Model development of untenable conditions during egress and stochastic evaluation in compartment fires

Bai-Nian Zhou[1] , Yi-Chun Lin[2*], Yuan-Shang Lin[3]

[1]Fire Service and Disaster Prevention Advocate Management, Hsinchu County Fire Department, Hsinchu 30049, Taiwan, ROC

[2]Department of Fire Science, Graduate School of Fire Science & Technology, Central Police University, Taoyuan 33304, Taiwan, ROC

[3]Graduate School of Disaster Management, Central Police University, Taoyuan 33304, Taiwan, ROC

* Corresponding author. Tel.: +886 3 328 2321#4615 or +886 928 086 675; fax: +886 3 328 1114

E-mail address: linyichuntw@yahoo.com.tw (Y. C. Lin).

Abstract— *This study aimed to develop an "improved simplified two-zone model authentication technology" in order to simulate the time to* ***untenable conditions*** *in compartments less than 200 m^2 in area, which include smoke layer temperature, visibility, carbon monoxide concentration,* ***fractional lethal dose****, and* ***radiation heat flux****. Based on* ***reliability-based design*** *and* ***structure function****, this study focuses on constructing "the* ***stochastic model*** *of egress safety/failure in a compartment fire". Moreover, stochastic parameters and probability distributions were assumed. Random numbers of parameters were generated by Monte Carlo simulation. After several simulations, the failure probability of occupants egress due to one or more than one of the untenable conditions was obtained. After constructing the model, 200 m^2 occupants in a ALA PUB disco ballroom located in Taichung, Taiwan were taken as an example. The simulation of polyurethane furniture fire was executed 100 times. The results showed that installation of automatic fire alarm equipments and emergency broadcasting equipments can substantially reduce the untenable conditions and failure probability of occupants egress. Some ideas for fire officers and future studies for fire researchers were also recommended.*

Keywords— Fractional lethal dose, Radiation heat flux, Reliability-based design, Stochastic model, Structure function, Untenable conditions.

HIGHLIGHTS

- The altitude effects on compartments less than 200 m^2 in area was explored and an "improved strengthened simplified two-zone model authentication technology" was developed.
- Time to untenable conditions was simulated and elucidated.
- Stochastic parameters and probability distributions was assumed. Random numbers of parameters were generated by Monte Carlo simulation.
- Based on reliability-based design and structure function, this study focused on constructing "the stochastic model of egress safety/failure in a compartment fire".
- 200 occupants in a ALA PUB disco was taken as an example.

I. INTRODUCTION

The fire incident of an entertainment quarters (ALA PUB) occurred on March 06, 2011. It is situated in Chung Hsing Street, Taichung City, Taiwan. The fire broke out at 1 am. It first initiated from the stage area on the second floor, so customers staying on the mezzanine were unable to escape, thus resulting in 9 dead and 12 wounded. After the fire incident, public safety in discos, bars, and musical performance places (live house) that sell alcoholic beverages became the focus of attention.

Over the past decades, compartment fire has been investigated in detail and its growth is well understood. From these literatures [1–3], it appears that great progress has been made in the typical building compartment fires with vertical openings, such as door and window. As a typical enclosure, the buildings, such as underground structures, entertainment compartments, and bars, only have the horizontal ceiling vents. Compartment fire with vertical wall vents or horizontal ceiling vents might have different behaviors, because the flow exchange at the openings and vents is of considerable importance in the compartment fire growth and spread.

After studying the fire safety engineering manuals of many advanced countries, we had deliberately selected the six most common factors that are likely to be encountered by fire victims in a fire evacuation process, or untenable conditions that may incapacitate those trying to escape from a fire. These conditions were described below:

(a) Smoke layer height;

(b) Convective heat, usually described as smoke layer temperature;

(c) Smoke obscuration, or visibility, often expressed as optical density per meter (OD/m);

(d) Density of asphyxiating gases, often described as carbon monoxide concentration;

(e) Radiant heat, often described as radiant heat flux; and

(f) Fractional effective dose (abbreviated as FED) composed of toxic and asphyxiating gases, the most commonly used are fractional lethal dose (abbreviated as FLD) and fractional incapacitating dose (abbreviated as FID).

From the full-scale experiment made by Wang [4] for measuring main fire hazard factors in small subdivided space, it was found that the "at 1.8 m above floor level, time for radiant heat flux to reach tolerance limit of 2.5 kW/m^2", was less than the "time for smoke layer height to drop to 1.8 m above floor level". The above "time for radiant heat flux to reach tolerance limit" can be regarded as the "threshold time before encountering untenable conditions during subdivided space personnel evacuation (or called "the time to untenable condition" in short)". The question is how to combine the above "time and time needed for evacuation" in order to assess whether personnel can escape safely from a fire in a subdivided space. This brought out the following three motives for this study:

(1) Using an alternative method (route B) to verify the performance of subdivided space fire evacuation, local model designers only calculated the "time for smoke to reach height of 1.8 m above ground level", and then compared the above time with the "time to evacuate from living quarters" based on the "living quarters evacuation verification method [4]." In case of actual fire, where the number of people in subdivided space reaches the control limit, the "time to evacuate from living quarters" has to be longer than normal. Is it possible that the convective heat, radiant heat flux, and carbon monoxide level at the fire scene could gradually reach intolerable levels, thus leading to failure in escaping from a fire as the fire and smoke become more potent? The first motive of this study was to answer the above question.

