1. Introduction

Fire is crucial for the development of human society, and it has become an important part of human civilization. Among different types of disasters, fire constitutes a significant threat to life and property in urban and rural areas. According to the data offered by the Fire Service Bureau, Ministry of Public Security, in 2011, a total of 125,417 fires were reported in mainland China, 1108 civilian deaths, 571 civilian injuries, and 2057 million Yuan (RMB) direct property losses [1]. Building fires, especially residential fires, remain a critical concern as 32,661 fires or 39.7% of all fires occurred in residential buildings, resulting in direct property damage of approximately 309 million Yuan (RMB), 853 civilian deaths and 347 civilian injuries [2–5]. Society has responded to the threat of fire in buildings in many ways, including fire department intervention, insurance, building regulations, education on fire hazards, controls on the use of materials and products in buildings, and the design of buildings to resist the effects of fire. A growing concern in China is how to take appropriate fire risk management measures in buildings, prevent and control potential fire accidents, reduce the casualties and losses of accidents, and ensure building fire safety.

This definition of risk management used in the paper has been adopted from ISO 31000:2009 [6,7]. According to the definition, risk management includes risk assessment and risk treatment, and the different stages in fire risk management procedures are illustrated in Fig. 1. The risk assessment of a system consists of identifying hazards, the comparison with targets, and the search for optimal solutions [8]. Fire risk assessment in buildings comprises three steps of fire risk identification, fire risk analysis, and fire risk evaluation. Fire risk identification is the systematic process to understand how, when, and why fire could happen. Fire risk analysis is the process of estimating magnitudes of consequence and probabilities of the adverse effects resulting from fire in a building [9]. The end result of fire risk analysis is expressed either in qualitative, mixed or quantitative terms depending on the type of risk, the purpose of risk analysis, how detailed the analysis is to be and the information resources available. Fire risk evaluation then involves applying the developed risk criteria and making a decision about the level of fire risk. Fire risk treatment is the process of improving existing risk controlling measures, developing new risk controlling measures and implementing these measures to reduce fire risk. Therefore, fire risk analysis is only one part of fire risk management process, and it serves as the foundation of regulatory decision-making on whether to take actions to reduce risk or choose appropriate risk treatment.
measures or not [10]. Research related to fire risk analysis is, therefore, critical and essential.

With development of performance-based design, some studies have been conducted on fire risk analysis in buildings from different perspectives and levels. Models such as FiRECAM [11,12] and FiERAsystem [13] were used to calculate the expected life risk. In other studies probabilistic methods have been used to assess levels of people safety in buildings [14]. Quantitative risk analysis approaches have also been used to quantify the risk to occupants using stochastic factors [15]. However, studies to date have largely been concerned with various aspects of fire risk analysis and there has been little in the way of development of systematic theoretical methods for analyzing fire risk in buildings in terms of fire risk management. Existing fire risk management involves the identification of alternative fire safety design options [16,17], the ongoing inspection, maintenance of fire protection systems [18] and evacuation training and drills [19]. In this study, basic process of fire risk analysis in building is described, and a fire risk analysis model based on scenario clusters is established with consideration of the characteristics of fire dynamics and occupants’ behavior. The number of deaths and directive property loss are selected as fire risk indices and the average fire risk of residential buildings is quantitatively analyzed, so that appropriate fire risk management measures can be adopted.

2. Fire risk analysis process of buildings

Fire risk is defined as the product of the probability of fire occurrence and the consequence or extent of damage to be expected on the occurrence of fire [20]. It is a function of three factors: loss of or harm to something that is valued (e.g., life, property, business continuity, heritage, the environment, or some combination of these), the scenario that may induce the loss or harm, and a judgment about the probability that the loss or harm will occur. Fire risk is a weighted average of the risk values of each scenario, and it can be presented with the following formula:

\[ FR = \sum_{i=1}^{n} P_i C_i \]  

where, \( FR \) is the fire risk (fatalities per year or money per year), \( P_i \) is the probability of occurrence of fire scenario \( i \) \( (\text{year}^{-1}) \), \( C_i \) is consequences of scenario \( i \) (fatalities or money), \( n \) represents the total number of scenarios.

