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Research on Assessment Method of Fire Protection System

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Abstract

Safety assessment of fire protection (SAFP) is a very important approach in fire safety management. Effectiveness and reliability are crucial to the SAFP, which has endowed the study of the assessment methods significant meaning. A new quantitative method named theoretical safety control method, based on modern control theory, was studied in the paper. Dynamic models, assessment indexes and analysis approaches of every index of the SAFP were put forward and three dynamic indexes, that are System Hazard Index-H, Control Capacity Index-C and Safety Degree-S which changed with the system states and presented the conflicting consequence between hazards and controlling of fire protection system, were used to evaluate the results of the method. This method can realize dynamic and quantitative management and the fire protection system controlling. A case study was defined and assessed by using the method in this paper, and the results of evaluation were viable compared with the actual situation.

Keywords: Safety Assessment of Fire Protection System, Safety Control Theory, Safety indexes

1. Introduction

Fire is one of the most frequent disasters which had been happened 3078150 times from 1950 to 1998 according to *Chinese Statistic Yearbook of Fire (Edition 1999)*. There were 161866 persons died, 310083 injured and 168476.62 million Yuan directly lost in those fires. Table1 is the basic data of fire statistics in China from 2000 to 2007.

Table1 The basic data of fire statistics in China from 2000 to 2007.

Year	Fire number	Death	Injury	Direct loss Ten Thousand Yuan
2000	189,185	3,021	4,404	20,013.9
2001	123,929	3,752	2,314	93,659.1

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2002	258,315	3,414	2,393	154,000.0
2003	253,932	2,482	3,057	159,000.0
2004	252,704	2,558	2,969	167,197.3
2005	235,941	2,500	2,508	136,603.4
2006	222,702	1,517	1,418	78,446.9
2007	159,000	1,418	863	990,000.0

Note: The fire-related statistics data over the years quoted from Chinese Statistic Yearbook of Fire

Table1 shows that the numbers of fire were large and the losses were serious. So, it is of great significance to reduce the occurrence rate of fire accidents and improve fire safety management by the development of fire science, fire safety technology and management methods. As for China, the management method must be fit for the current economic development and social needs. SAFP is a very important approach in fire safety management. Its theory and method is an important part of fire science and a scientific base of fire prevention with effectiveness, rationality and economy.

Nomenclature

A,B,C	Detection grade	A_t	The total areas
A	Matrix	$S(k)$	The safety degree
$B(k)$	The control effect of annual	k	The annual
C	Control capacity coefficient of risk	α，β	Constants
H	The hazard coefficient，	H_p	The personal density index in building
w_i	The weight	γ	The correction index
M_v	The weight of one combustible matter	Δh_c	The effective heat value of one combustible matter

2. The assessment theory and indexes of the fire fighting system

Fire safety assessment began to be studied in many countries from the early of 1970s. Some developed countries such as England, Japan, Australia, America, Canada, New Zealand, North Europe and etc, have been invested a lot of money in it, major in performance-based fire design. Performance-based fire design, based on the fire safety engineering, uses the fire safety engineering principle and method to forecast and quantitatively evaluate the risks of fire and the damages of buildings according to the specific circumstances such as the building structure, purpose, inner inflammable matters. As a result, a rational fire safety planning can be obtained and the buildings can be protected reliably.

Researches of fire safety assessment in China are very later. The main research organizations are Institute of Fire, China Academy of Building Research, State Key Laboratory of Fire Science, University of Science and Technology of China, the four Fire Research Institute, China Academy of Safety Science and Technology, Tongji University and etc. In recent years, some results have been achieved [1].

There are many methods about fire safety assessment at present which are categorized into qualitative, half-quantitative and quantitative. Qualitative methods include SCA, PHA, DOW, MOND, HAZOP, WHAT-IF and etc. Half-quantitative methods include NFPA101M fire assessment system [2], SIA81 method (i.e. Gretener) [3], Fire Risk Index method [4], Gustave method [1] and etc. NFPA101M fire assessment system is a united method for the assessment of hygiene establishment which is developed in America and mainly undertakes dynamic decision-making in public locations and residential areas management. SIA81 method is developed in Switzerland which takes the losses as a base and takes the experiences decision as a complement. This method can assess the fire risk by statistic approach. Fire Risk Index method was brought forward by Swedish which is used to evaluate the fire risk of frame house in North Europe, is also used in the flammable and non-flammable tier mansion-building. Gustave method is a plane analysis approach which estimated the fire risk of building by using the damage grade of the building and the harm grade of the staff and properties in the building.