(2) Numerous objects in the building are combustible, so it is hard to dismiss all their combustible characteristics. If the model designer does not cover all possible parameters, for instance, combustion heat of all combustible materials within subdivided space, it leaves too many uncertainties for the deterministic equations (group). Thus, a stochastic model was used to overcome the uncertainty problem of the deterministic model. This is the second motive of this study.

(3) Among the results of the fire risk assessment, the one that is more commonly seen is "expected casualties in the fire incident" [5]. If the "incident with personnel casualties" is set equivalent to the "incident coupled with evacuation failure attributable to one or more untenable conditions" under the same fire conditions, the question is: Does automatic fire alarm and emergency broadcast equipment installed in subdivided space make a difference in calculating the risk of personnel casualties? Therefore, analyzing the probability of reduced personnel casualty rate when such equipment is installed in a subdivided space was the third motive of this study.

II. METHODOLOGY

Based on the above research motives, this paper endeavored to explore all untenable conditions and other factors that may cause evacuation failure when a fire breaks out in a subdivided space. Accordingly, the following objectives were established for this study:

(a) Using a predictable heat release rate and smoke generation rate of the "Simple Two-Layer Authentication" [6] in conjunction with the "modeling equation for predicting untenable conditions during fire evacuation in subdivided space", to construct a dynamic "fire and smoke growth model" to predict the "threshold time to untenable condition" in subdivided space fire evacuation. This time is then compared with the "time for one or more people to escape from a fire in subdivided space" obtained from "personnel evacuation model", to set up a "deterministic model to predict the outcome of fire evacuation in subdivided space".

(b) The above deterministic model was based on a reliability-based design [7], and supplemented by the Monte Carlo simulation method to establish a "stochastic model for predicting the outcome of fire evacuation in subdivided space".

(c) Using a place used for specific purposes with the same dimensions, we will then compare the probability of evacuation failure when fire victims are faced with one or more untenable conditions in two scenarios: One with a control limit on accommodating capacity of subdivided space, and the other without. This can be a reference model for the building administration and fire departments in determining the life threat severity to personnel being caught in specific purpose quarters in the event of a fire.

Main research methods used for this study were described as follows:

(1) Literature review method: Using a stochastic model assessment method to review the main points in related literature and applications and collect relevant parameters appropriate for application in subdivided space fire evacuation. For instance, if flaming combustion is observed at the fire scene, relevant combustion parameters such as carbon monoxide production rates, heat combustion, and combustion efficiency of combustible materials should be incorporated in the equation. Furthermore, referring to the untenable conditions for fire evacuation in all kinds of subdivided space as defined by developed countries, a prediction equation should be established for subdivided space fire evacuation.

(2) Experimental analysis method: Set the presence or absence of automatic fire alarm and emergency broadcasting equipment in subdivided space as an independent variable in the research; and set the probability of failure for personnel evacuation in subdivided space as a dependent variable in the research, when fire victims were faced with one or more untenable conditions in subdivided space. A subdivided space with similar conditions, size and combustibles were then set up to observe the effect of independent variable on dependent variables.

(3) Computer simulation method: Using the Monte Carlo simulation method with computer simulation to generate random numbers corresponding to parameter-determined probability distributions, the deterministic simulation model developed by this study was run several times to verify the probability of failure for subdivided space fire evacuation if fire victims are faced with one or more untenable conditions.

III. SCOPE OF OUR RESEARCH

The scope of this study was set as follows:

(a) In this study the so called subdivided space may refer to enclosed living quarters or compartments according to the "Architectural Technology Rules". Enclosed living quarters generally include space used for living, working, meeting, recreation, cooking, etc., whereas hallways, corridor, staircases, coatrooms, toilets, bathrooms, storage rooms, mechanical rooms, garages, etc. are not viewed as living quarters. However, for hotels, residential houses, multi-story residential buildings, and hostels, the criterion in principle is that the total area of coat rooms and storage rooms do not exceed 1/8 of the total floor area.

(b) A fire scene in this study refers to a fire that is initiated and spread out setting combustible materials nearby ablaze, but confined in the subdivided space where it initially started. The scope of this study did not cover other conditions, such as when the fire spread beyond the limit of the subdivided space, or when it was put out or burned out.

(c) Accumulated calorific value of combustible materials stored in places defined by this study, or referred to as fire load per unit area, was limited to 960 mJ/m^2. If the fire load per unit area exceeded the above standard, then the places were considered to have a high fire load, and were not included in the scope of this study.

(d) For the purpose of this study, the total floor area of subdivided space should be less than 200 m^2, and ceiling height less than 8 m, forming a single rectangular space. Any dimensions greater than the above standard should not be included in the scope of this study.

(e) For this study, the building needed to be constructed with a fire-proof structure and had fire protection equipment installed, such as fire-extinguishers and smoke exhaust equipment. Their operations were not included in the scope of this study.

(f) Personnel in the subdivided space should be conscious and had the ability to escape on their own. Personnel sleeping or cannot escape on their own will not be included in the scope of this study.

(g) In this study, only the center of the subdivided space was used to represent the location of combustibles, all other locations were not included in the scope of this study.

(h) Interior decoration and trimming materials (ceilings, walls and other parts) used in the subdivided space were all in conformance with grade 2 or higher fire resistant materials. Grade 3 fire resistant materials or other decoration materials not in conformance with fire resistant standards were not included in the scope of this study.

The limitations of this study can be summarized into the following four points:

A. The development of the "stochastic model of predicting the target outcome of fire evacuation in subdivided space" was based on the probability of failure with respect to fire evacuation in subdivided space when fire victims were faced with one or more untenable conditions.