There are many quantitative measures for building fire risk, such as fire death rate per 100,000 population, annual mortality rate, loss of life expectancy, and so on. In this paper, the risk of occupant deaths (\( FR_o \)) and risk of the directive property loss (\( FR_p \)) are selected as fire risk indexes to quantify building fire risk [21].

\[ FR_o = P_f C_o/f \] (2)

\[ FR_p = P_f C_p/f \] (3)

where, \( P_f \) is the frequency of occurrence of a developed accidental fire in buildings, \( C_o/f \) is the number of deaths due to the occurrence of fire accidents, \( C_p/f \) is the directive property loss due to the occurrence of fire accidents.

The different stages involved in analyzing building fire risk are shown in Fig. 2. Each of these steps is now considered in turn.

2.1. Definition of the target building

The first step is to obtain relevant information about the target building. Required information related to the building includes the size, location, construction, the processes carried out in the building, fire safety prevention systems, the nature and likely state of occupants and the information on fire department such as the distance to the target building should be acknowledged.

2.2. Identification of fire hazards

Identification of fire hazards is a process of recognizing that hazards exist and de...

2.3. Design of fire scenario clusters

A 'fire scenario cluster' is a subset of fire scenarios that resembles each other. It could group the universe of possible fires into a manageable number of scenario subsets so that all the elements are present [22]. A fire scenario is a sequential set of fire events that are linked together by the success or failure of certain fire protection systems or actions [23]. A fire event is an occurrence that is related to fire initiation, or fire growth, or smoke spread, or occupant behavior, or fire department response [24]. In the process of understanding fire risk analysis, three fire scenario clusters can be considered important to support calculations of frequency and consequence; namely a fire scenario cluster, a fire automatic suppression scenario cluster, and a behavior cluster.

The fire scenario cluster must specify all the elements including design fire curve and as well many other surrounding circumstances of the fire, such as compartment geometry and properties,
dimensions of the fire origin room, the thermal properties of the compartment boundaries [25]. Design fire curve is meant that fire growth rate and other specification, such as the point of fire origin, are required for a full description [26]. The fire automatic suppression scenario cluster describes the process of fire repression, either through the extinguishing of the fire or the control of the fire from further progress using for example knowledge of construction engineering. Initial status of fire detection and alarm equipment [27], fire sprinklers [28], smoke control systems [29] all would be included, and they could induce different fire suppression scenarios. The principal elements a fire scenario and a fire automatic suppression scenario are shown in Fig. 3.

The behavior scenario cluster describes the behavior of occupants in response to the onset of the fire and the intervention of fire and rescue services in the case of building fires. The location, personality traits, knowledge and experience, powers of observation and judgment, mobility, awareness, roles or responsibilities in buildings, and familiarity with the layout of buildings all influence occupants behaviors [30]. Major factors influencing fire brigade intervention are intervention time, crew size and fire fighting water resources [31,32]. Elements of behavioral scenarios of occupants in buildings and fire department intervention are shown in Fig. 4.

2.4. Estimation of frequencies

Based on three scenario clusters established in the process of fire risk analysis in buildings, the frequency of occurrence of a developed accidental fire in a building with ground area $A$ during the reference time of 1 year ($P_f$) is the product of the ignition frequency ($P_i$), the probability of failure of firefighting by automatic extinction system ($P_2$), and the probability of failure of firefighting by users or fire department ($P_3$).

$$P_f = P_i P_2 P_3$$  \hspace{1cm} (4)

2.4.1. Ignition frequency

For quantitative estimation of fire risks, reliable ignition frequency is a prerequisite. Annual ignition frequency depends on building category [33], and ignition frequency within each building category depends on the floor area of the building [34]. Average ignition frequency of residential building categories for different countries is derived from different countries' fire statistics [21]. However, analysis of the statistics of floor area shows that they can have distributions of many functional forms [35]. A more flexible functional form to model the dependence of the average annual probability of a fire starting in a building in the category under study on the floor area of the building, is a generalization of a model originally proposed by a French probabilist called Barrios in 1835. Parameters of the generalized Barrios model are shown in Table 1 [36].

$$P_1(A) = c_1 A^r + c_2 A^s$$  \hspace{1cm} (5)

where, $P_1(A)$ is ignition frequency of building with a floor area $A$ during the reference time of 1 year, $A$ is the total floor area of the building, $c_1$, $c_2$, $r$ and $s$ are coefficients.