Quantitative methods include L-curve, CrispII(England), FIRECAMTM, CESRE-Risk (Australian), ETA, FTA and Fuzzy math method[1].

Majority quantitative methods above need a large number of data to calculate the accidental probability and the consequence of the building fire. Since the established time of China is short, the changes of politics and economy are prominent since 1949. Thus only the fire-related statistics data since the 1980s are suitable for these assessment methods. There is a problem belong to small sample while large noise in using these data. In order to quantitative assess fire protection systems in China, theoretical safety control method was put forward in this study. Safety System Engineering method was used in this method to identify the risks of fire protection system of building and discover the hidden troubles of the system in time. And a math model about fire control and forecast was developed, which is based on the Modern Control Theory, to evaluate the dynamic safety of fire system scientifically and make decision to improve the safety degree of the fire protection system. A case study was defined, which derived from the actual building.

Fire protection system is a large complex system which contains planning, design, installation, debugging, running, maintaining, inspection, management, personnel disposition and safety consciousness. Those systems were categorized into three kinds which are fire technology, personnel disposition, and management. So the safety evaluation of fire system is the comprehensive evaluation of the technology, management and persons, then judge the hazard resources, the control capacity of hazards and safety degree of the system. Theoretical safety control method, based on the methodology, control-mechanism and math models of Modern Control Theory, uses safety checklist analysis, questionnaire, scoring method and etc to realize dynamic and closed loop controlling of the safety system. The control process figure sees the *Figure1*.

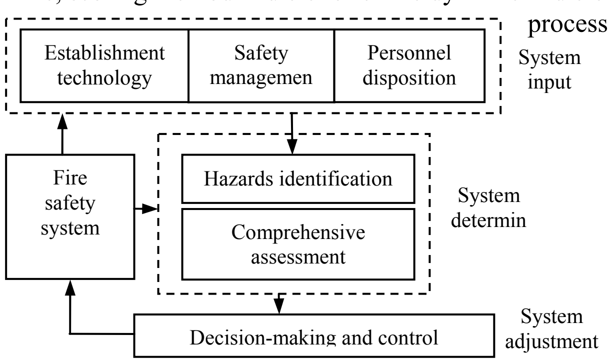

Fig. 1 The control process of fire safety assessment

3. The assessment theory and indexes of the fire fighting system

3.1. Models

(1) The definition of safety degree [5],

$$S = -12.1 \ln Y = 12.1 \ln Mt \quad (1)$$

Where, Y is annual million casualty rate of system, M is the number of people in the system，t is the average non-accident time.

(2) The dynamic models of safety degree

Safety degree of system is changing dynamically with the difference of safety state of the system. The motivity of dynamic variety is the result of conflict between hazard and control, namely hazard control effect. The safety degree of system is the summation between primitive safety degree and hazard control effect of the system in a certain time. They obey functions (2) and (3),

$$S(k) = S(k-1) + B(k) \quad (2)$$

$$B(k) = \alpha C - \beta H \quad (3)$$

Where $S(k)$ is the safety degree of annual, $S(k-1)$ is the primitive safety degree, k is the annual, C is the control capacity coefficient of risk, H is the hazard coefficient，$B(k)$ is the control effect of annual, α，β are constants, usually, they are：$\alpha=0.0688$，$\beta=0.55$。

Function（2）is the dynamic model of safety degree, it shows that the safety degree of system has accumulative effects. Function（3）is the result of conflict between hazard-H and control-C of the safety system. When $B(k)>0$, it represents that C is dominant and S is increasing. When $B(k)=0$, it represents that H and C are in the same level and S is steady. *When* $B(k)<0$, it represents that C is inferior and S is decreasing.

3.2. The indexes with respect to the control effect of system

3.2.1 Hazard coefficient-H

H is comprehensive result of many hazard sources in the system. The following is the expression of H:

$$H = \gamma Hs Hp H_1 H_2 H_3 \quad (4)$$

Where, γ is the correction index of building type; Hs is intrinsically hazard index of fire system, H_p is the personal density index in building, H_1 is the hazard index of fire establishment, H_2 is the hazard index of fire management, H_3 is the hazard index of fire loads of building or location.