B. The development of "fire and smoke growth model" was based on "Simple Two-Layered Authentication". We had studied the defects [8] or limitations of this verification technology, and made the following assumptions for the fire and smoke growth model:

(1) Target building was constructed with no openings, and cannot reflect outside temperature, wind speed and energy exchange.

(2) The model can only reflect the smoke layer changes in a single subdivided space and cannot simulate smoke layer changes in adjacent subdivided space.

(3) The fire growth time should be in line with the fire growth model, and the fire source should be located at the center of the rectangular space.

(4) Use of a two-layer fire zone model for calculating the decrease of smoke layer height.

(5) Only using fire radiant heat from fire source for calculating the fire radiant heat flux received at the location of individual people, while the smoke layer or radiant heat from surrounding walls were not considered.

C. Using the "fire and smoke growth model" to calculate the "threshold time to untenable condition" during the fire evacuation process in the subdivided space, also called available safe egress time (ASET). Factors influencing the ASET can be broken down into physical, physiological, and psychological components. This study only examined the physical and physiological components, while those involving psychological factors (stress and panic) were not considered in this study.

D. The development of the "personnel evacuation model" had referenced the computation of "walking time to reach the subdivided space" and "time needed to pass through the egress of subdivided space" described in the "Technical Manual for Structure Fire Evacuation Safety Verification", so the following assumptions are made for the "personnel evacuation model":

(1) Personnel remaining in subdivided space were evenly distributed.

(2) In the subdivided space with no automatic fire alarm devices installed, the "starting time for one or more persons to escape from a fire" was evenly distributed, meaning personnel do not evacuate at the same time; the subdivided space set up with automatic fire alarm and emergency broadcast equipment, regardless of the accumulated time for the fire detector central control and emergency broadcast systems, the "start time for one or more persons to escape from a fire" was set equal to the "fixed temperature detector activation time", and personnel would start evacuating all at once.

(3) All evacuees should take the given evacuation route, with no turn backs.

(4) The flow of evacuation was subjected to the width of exits.

(5) During evacuation, no one put out the fire nor turns on the smoke exhaust systems installed on windows for effective ventilation.

IV. LITERATURE REVIEW

4.1 Risk-based assessment methods

When Ramachandran [9] conducted research on fire disasters in various types of buildings, the attention was placed on the fire growth of different periods, with its multiple interactions producing uncertainties in fire development models. It was possible through computation of probability (uncertainty) occurrence of various types of fire and estimated limit of confidence to derive a non-deterministic fire model. Such a model can be developed as either a probabilistic model, or a stochastic model. The first type that involved the computation of probability can be called a static model, because it took into account the collective risk in fire protection and insurance for different types of buildings, this model can provide sufficient research tools, but the computations of probability distributions and fault tree had not examined the basic physical process and variance [10] in the fire growth period (time). The second type was a dynamic model, which can be seen as an inference model, and can forecast the fire growth and change capability [10] in the building.

Hadjisophocleous [11] pointed out that the judgment criteria used for performance type designs can be roughly divided into two types:

1. Deterministic criteria involve personnel safety, fire growth, and fire spread conditions, damage effects from exposure to fire scene, building structures and functions.
2. Probabilistic criteria involved the extent of incident damage and the possibility of occurrence.

Hasofer's research [12] transformed the deterministic model into a stochastic model, using two methods: 1. Deterministic model inputs are transformed to stochastic model inputs, and is the more common method. This study chooses to transform deterministic type inputs to stochastic type inputs, and the deterministic types "flame growth model" and "personnel behavior model" are transformed into stochastic types "flame growth model" and "personnel behavior model". 2. The number of random entries in the modeling program was increased, which means that the existing deterministic type modeling program cannot precisely forecast the values actually observed. Therefore, it is necessary to introduce random entries. This method can be applied to the "smoke flow model".

Although Hasofer and Qu [13] explained that the use of deterministic type fire growth prediction model had a sound predictability for fire development process, the input parameters are not readily available, and some of the input parameters were essentially random in nature, so the equation cannot be deduced from pure physics, meaning that the program designer cannot precisely predict the fire development with a deterministic model. The way to cope with this problem was to treat unknown input parameters as random variables. Supposedly, there were k stochastic parameters, so theoretically a k-dimensional output space can be obtained, and then using the reliability-based design [14] the chance of success or failure can be calculated. However, because the computer-based fire simulation model involved evaluation equations that were too complicated, it is not suitable for the above calculation. At this point, this study decided to switch to the Monte Carlo simulation model, and all predetermined parameter distributions were altered to corresponding random number distributions. After several simulation runs, this study can analyze the output probability distribution obtained so as to assess the reliability of model design.

The article of Nystedt [15] discussed the installation of fire protection measures in residential buildings such as smoke detectors or water sprinkler systems that can effectively reduce fire deaths. According to Nystedt's research method, the risk of fire death is defined to be equivalent to the probability of evacuation failure in the time period from fire initiation to the moment when fire victims were faced with untenable conditions, and the Monte Carlo simulation method was used to overcome uncertainties in the model. From the research results, we found that the installation of smoke detectors and water sprinkler systems in residential buildings can effectively reduce the risk of fire death by 11% and 53%, respectively.

Summary: Through the above literature review, this study had decided to switch deterministic type input parameters into stochastic type input parameters, and the fire model was switched from a deterministic type to a stochastic type.

