mathrm{out}}\right) \cdot \mathrm{DT} \tag{1}$$

$$\mathrm{A:}\ \mathrm{out_i K} = \mathrm{out_i J} + (\mathrm{X_i JK}) \cdot \mathrm{DT} \tag{2}$$

$$\mathrm{R:}\ \mathrm{R_i KL} = \mathrm{Z_i} \cdot (\mathrm{out_i K}) \tag{3}$$

$$\mathrm{N:}\ \mathrm{L_i} = \text{The initial value} \quad \mathrm{out_i} = \text{The initial value} \tag{4}$$

$$\mathrm{C:}\ \mathrm{X_i} = \text{constant} \quad \mathrm{Y_i} = \text{constant} \quad \mathrm{Z_i} = \text{constant} \quad \mathrm{M_i} = \text{constant} \tag{5}$$

Among them: DT — Step length;

$\mathrm{X_i}$ — The growth rate of input by various factors;

$\mathrm{Y_i}$ — The reduction rate of each factor input

$\mathrm{Z_i}$ — The influence coefficient of each factor;

$\mathrm{out_i}$ — The level value of each factor input;

$\mathrm{R_i}$ — The rate of influence of each factor

$\mathrm{M_i}$ — The contribution level of each factor to the system;

L — The horizontal value of each factor; K — The present moment;

J — The previous moment; JK — The interval between the two moments

V. SIMULATION ANALYSIS OF SYSTEM DYNAMICS MODEL

5.1 Data Acquisition

5.1.1 Assumptions of the Model

In this paper, two methods, direct and indirect, are used to obtain data information to construct the system dynamics model of high-rise building fire safety system. The model takes the fire

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safety level as the output end and the safety awareness, design level and fire protection configuration as the input end, so as to identify the influence of each variable on the system safety.

Hypothesis 1: The safety level of the system is determined by the above related factors. It is assumed that all major variables are consistent with the above causal diagram, but the specific parameters should be adjusted continuously according to the data substituted into the model.

Hypothesis 2: To ensure the applicability of the model, it is assumed that there are no other risk factors affecting the fire safety system of high-rise buildings during the simulation.

5.1.2 Variable Setting

In this paper, the values of variables in the system equation are mainly obtained by the following methods : Referring to relevant literature, questionnaires, the official website of the national bureau of statistics and the 2018 China fire yearbook; Determine from the relationship between some variables in the model; Estimation of reference behaviour characteristics according to the model; Expert rating.

According to the dynamic model established above, the following variable sets are determined:

First, it is assumed that the initial value of input level of each factor (safety awareness level, fire protection configuration level, design level and management level) = (out1, out2, out3, out4) = (0, 0, 0,0). The simulation time is from 2017 to 2027, and the simulation step length DT is 1 year.

Secondly, after expert evaluation, the initial level of each factor is (L1, L2, L3, L4) = (75, 85, 85, 80). The influence coefficient of each factor is (Z1, Z2, Z3, Z4) = (0.3, 0.3, 0.2, 0.2), and the contribution rate of each factor to the system is (M1, M2, M3, M4) = (0.5, 0.3, 0.1, 0.1).

Finally, after synthesizing relevant studies, official data and referring to expert opinions, the initial value of input growth rate of each factor is (X1, X2, X3, X4) = (0.5, 0.4, 0.6, 0.4), and the initial value of input reduction rate of each factor is (Y1, Y2, Y3, Y4) = (0.03, 0.05, 0.05, 0.06).

5.2 Simulation Results of System Dynamics Model

In order to explore the extent to which various influencing factors in the fire safety hidden danger system affect the system effect, system dynamics software Vensim was used in this simulation, and only one factor was changed while other influencing factors remained unchanged. In this paper, the above four influencing factors are simulated, and the simulated system change results are put into the same figure for comparative analysis. The simulation schemes of different factors are shown in TABLE I.

As can be seen from the above table, this experiment has been simulated for 5 times. Current0 represents the initial state of the system, that is, the initial value when all factor inputs are not adjusted. Current1 represents the rate of increase in security awareness, other factors remaining constant; Current2 represents the rate of increase that only increases the level of fire protection configuration, other factors remain the same, and so on. For the four different influencing factors of high-rise building fire safety hazard only change the input level of one factor at a time, Vensim software can be used to calculate the safety level index of the system under each state and the influence rate of each factor on the system. The specific data are shown in TABLE II and TABLE

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III, and the trend chart of each index changing over time is shown in Fig 3.