Some risk indexes of building are shown in *Table2* [6]:

Table 2 the risk index

The correction index of building type γ							
Type	Workshop	Residence	Office building	Teaching building	Hotel	Hospital building	Business building
index	0.8	1.0	1.1	1.2	1.3	1.4	1.5
The personal density index in building H_p							
Density	0.1	0.5	1.0	1.5	≥2		
Index	1.0	1.1	1.3	1.6	2.0		

3.2.2 Control capacity coefficient of risk-C

In order to determine the coefficient *C*, effect factors include running state of fire system (which contains fire control plan, fire-restarted technology, fire detected technology, fire extinct technology and fire exit system), fire safety management, comprehensive qualities and safety consciousness of personnel should be considered.
Fire control plan involves design of smoke control, fire compartment, and fire separation (namely, fire doors, fire windows, fire curtains, smoke blocking wall, fire safety distance). Fire-restarted technology contains fire restarted coating material, fire resistant walls, fire restarted chemical, smoke control chemical and etc. Fire detected technology includes smoke detection, temperature detection, infrared detection, TV monitor, ultrasonic detection, flammable gas detection and so forth. Fire extinct technology contains water spray auto-fire-extinguishing system, foam spray auto- fire-extinguishing system, gas spray auto-fire-extinguishing system, dry power spray auto-fire-extinguishing system, portable fire extinguisher, fire extinguisher of push-type, indoor hydrant, fire fighting cannon, fire hydraulic gun, fire alarming equipment and so on. Fire exit system involves exit passage, fire elevator, exit signs, emergency lights, emergency broadcasting, fire alarm bell, fire power distribution system and etc.

The accumulative expression of *C* is:

$$C = \sum_{i}^{n} w_i C_i \tag{5}$$

Where, C_i is the control capacity index of every effect factor, it is scored by using the relative safety checklist or detection rules of fire establishment according with the difference of the assessment objects. w_i is the weight of every effect factor which is scored according with the difference of the assessment objects, and $\sum_i w_i = 1$. Finally, *C* is calculated by formula (5).

4. The case study

The case is about the quantitative risk assessment of an office building which has five layers. For the basis instance see *Table3*.

Table 3 the basis instance at the present case-studied

Basis information	The building has five layers which are 15000 square meter per layer, 40 offices which are 300 square meters per room, and a man lift. Personnel flux of the building is 200 persons per day, and average personnel density is less than 0.1.
Layer equipment	There are 400 computers worth 30 ten thousand Yuan, 350 apparatus and instrument worth about 1000 ten thousand Yuan, 5 severs worth 30 ten thousand Yuan, 200 wall air-condition worth about 60 ten thousand Yuan. There are many the desks and chairs, books and papers, management files and etc worth about 150 ten thousand Yuan, and fitment material for the building worth 16 ten thousand Yuan.
Fire establishment	There are 2 indoor hydrants, 16 ABC hand-hold fire extinguisher, 6 gas masks, 2 infrared detector of safety (not for fire), 3 electric emergency bells at each floor. The building has 2 exit stairs, 4 exits toward outer on the first floor. There is 1 emergency light in every room. There are 3 emergency lights, evacuation signs spaced 12 meters in each corridor. There is auto-water-spray fire extinguishing devices in some files management offices. Around this building, there are neither outdoor hydrants nor fire fighting pool.

4.1. Determining the value of H

According with the basic information of the building above and compared with *table 2*, let $\gamma=1.1$ and $Hp=1.0$. Let $Hs=1$ because there has not taken any equipments and methods in the aspect of intrinsically safety to prevent the domino effect from the risk-protection, establishment failure and miss-operating.

Fire load calculation is the foundation to forecast the size and severity of potential fire. Fire load is defined as the gross heat value released from all the combustible matters burning in the building, and the fire load density is the heat value in area unit.

The calculation equation of fire load density is [7]:

$$q = \frac{\sum Mv\Delta hc}{At} \tag{6}$$

Where, M_v is the weight of one combustible matter (kg); Δh_c is the effective heat value of one combustible matter (MJ/kg); A_t is the total areas (m^2).