4.2 Modeling program to simulate untenable conditions during the fire evacuation process in subdivided space

According to the research of Mingjin et al. [16], the temperature of smoke layer can be estimated with the following Eq. (1):

$$T = T_0 + \frac{\int_0^t \left(\dot{Q} - \dot{Q}_w\right) dt}{C_p \times \rho_s \times Z_s \times A} \tag{1}$$

According to the study made by Jin [17] and Mulholland [18], the visibility of light-emitting equipment (referred to egress-marking lights and emergency lights) can be estimated according to the following Eq. (2):

$$S = \frac{8}{K_{10}} = \frac{8 \times V_{room}}{2.3 \times D_m \times \Delta M} \tag{2}$$

According to the research of Milke et al. [19, 20], the concentration of carbon monoxide in smoke layer can be estimated according to Eq. (3):

$$\text{ppm}CO = \frac{M_{air}}{M_{CO}} \times Y_{CO} \times 10^6 = \frac{M_{air}}{M_{CO}} \times \frac{f_{CO}Q}{\rho_s \chi \Delta H_c A(H - Z_s)} \times 10^6 \quad (3)$$

According to the research made by Purser [22,23], the concentration of carbon monoxide in the blood to reach tolerance limits, or when changed to fractional incapacitating dose (abbreviated as FID), can be estimated according to Eqs. (4) and (5):

$$F_{I_{CO}} = \frac{\%COHb}{\%D} = \frac{3.317 \times 10^{-5} \times \text{ppm}CO^{1.036} \times \text{RMV} \times \text{t} \times V_{CO_2}}{30} \quad (4)$$

$$V_{CO_2} = \frac{\exp(0.2468 \times \%CO_2 + 1.9086)}{6.8} \quad (5)$$

According to the research of Drysdale [24], the fire radiant heat flux can be estimated according to Eq. (6):

$$\dot{q}_r'' = \frac{\dot{Q}_r}{4\pi R^2} = \frac{\chi_r \dot{Q}}{4\pi R^2} = \frac{\chi_r \alpha t^2}{4\pi R^2} \quad (6)$$

After studying the SFPE Handbook of Fire Protection Engineering [25], the tolerance limits of all untenable conditions during the fire evacuation process in subdivided space are shown in Table 1.

TABLE 1
TOLERANCE LIMITS OF ALL UNTENABLE CONDITIONS DURING THE FIRE EVACUATION PROCESS IN SUBDIVIDED SPACE

Untenable condition	Smoke layer temperature	Visibility	Carbon monoxide concentration	Radiant heat flux	Fractional incapacitating Dose(FID)
Tolerance limit	200 °C	5 m	1, 400 ppm	2.5 kW/m^2	1

Summary: After the above literature review, this study used the “Simple Two-layered Authentication Technique” to obtain smoke layer temperature per unit time and related fire and smoke parameters. Using the above computation equation for visibility, carbon monoxide concentration, fractional incapacitating dose (abbreviated as FID), and radiant heat flux, as well as tolerance limits, this study was able to construct the “fire and smoke growth model” for estimating the “threshold or provisional time for individuals to encounter untenable conditions”.

4.3 Time needed for personnel evacuation

Nystedt [26] defined several scenarios depending on the locations of individual persons (in living quarters on fire or other rooms), physiological status (awake or asleep) and alarm device (installed or uninstalled), using probability distribution to determine the “individual detection time” and “response time” in some specific situations. The results are summarized as in Table 2; for other specific situations, this study used the “alarm activation time” to represent the sum of the above 2 time values.

TABLE 2
PROBABILITY DISTRIBUTION OF DETECTION AND RESPONSE TIME FOR INDIVIDUALS DURING FIRE

Scenario	Random variable	Mean value	Parameter distribution	Range
No alarm devices, fire initiated in living quarters, conscious	Fire detection time	30 s	Even distribution	(20, 40)
	Response time	20 s	Even distribution	(10, 30)

The different types of detectors used in the tests. All thermal detectors are based on the differential detectors and temperatures detector principle. The reason that no ionization smoke detectors, aspirating smoke detectors and photoelectric smoke detectors were tested was due to the fact that the heat detectors were more common among the compartment fires alarm and suppression system suppliers.

According to research made by Schifiliti et al. [27], if the fixed temperature detector and alarm device were installed on the ceiling, the temperature to be detected by the sensor can be calculated according to Eq. (7). If that temperature is greater than the nominal temperature for detector activation, the activation time can be obtained.

$$T_{d,n} = \Delta T_{d,n} + T_{d,n-1} = \left[\frac{u_n^{1/2}\left(T_{g,n} - T_{d,n-1}\right)}{\mathrm{RTI}} \Delta t \right] + T_{d,n-1} \tag{7}$$

If fire breaks out in subdivided space, the above mentioned gas can be separated into two components: Fire plume and ceiling jet flow Schifiliti et al. [27] used a series of extended static-state heat release rate models to simulate the fire growth process. The temperature and speed of the fire plume and ceiling jet flow in the nth stage can be calculated as follows:

$$T_{g,n} - T_{g,(n-1)} = \frac{16.9\left(\dot{Q}_n\right)^{2/3}}{H^{5/3}},\ u_n = 0.946\left(\frac{\dot{Q}_n}{H}\right)^{1/3},\ r \le 0.18H \quad \text{(Fire plume)} \tag{8}$$

$$T_{g,n} - T_{g,(n-1)} = \frac{5.38\left(\dot{Q}_n / r\right)^{2/3}}{H},\ u_n = \frac{0.197\dot{Q}_n^{1/3} H^{1/2}}{r^{5/6}},\ r > 0.18H \quad \text{(Ceiling jet flow)} \tag{9}$$