2.4.2. Probability of failure of firefighting by automatic extinction system

One way to control fire development is the use of automatic suppression systems, which either extinguish the fire or control it from further development. The probability of success of suppressing a fire depends on the reliability and effectiveness of the suppression system, and can be obtained from fire statistics.
Three fire types including smoldering fires, non-flashover flaming fires, and flashover fires can be identified based on fire statistics. For flashover fires, the probability of success of suppression system is usually high, because the heat release rate can activate the system. The probability of success is not so high for non-flashover fires, and the probability of success is basically zero for smoldering fires. Table 2 shows the sprinkler performance for large fires including flashover fires and some large non-flashover fires that should activate the sprinkler [37]. In this table, reliability is the probability of sprinkler activation against large fires, the effectiveness is the probability of controlling fires once sprinkler is activated, probability of success is the product of reliability and effectiveness.

Table 1
Parameters of the generalized Barrios model.

| Building category                  | C1        | C2 × 10^-6 | r    | s    |
|-----------------------------------|-----------|------------|------|------|
| Residential buildings             | 0.010     | 5          | -1.83| -0.05|
| Commercial buildings              | 7 × 10^-5 | 6          | -0.65| -0.05|
| Office buildings                   | 0.056     | 3          | -2.00| -0.05|
| Transport, fire-fighting and rescue-service buildings | 7 × 10^-5 | 1          | -0.65| -0.05|
| Institutional care buildings      | 2 × 10^-4 | 5          | -0.61| -0.05|
| Assembly buildings                 | 0.003     | 2          | -1.14| -0.05|
| Educational buildings              | 0.03      | 3          | -1.26| -0.05|
| Industrial buildings               | 3 × 10^-4 | 5          | -0.61| -0.05|
| Warehouses                         | 3.62      | 2          | -2.08| -0.05|
| Other buildings                    | 1.18      | 100        | -1.87| -0.20|

Table 2
Sprinkler performance.

| Occupancy                      | Reliability of activation (%) | Effectiveness of suppression (%) | Probability of success (%) |
|--------------------------------|------------------------------|---------------------------------|---------------------------|
| Apartments                      | 98                           | 98                              | 96                        |
| Health care or correctional     | 96                           | 100                             | 96                        |
| One or two family dwelling      | 94                           | 100                             | 94                        |
| Educational                     | 92                           | 100                             | 92                        |
| Hotel or motel                  | 97                           | 94                              | 91                        |
| Stores and offices              | 92                           | 97                              | 90                        |
| Manufacturing                   | 93                           | 94                              | 87                        |
| Public assembly                 | 90                           | 89                              | 81                        |
| Storage                         | 85                           | 90                              | 77                        |

2.4.3. Probability of failure of firefighting by users or fire department

The probability of successful manual extinguishing was based on the fire accident statistics. There is very little information in the literature about the extinguishment of a fire by a building’s occupants, even though in 78% of the domestic fires in Great Britain and 75.2% of those in Australia, the fire service was not called out [38]. This suggests that about three quarters of the fires in these countries had either extinguished themselves, or this had been achieved through the actions of occupants.

The probability of success of fire department intervention largely depends on intervention time of fire department, availability of adequate response resources, and fire development in buildings. The intervention time is defined as the duration from the time of ignition of a fire to the time when the fire department commences fire extinguishment and rescue efforts. The quicker the intervention time, the less severe is the fire, and the smaller the effort that is required to fight the fire and to rescue any trapped occupants. The effectiveness of fire extinguishment can be modeled as a function of the ratio of the firefighter’s intervention time to the flashover time [16].

2.5. Estimation of consequences and calculation of fire risk

Consequences of building fires involve more than occupant fatalities, it involves also the loss of property, loss of business and so on, as a result of fires. In this paper the consequences of building fires are confined to those resulting from occupant fatalities and directive property loss. For different building categories, the number of occupant fatalities and the loss of directive property can be obtained from fire statistics. Then, the fire risk of building, i.e. the expected risk to life to the occupants and the expected loss of directive property are estimated according to Eqs. (2) and (3).

3. Case study

In China, buildings were categorized into four different building categories including residential buildings, industry buildings, public buildings and agricultural houses. Fire occurrences from 2007 to 2010 in China are presented in Table 3 [2]. Average 39% of all fires from 2007 to 2010 occurred in residential buildings, and residential building fires are selected for consideration.