TABLE I. Simulation schemes under different conditions

	Level of safety awareness	Level of fire protection configuration	Level of design	Level of management
Current0	0.50	0.40	0.60	0.40
Current1	0.75	0.40	0.60	0.40
Current2	0.50	0.60	0.60	0.40
Current3	0.50	0.40	0.90	0.40
Current4	0.50	0.40	0.60	0.60

TABLE II. Change table of level index data of fire safety system in high-rise buildings (Part 1)

Year	1	2	3	4	5
Current0	79.5	159.12	318.36	636.85	1273.81
Current1	79.5	159.16	318.48	637.11	1274.38
Current2	79.5	159.14	318.42	636.97	1274.08
Current3	79.5	159.13	318.38	636.89	1273.90
Current4	79.5	159.13	318.38	636.88	1273.88

TABLE III. Change table of level index data of fire safety system in high-rise buildings (Part 2)

Year	6	7	8	9	10	11
Current0	2547.75	5095.62	10191.40	20382.90	40765.80	81531.80
Current1	2548.91	5097.98	10196.10	20392.40	40785.00	81570.10
Current2	2548.31	5096.76	10193.70	20387.40	40775.00	81550.20
Current3	2547.94	5096.00	10192.10	20384.40	40768.90	81537.90
Current4	2547.88	5095.87	10191.90	20383.90	40767.90	81535.90

It can be seen from TABLE II, TABLE III and Fig 3 that Current0 is the security level state of the system without any input increase or decrease in each factor. With the increase of the safety investment level of each factor, the safety level index of the system is changing constantly. Take Current0 value as an example, the average value of the safety level index of the system is

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14,816.64. When the value corresponding to Current1 is subtracted from it, the average value is calculated to get 3.48, and then the two mean values are compared to get 0.0026. According to relevant literature [3], it reflects the impact on the fire safety system of high-rise buildings when the increase rate of safety awareness level investment increases the most. Based on the above calculation, the influence rates of fire protection configuration level investment, design level investment and management level investment on system safety are 0.0025, 0.0008 and 0.0006.

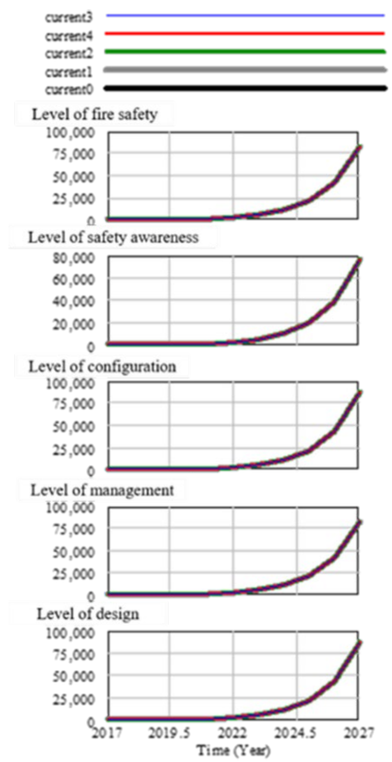

Fig 3: Change value of safety level index of fire control system at the same rate of increase of safety input of each factor

VI. CONCLUSION

High-rise buildings are characterized by multiple floors and complex structures. In case of fire, it is difficult to evacuate and difficult for residents to escape. Therefore, for high-rise building fire, the emphasis is on prevention. This paper analyzes the main factors affecting the fire safety system of high-rise buildings, establishes the system dynamics model by using Vensim software, and draws conclusions by analyzing the relevant basic data.

First, through questionnaire and literature collection, four kinds of factors influencing fire safety of high-rise buildings are screened out. Secondly, the system dynamics model of high-rise building fire safety is constructed, the causal relationship between each factor and the system is studied, the dynamic equation is established through the system flow diagram, and the influence degree of each influencing factor on high-rise building fire safety system is obtained. Finally, through the analysis and sequencing of the simulation results, it is clear that the level of safety

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awareness is the most important factor affecting the fire safety of high-rise buildings and the focus of fire hazard prevention and control, so as to provide reference for the fire safety hazard detection and fire prevention of high-rise buildings.

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