If $n = 1$, let $T_{g,(n-1)} = T_a$ and $u_n = 0$

According to the investigation made by Chen [28], the walking time to reach the exits of enclosed living quarters can be calculated as Eq. (10) shown:

$$t_{travel} = \max\left(\sum \frac{l_i}{v}\right) \tag{10}$$

Takeyoshi [29] actually measured the free walking speed of individuals, ranging from 1.0 to 2.0 m/s, in which the free walking speed of men is about 1.4 m/s, while the free walking speed of women is about 1.2 m/s. Moreover, under different conditions, the walking speeds of individuals will be somewhat different, as listed in Table 3.

TABLE 3
WALKING SPEEDS OF INDIVIDUALS UNDER DIFFERENT CONDITIONS

Condition	Speed	Condition	Speed
Jogging	3.00 m/s	In the dark (unknown place)	0.30 m/s
Running	4.00 m/s	Crawling with elbows and knees	0.30 m/s
Running quickly	6.00 m/s	Crawling with hands and knees	0.40 m/s
Sprinting	8.00 m/s	Crawling with hands and feet	0.50 m/s
In the dark (known place)	0.70 m/s	Walking with low-profile	0.60 m/s

According to the research made by Chen [30], the time needed to pass through the egress of enclosed living quarters can be calculated as follows:

$$t_{queue} = \frac{\sum pA_{area}}{\sum N_{eff} B_{eff}} \tag{11}$$

Summary: Following the above literature review, this study used 2 scenarios, one with automatic fire alarm and emergency broadcasting equipment installed, and the other without. Having the activation time of fixed temperature detector, personnel detection time and response time to represent the starting time for evacuation and adding walking time, in evacuation and time needed to pass through egress to construct the "personnel evacuation model" in order to calculate the "time needed for one or more persons to evacuate".

V. USING DETERMINISTIC MODEL TO PREDICT THE OUTCOME OF FIRE EVACUATION IN SUBDIVIDED SPACE

5.1 Modeling and computer simulation

After using this model to assess a fire experiment in subdivided space, this study used a deterministic model to predict the probability of success if the kth person is not faced with any untenable conditions; or predict the probability of failure if the kth person is faced with one or more conditions leading to evacuation failure. The assessment method is described as follows: When $t_{critical\_i,k} - t_{escape,k} < 0$, it indicates that the kth person has encountered the ith untenable condition, which means failure to evacuate; conversely, when $t_{critical\_i,k} - t_{escape,k} \geq 0$, it represents the kth person has not encountered the ith untenable condition, meaning a successful evacuation. Wherein, subscript k represents the kth person, while subscript i annotates the ith untenable condition for the subdivided space fire evacuation.

$t_{critical\_i,k}$, $i = 1, 2, 3, 4, 5$: Means the time needed for the kth person to encounter 5 untenable conditions for the subdivided space fire evacuation (s), to be calculated with the "fire and smoke growth model".

$t_{escape,k}$: Means the time needed for the kth person to evacuate from subdivided space (s), to be calculated using the "personnel evacuation model".

Then, by adding all persons facing one or more untenable conditions, the "total number of persons that failed to evacuate" can be obtained; conversely, by adding all persons that did not face any untenable conditions, the "total number of persons with a successful evacuation" can be obtained.

(A) Fire and smoke growth model

In this study, we set the time for the kth person to encounter the ith untenable condition, denoted by $t_{critical\_i,k}$, $i = 1, 2, 3, 4, 5$ and set $n_i \Delta t$, $i = 1, 2, 3, 4, 5$ to represent the cumulative time to encounter the ith untenable condition for i=1 to 5. The calculation procedures using computer computation with the "fire and smoke growth model" are given as follows:

(1) Inputting all known parameters, subdivided space, personnel, and deterministic parameters of combustible materials (which are often used as constants in one or more simulations) into the modeling program (the detailed procedures and values are given in Table 4);

(2) Using the smoke layer thickness, density, and related conditions of preceding unit time to calculate the fire and smoke growth at the specific unit time, when the smoke layer temperature meets the convergence criteria, the smoke density at the specific unit time can be calculated. If the smoke layer temperature does not meet the convergence criteria (refer to the research by Wu and Xiao (2007) [31]), the calculation of "smoke layer temperature" is put in iteration (using interval of 10^{-6} K), so the "smoke layer temperature" is recalculated as illustrated in step 2 of Fig. 1.

(3) Using the fire and smoke conditions, breathing rate and location of personnel to calculate the threshold time to encounter the 5 untenable conditions.

(4) The program will end after completing the calculation of threshold time for the 5 untenable conditions.

The calculation procedures of the "fire and smoke growth model" are given in Fig. 1.

Note 1: This study has treated the interior trimming materials as surrounding walls, so the interior trimmings are in compliance with grade 2 fire-resistant fiber requirements.

Note 2: Using the example of Rohr [32] who surveyed a residential fire death in U.S.

Rohr discovered that two items, furniture mattresses and upholstered chairs, are most likely to burn in a fire, because these two types of furniture consist of PU foam. Not surprisingly, the structure of this kind of furniture found in this country is very similar. In this study, PU made furniture is selected as representative furniture in subdivided space.