3.1. Average fire risk in residential buildings

The statistics of fire occurrence and floor area during 2007–2010 were collected from China fire services [2] and China statistical yearbook [39], and presented in Tables 4 and 5. By combining these two data sources, the average frequency of residential building fire occurrence can be obtained by dividing the number of fires by the total floor areas from 2007 to 2010 in China, which is 2.81 × 10^-6 times/year m².

Fire statistics show that the average number of fire deaths in residential buildings from 2007 to 2010 was 968, and the average risk of deaths, therefore, was 4.95 × 10^-8 deaths/year m² according to Eq. (2). Similarly, the average risk of directive property loss is 1.36 × 10^-8 million Yuan (RMB)/year m² according to Eq. (3).

3.2. Fire risk management in residential buildings

The above inherent risk values of residential buildings were based on fire statistics, which included some fire protection measures, such as smoke alarm systems that were required by regulations. If additional fire protection measures or operations are put in place, they have impact on either the probability of fire occurrence or the consequence of a fire occurrence, and the inherent fire risks would be further reduced. Scenario clusters based on fire protection measures are presented in Fig. 5. Usually, a residual multiplication factor of the inherent values of the
probability or the consequence is used to assess the impact of each fire protection through the use of statistical information. If no such information is available, subjective judgment may be required. Otherwise, the use of fundamental and rational approach to quantification is required.

### 3.2.1. Measures to prevent fire ignition – no smoking materials in residential buildings

The normal fire protection measure to prevent residential fire event from happening is fire safety education, such as educating people about the danger of cigarettes and matches as an ignition source. For example, the measure of ‘no smoking material in living room of residential building’ would have an impact on lowering the probability of fire occurrence. Based on fire statistical information [40], the reduction of fire occurrence in the main living room of home fires is 0.12, and the corresponding residual reduction multiplier is 0.88 of the inherent values. If the value can apply to Chinese homes, then the average residual fire risk of deaths is $4.36 \times 10^{-8}$ deaths/year m$^2$ by successful planning of ‘No smoking materials in residential building’. If there is not statistical information available, assumptions have to be made regarding the residual reduction multiplier.

### 3.2.2. Measures to control fire growth and smoke spread – inspection and maintenance on fire protection systems

There are some fire protection systems installed in residential buildings to control fire growth and smoke spread, such as heating and air conditioning system, mechanical smoke exhaust system, and sprinkler system. Regular inspection and maintenance of these systems is the key to good reliability and performance, otherwise, the installed systems may not work reliably as intended nor as well as designed. For example, the measure of ‘sprinkler system’ would have an impact on lowering the consequence of a fire occurrence by suppressing or controlling the fire. Statistics show that the reduction in deaths in one and two dwellings with sprinkler system is 51% and the reduction in deaths in apartment buildings with sprinkler system is 81%, when compared with similar buildings without sprinklers [37]. The corresponding residual multiplication factor of the inherent consequence value by installing sprinkler system is therefore 0.49 and 0.19 respectively. If the value can apply to the apartment buildings in China, then the average residual fire risk of deaths is $0.94 \times 10^{-6}$ deaths/year m$^2$ by inspection and maintenance on sprinkler system to ensure its probability of success.

### 3.2.3. Measures to facilitate occupant response and fire department operation – regular evacuation drills and adequate fire stations and resources

There are some fire protection measures to facilitate occupant response, such as evacuation planning, training and drill, refuge areas and safe elevators. These measures can help minimize the required evacuation time and encourage occupants to move faster, including those with disabilities. Fire protection measures to facilitate fire department operation include adequate number of fire stations and resources to provide effective rescue and fire extinguishment efforts.

For example, the measure of ‘regular evacuation drill’ would have an impact on lowering the consequence of a fire occurrence in residential buildings by allowing the occupants to evacuate more quickly. Study showed that evacuation exercises in a building

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**Table 3**

Fire numbers from 2007 to 2010 in China.