According with equation (6) and Table 3, the gross heat can be calculated and converted into the standards equivalent of timber. The calculated values are that the total heat value is 2580000MJ and the equivalent of timber is 34.490.7MJ/m^2. Then, compared the calculated result with the density of fire loads in building in Table 4, we get H_3=3.

The advance safety checklist is used to check and inspect the statue of the equipments, establishments, processing, and the management. Compared the results with the design, installation and debugging files of the project, we paid the risk of fire establishment a value that of this building is 78 , and paid the risk of fire system management another value that of this building is 80, while the full values are 100. Then, compared those values with the marks in Table 4, we get H_1＝1 and H_2＝0.8.

Table4 the risk index II

Risk index of fire establishment H_1							
Mark	<30	40	50	60	70	80	>90
Index	5	4	3	2	1	0.8	0.5
Risk index of fire system management H_2							
Mark	<30	40	50	60	70	80	>90
Index	5	4	3	2	1	0.8	0.5
The density index of fire loads in building（Equivalent wood kg/m2）H_3							
Density	<10	20	30	50	>50		
Index	1.5	2	3	4	5		

Then, the value of H of this building is

$$H = \gamma HsHpH_1H_2H_3 = 1.1*1*1.0*3*1*0.8=2.64$$

4.2. Confirmation C

4.2.1 The different impact factors of C

The operation of the fire system is inspected or tested one by one based on the rules of fire establishments' detection, and every items was scored. Because there are a large number of items, the full mark is set for 1000 points for the sake of scoring rationality. The safety management, personal disposition and safety consciousness is scored according to the inquiry of the staff in the building by the way of Question and Answer. The results were converted to hundred-mark system.

(1) The confirmation of check and testing of fire establishments-C_1

In the light of the rules of fire establishments' detection as shown in *Table 5* (here only a segment is shown), the fire establishment in this case study was checked and tested, and the results are shown in *Table 6*. There are 500 points adapted to the office building which obtained 405 points that is 81 points in hundred-mark system.

Table 5 A segment of the rules of fire establishments' detection

Number	Check items	Grade	Check standard	Check kind	Check tools
010108	"119"straight telephone	B	Should setup straight alarm telephone and call normally(GB50116-98 5.6.4 and GA503-2004 4.13.3)	Qualitative	/
0102	Fire alarm controller				
010201	The type and the mark of controller	C	The mark must be evident and clear（GA503-2004 4.1.2 and 4.9.1.2）	Qualitative	/
010202	Installation dimension	C	Positive operating distance≥1.2m（GB50116-98 5.2.2.5）	Quantitative	5m steel tapeline(the scale is mm)
010203	Installation dimension	C	Side distance close axis≥0.5m（GB50116-98 5.2.2.5）	Quantitative	5m steel tapeline(the scale is mm)
010204	installation fastness extend	C	Fastness, stationary and no-slant（GB50166-92 2.5.2）	Qualitative	level ruler
			…… ……		

Notice: For every item, there is a corresponding blank sheet to record the results, here is omitted.

Table 6 The check results of this case study

Items No.	Grade	Check standard	Results	Score deduct
010108	B	Should set alarm telephone-"119",and can call normally（GB50116-98 5.6.4 and GA503-2004 4.13.3）	no	10
030501	A	Should set the outdoor hydrant and fire pool（GB 50016—2006 8.3.2 and 8.3.3）	no	15
040101	B	The walkway and the office in the building should set spray water shut-auto fire extinguishing system（GB 50016—2006 8.7.1）	Only some rooms of files management set	10
060101	A	The inner exit stairs in the public building should set stair well, and other stairs over five layers should set shut stair well（GB 50016—2006 5.3.7）	Not set stair well	15
060112	A	The safety exits of public building isn't less than two(GB 50016—2006 5.3.1)	The exits are enough, however, only one is opened, and the other three are locked	8
201003	A	The numbers of fire extinguishers are enough（GB50140－2005 6.1.1 and GB50160－92 7.7.3）	The numbers are shortage	15
		…… ……		
Total				95

(2)The confirmation of safety management C_2 , personnel disposition and safety consciousness C_3

There are 7 building managers and 200 persons in offices who are investigated, and the evaluation results are shown in *Table 7*.