Assuming the combustion efficiency is 0.8, the combustion heat of PU is 23,900 kJ/kg [33], and a combustion heat parameter value of 0.059 kW/s^2 will be slightly higher than the "rapid fire growth coefficient" of 0.04689 kW/s^2.

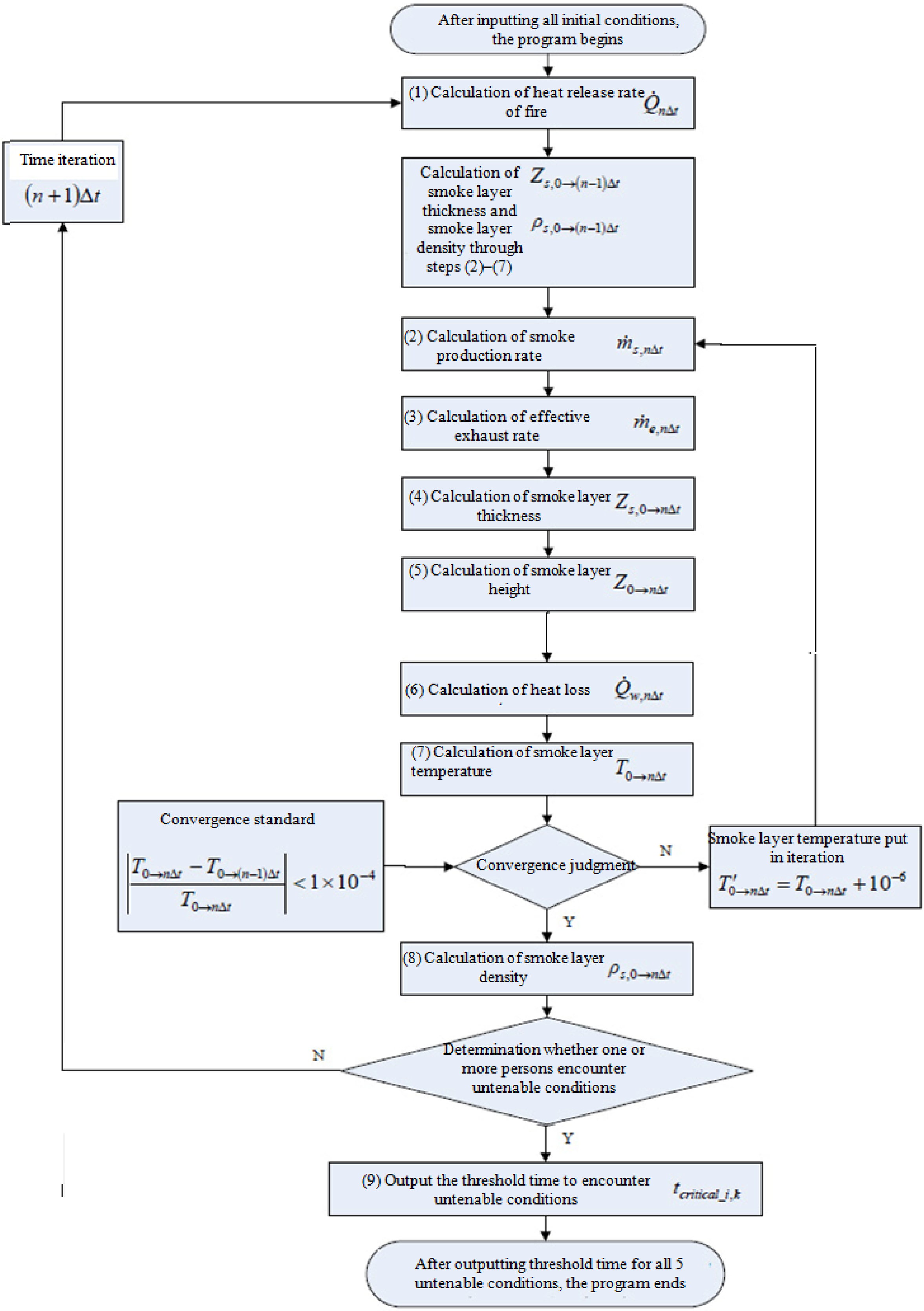

FIG. 1. COMPUTATION FLOW CHART WITH THE FIRE AND SMOKE GROWTH MODEL.

TABLE 4
DETERMINISTIC PARAMETERS FOR THE "FIRE AND SMOKE GROWTH MODEL".

Subdivided space parameter	Value	Initial physical condition	Value
Total floor area of subdivided space	200 m^2	Experiment coefficients	0.076 kg/s $kW^{1/3}$ $m^{5/3}$
Ceiling height of subdivided space	3 m	Initial temperature	303 K
Heat radiation rate from surrounding walls	0.04 W/m K	Calculated time interval	0.1 s
Thickness of surrounding walls	0.125 m	Parameters of combustible materials	Value
Density of surrounding walls	300 kg/m^3	Fire growth rate	0.059 kW/s^2
Specific heat of surrounding walls	1.63 kJ/kg・K	Combustion heat	23900 kJ/kg
Smoke discharge rate from exhaust port	0 m^3/min	Combustion efficiency	0.8
Personnel parameters	Parameter value	Optical density per unit mass of smoke	420 dB m^2 /kg
Number of persons	Same as accommodating capacity	Carbon monoxide production rate	0.03 kg_{CO}/kg_{fuel}
Breathing rate per minute	25 L/min	Carbon dioxide production rate	1.5 kg_{CO2}/kg_{fuel}

(B) Personnel evacuation model

In this study, the time needed for the kth person to evacuate from subdivided space is denoted as $t_{escape,k}$, that represents the sum of start time for the kth person to escape from a fire, walking time to reach the egress ($t_{travel,k}$), and time needed to pass through the egress ($t_{queue,k}$). The above time values are computed by the computer program with the "personnel evacuation model" developed by this study. The computation procedures are narrated as follows:

(1) Inputting all known initial parameters, subdivided space, personnel, and deterministic parameters for combustible materials (as constants used in one or more simulations). The detailed procedures are given in Table 5.