| Building categories | Fire numbers/(times) |
|---------------------|---------------------|
|                     | 2007 | 2008 | 2009 | 2010 |
| Residential buildings | 163,521 | 136,835 | 129,382 | 132,497 |
| Dormitories         | 42,784 | 36,915 | 37,507 | 39,078 |
| Industry buildings  | 19,498 | 16,223 | 13,867 | 13,583 |
| Factories           | 9,038 | 7,382 | 6,831 | 7,181 |
| Warehouses          | 9,236 | 7,963 | 6,959 | 6,344 |
| Public buildings    | 6,870 | 5,956 | 5,634 | 5,259 |
| Commercial          | 4,680 | 3,521 | 3,251 | 3,357 |
| Restaurants         | 1,715 | 1,484 | 1,319 | 1,311 |
| Offices             | 1,594 | 624 | 761 | 627 |
| Schools             | 418 | 323 | 313 | 294 |
| Hospitals           | 46 | 44 | 53 | 46 |
| Hotels              | 1,077 | 859 | 695 | 684 |
| Transports          | 1,203 | 916 | 778 | 788 |
| Other               | 14,211 | 8,595 | 8,763 | 8,303 |
|                      | 13,847 | 11,994 | 11,879 | 11,421 |
|                      | 25,583 | 22,902 | 19,692 | 19,878 |

**Table 4**

Total residential building floor areas of urban in China from 2007 to 2010.

| Year | Per capita residential building area (m$^2$) | Urban population ($\times 10^5$) | Total floor area ($\times 10^6$ m$^2$) |
|------|---------------------------------------------|---------------------------------|--------------------------------------|
| 2007 | 30.1                                        | 60,633                          | 18,251                               |
| 2008 | 30.6                                        | 62,403                          | 19,498                               |
| 2009 | 31.3                                        | 64,312                          | 20,192                               |
| 2010 | 31.6                                        | 66,578                          | 21,165                               |

**Table 5**

Fire statistics of residential buildings in China from 2007 to 2010.

| Year | Fire occurrences | Deaths | Injuries | Directive economic loss ($\times 10^6$ Yuan (RMB)) |
|------|------------------|--------|----------|--------------------------------------------------|
| 2007 | 62,282           | 1,079  | 442      | 230.06                                           |
| 2008 | 53,138           | 1,061  | 376      | 237.49                                           |
| 2009 | 51,374           | 877    | 335      | 291.25                                           |
| 2010 | 52,661           | 853    | 347      | 309.33                                           |

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**Fig. 5.** Scenario clusters based on fire protection measures.
are performed once every 3 years, there is a probability 91.4% that there is no victim [19]. If there is no information available on the reduction of death rates of residential buildings, the residual multiplication factor of implementing regular evacuation drills needs to be judged and agreed upon fire protection engineers and regulators. It is assumed that the residual multiplication factor of implementing regular evacuation drills in a residential building is 0.30 by fire protection engineers' judgment. Then, the average residual fire risk of deaths is \(1.49 \times 10^{-8}\) deaths/year m\(^2\) by successful planning of regular evacuation drills. Similarly, the residual multiplication factor of the inherent consequence value by providing adequate number of fire stations and resources can be judged. Fire risk analysis of residential buildings based on some fire protection measures is presented in Table 6.

With the data provided by fire risk analysis in residential buildings, combining with applying the accepted risk criteria, the appropriate fire risk management measures in residential buildings could be taken by the fire risk management department to control or reduce fire risk.

4. Conclusions

In this paper, ideas for carrying out fire risk analysis and implementing a quantitative analysis model are described. According to fire statistics in China, the average fire risk of deaths in residential buildings is \(4.95 \times 10^{-8}\) deaths/year m\(^2\), and the average fire risk of directive property loss is \(1.36 \times 10^{-8}\) million Yuan (RMB)/year m\(^2\) over the past 4 years. However, the above inherent risk values of residential buildings are based on some fire protection measures. If additional fire protection measures or operations are put in place, the inherent fire risks would be further reduced by using the residual multiplier. In theory, the more fire protection measures provided for any given building, the better the fire safety level is, and the more the fire cost is. For example, although refuge areas and safe elevators designed in a high-rise building can provide added fire safety, especially to those with disability, they represent an added cost to fire protection. Therefore, the fire risk management department must make trade-off between cost and risk according to the actual condition of buildings.

The fire risk analysis method allows a quick check of any safety deficiencies in residential buildings and any need to provide additional fire protection measures to minimize fire risk. However, it does not include the consideration of the logical development of fire events, and the quantification parameters of fire risk are based on statistical data if they are available, or engineering judgment based on the simulation method and actual fire drills if such data are not available. Accordingly, future research will be needed on the verification methods of some parameters in international contexts, the measurement method of the impacts of fire on business continuity, heritage and the environment, and the appropriate risk management strategy to reduce fire risks in residential buildings.

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