Table 7 The evaluation results of C2 and C3

Persons	Number	Personnel disposition and safety consciousness	Safety management	Score
The building managers	7	Know some knowledge about fire safety information. Have fire prevention consciousness and the capacity of control and management hidden trouble about fire	Fire safety state was inspected only at several great feasts and holidays. The fire alarm and detection system has not been used. The fire system did not be maintained and tested.	75
The persons in offices	200	Know some knowledge about fire safety information. Can not be alarmed when firing. Have safety prevention consciousness and some knowledge about escaping	Could cooperate with the others when firing, but they are still likely to act alone.	82

From above evaluation, we get $C_1=81$, $C_2=75$, and $C_3=82$.

4.2.2 The weights of C_i -w_i

In order to avoid the *subjective* effect, Analytic Hierarchy Process (AHP) method, which is based on the modern decision-making and statistic analysis theory, was applied to calculate the weighs of C_i. AHP method is realized by a comparative matrix A, that is $A=(a_{ij})_{n\times n}$. Where, $a_{ij}=A_i/A_j$ is the significance degree ratio between each two factors. A_i and A_j are valued according to the rules in table 8. Furthermore subdivided, the values of them may adopt the middle numbers such as 2, 4 and 6….In the case study, a triple matrix is used to calculate the weighs of C_i, and its expression is,

$$A=\begin{bmatrix}\frac{A1}{A1} & \frac{A1}{A2} & \frac{A1}{A3}\\ \frac{A2}{A1} & \frac{A2}{A2} & \frac{A2}{A3}\\ \frac{A3}{A1} & \frac{A3}{A2} & \frac{A3}{A3}\end{bmatrix}=\begin{bmatrix}1 & 3/2 & 3\\ 2/3 & 1 & 2\\ 1/3 & 1/2 & 1\end{bmatrix}.$$

Where, A_1 represents the check and testing results of fire establishments, A_2 represents the safety management level, and A_3 represents the personnel disposition and safety consciousness level.

Table8 The rules of significance degree of Ai and Aj

Value	Comparison Results-a_{ij}
1	A_i is as important as A_j
3	A_i is more important than A_j
5	A_i is much more important than A_j
7	A_i is highly important compared with A_j
9	A_i is extremely important compared with A_j

After matrix calculation and normalization, we get the weights of C_i which are $w=(0.5，0.33，0.17)$. According to equation (5)，$C=\sum_{i}^{n} wiCi$ =79.5.

This building has been used for five years, so $k=5$. Apply the results of C and H to calculate equation (3), obtain $B(5)$=4.02>0 that represents C is dominant and S is increasing.

5. Discussion

As shown in Figure2, the safety degree is divided into 5 grades while 60 points is the threshold of pass.

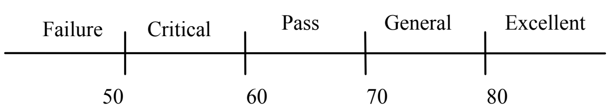

Fig. 2 The grades of safety degree

According to the state equation of safety control theory [5]:

$$Y(k)=(1-C(k))Y(k-1)+H(k) \qquad (7)$$

From equation (7), we conclude that $\lim_{k\to\infty} Y(k)=\frac{H}{C}$. It represents that when the system has been running some years, the casualty rates will keep a stable value.

For $\lim_{k\to 0} Y(k)=Y(0)$, $Y(0)$ is the initial casualty rate that is the casualty rate when the safety degree $S_0=60$.

Assumed the controlled effect of the building is basic balance in the first five years, then $B(1)= B(2)= B(3)= B(4)= B(5)=4.02$.

The safety degree of system $S(5)$=80.1 which is referred from equation (2). Status of the building is excellent which is concluded from *Figure2*. However, the fire management should be strengthened and the corresponding contents of management will be included in the assessed items.

6. Conclusion

- (1)In order to realize dynamic and quantitative fire management and control, a new quantitative fire safety assessment method Modern Safety Control Theory was put forward in the study.
- (2) Some math models and assessment indexes of fire system were proposed.
- (3) The corresponding factors with H and C are found out, and AHP approach is used to calculate the weights of all those factors.
- (4) The dynamic model of safety degree was cited which is changed with the safety status of the system, and which is the contradicting consequence between hazard and control in fire system.
- (5) This new assessment method was used to assess an actual case building. The results show that this method is suitable for building fire safety assessment.

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