TABLE 5
DETERMINISTIC PARAMETERS OF THE "PERSONNEL BEHAVIOR MODEL".

Subdivided space parameter	Parameter value	Initial physical condition	Parameter value
Length of subdivided space	14.2 m	Initial temperature	30 °C
Width of subdivided space	14.2 m	Compute time interval	0.1 s
Ceiling height of subdivided space	3 m	Effective flow coefficient	1.5 persons/s m
Width of egress	2 m	Combustible parameter	Value
Personnel parameter	Value	Fire growth rate	0.059 kW/s^2
Individuals' walking speed	1.3 m/s	Combustion efficiency	0.8
Fire detection time	30 s	Detector parameter	Value
Response time	20 s	Nominal activation temperature	57 °C
Location of individual person	Uniform distribution	Response time index	50 $m^{1/2}s^{1/2}$

(2) If the subdivided space has automatic fire alarm and emergency broadcast equipment installed, set the value of "fixed temperature detector activation time" equal to the "start time for one or more persons to escape from a fire"; if the subdivided space has no automatic fire alarm and emergency broadcast equipment installed, set the sum of "individual fire detection time" and "individual response time" equivalent to the "start time for one or more persons to escape from a fire".

(3) Using parameters like "locations of individuals", and "walking speed" to calculate the "time needed for personnel to reach the egress of subdivided space" and "time needed to pass through the egress of subdivided space".

(4) The program will end after completing the calculation of the "time needed to evacuate all personnel from subdivided space".

The calculation process with the "personnel behavior model" is demonstrated in Fig. 2.

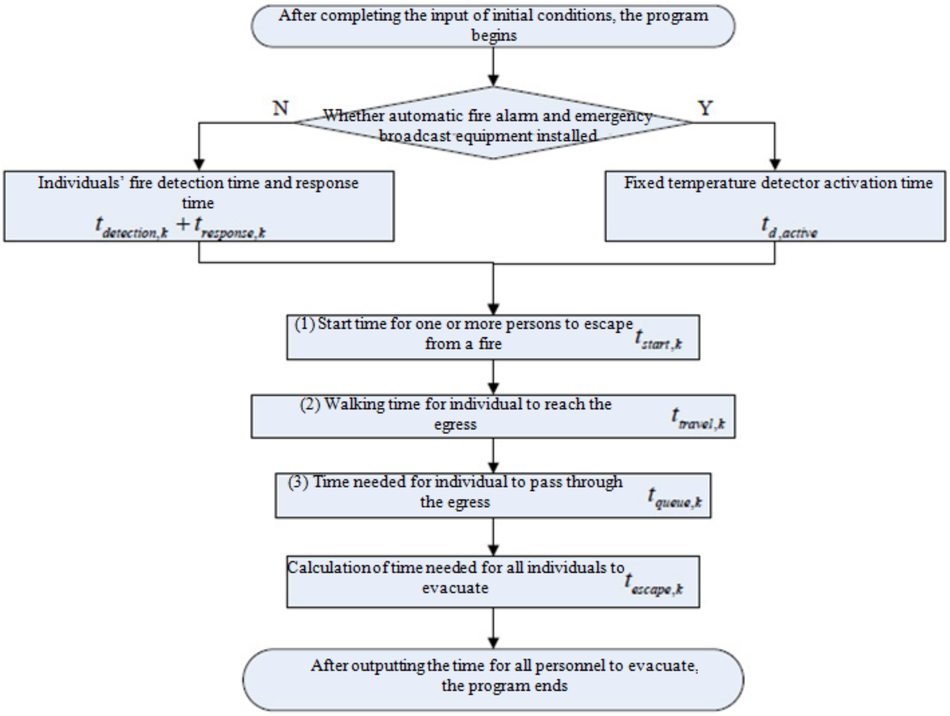

FIG. 2. CALCULATION FLOW CHART WITH PERSONNEL BEHAVIOR MODEL.

Note 1: This study has made reference to the research of Nystedt [34]. Under the context of no fire alarms and emergency broadcast equipment, fire initiation in subdivided space, and personnel in conscious state, the parameter value of an individual's "fire detection time" is set to 30 s and "response time" is set to 20 seconds, respectively; also, by reference to the research of Takeyoshi [35], using the average free walking speed of men and women to set the parameter value of "personnel walking speed" as 1.3 m/s.

Note 2: In this study, the subdivided space is defined as a rectangular space, with no person holding up the egress. Therefore, the effective flow coefficient is set with a standard value of 1.5/s m. Since the representative combustible is placed on ground at the center of the subdivided space, the burning of combustible will not hamper personnel movement near the egress. For the sake of simplification, the effective width of egress is set and equivalent to the width of subdivided space with a parameter value of 2 m.

5.2 Concept of converting deterministic model to become stochastic model

Using the "fire and smoke growth model" and "personnel evacuation model" developed by this study, the subdivided space parameters (floor area, ceiling height, surrounding walls, etc.), fire parameters (fire growth rate, combustion heat of combustibles, combustion efficiency, and so on), and personnel evacuation parameters (fire detection time, response time, walking speed, effective width of egress, and effective flow coefficient, and so forts) are assumed to be fixed values (or called deterministic parameters). However, considering that the fire parameters and personnel parameters are random in nature, if a deterministic model is used for predicting number of persons failed to escape from a fire in subdivided space, the obtained results may not be objective.

In the next paragraph, this study will use the reliability-based design (with 5 performance functions) and structural function to construct a stochastic model for predicting outcome of subdivided space fire evacuation. In the process, part of the deterministic parameters will be converted to stochastic parameters, and supplemented by the Monte Carlo simulation method. Eventually, the model can simulate the fire test with different types of subdivided space.

VI. STOCHASTIC MODEL FOR PREDICTING THE OUTCOME OF SUBDIVIDED SPACE FIRE EVACUATION

6.1 Modeling and computer simulation

(A) Model for testing whether fire victims are faced with one or more untenable conditions leading to evacuation failure. Let $[A]$ to be a set with positive integers from 1 to A, that is $[A]=\{1,2,...,A\},\ A\in N.$ There are M trials in the test, and in each trial there are k numbers of individuals involved, and all will encounter different untenable conditions. Any one trial is called the mth trials; any one person is called the kth person; and any one untenable condition is called the ith untenable condition.

Using reliability-based design to construct a model for predicting the outcome for subdivided space fire evacuation when personnel may be faced with one or more untenable conditions (including 5 performance functions), the detailed steps are given as follows:

Let $G_{i,m,k}$ be the performance function for predicting the outcome of fire evacuation depending on whether the kth person, after the mth trial, is faced with the ith untenable condition that may result in evacuation failure.

$$\text{Defining } G_{i,m,k} = t_{critical\_i,m,k} - t_{escape,m,k} \tag{12}$$

where $i\in[5], m\in[M], k\in[K]$

When the performance function produces the outcome ($G_{i,m,k} < 0$), that means, after the mth trial, the kth person has encountered the ith untenable condition, thus resulting in evacuation failure.

Conversely, when the performance function produces the outcome $G_{i,m,k} \geq 0$, that means, after the mth trial, the kth person has not encountered the ith untenable condition, thus resulting in successful evacuation.

(B) Model for predicting the outcome of subdivided space fire evacuation depending on whether fire victims are faced with one or more untenable conditions. Using structure function to construct a model for predicting the outcome of subdivided space fire evacuation that depends on whether fire victims are faced with one or more untenable conditions. The detailed steps are given as follows:

$$\text{Let } x_{i,m,k} = \begin{cases} 0, & \text{if } G_{i,m,k} < 0 \\ 1, & \text{if } G_{i,m,k} \geq 0 \end{cases}, i\in[5], m\in[M], k\in[K] \tag{13}$$

where $x_{i,m,k}$ is an indicator variable used for predicting the outcome of fire evacuation depending on whether the kth person is faced with the ith untenable condition after the mth trial.

If the k^{th} person has encountered the ith untenable condition after the m^{th} trial, resulting in evacuation failure, which means the i^{th} performance function has produced a failed operation, so $x_{i,m,k} = 0$.

Conversely, if the k^{th} person has not encountered the i^{th} untenable condition after the m^{th} trial, resulting in successful evacuation, which means the i^{th} performance function has produced a successful operation, so $x_{i,m,k} = 1$.

$$\text{Let } \phi_{m,k} = \begin{cases} 0, & \text{if } \prod_{i=1}^{5} x_{i,m,k} = 0 \\ 1, & \text{if } \prod_{i=1}^{5} x_{i,m,k} = 1 \end{cases},\ m\in[M],\ k\in[K] \tag{14}$$

where $\phi_{m,k}$ is a structure function used for predicting the outcome of fire evacuation depending on whether the kth person has encountered one or more untenable conditions after the mth trial.

If after the mth trial, the kth person is faced with one or more untenable conditions leading to evacuation failure, that indicates one or more performance functions have produced failed outcome $\exists i \in [5]$ s. t. $G_{i,m,k} < 0$, so $\phi_{m,k} = 0$.

Conversely, if after the mth trial, the kth person is not faced with any one untenable condition leading to successful evacuation, revealing that all five performance functions have produced successful operation [36–37] $\forall i \in [5]$ s. t. $G_{i,m,k} \geq 0$, so $\phi_{m,k} = 1$.

Assume that each trial is an independent event, then after the mth trial, the MKth person is faced with the ith untenable condition leading to the probability of evacuation failure. [38-39]

$$P_{fail\_i,[M]} = 1 - P_{safe\_i,[M]} = 1 - \left(\sum_{m=1}^{M} \sum_{k=1}^{K} x_{i,m,k} \Big/ MK \right),\ i \in [5] \tag{15}$$

Similarly, after the mth trial, the MKth person is faced with one or more untenable conditions leading to the probability of evacuation failure.

$$P_{fail,[M]} = 1 - P_{safe,[M]} = 1 - \left(\sum_{m=1}^{M} \sum_{k=1}^{K} \phi_{m,k} \Big/ MK \right) = 1 - \left(\sum_{m=1}^{M} \sum_{k=1}^{K} \prod_{i=1}^{5} x_{i,m,k} \Big/ MK \right) \tag{16}$$

The above probability value was obtained from computer computation using the stochastic model for predicting the outcome of subdivided space fire evacuation. The calculation steps are depicted in Fig. 3.

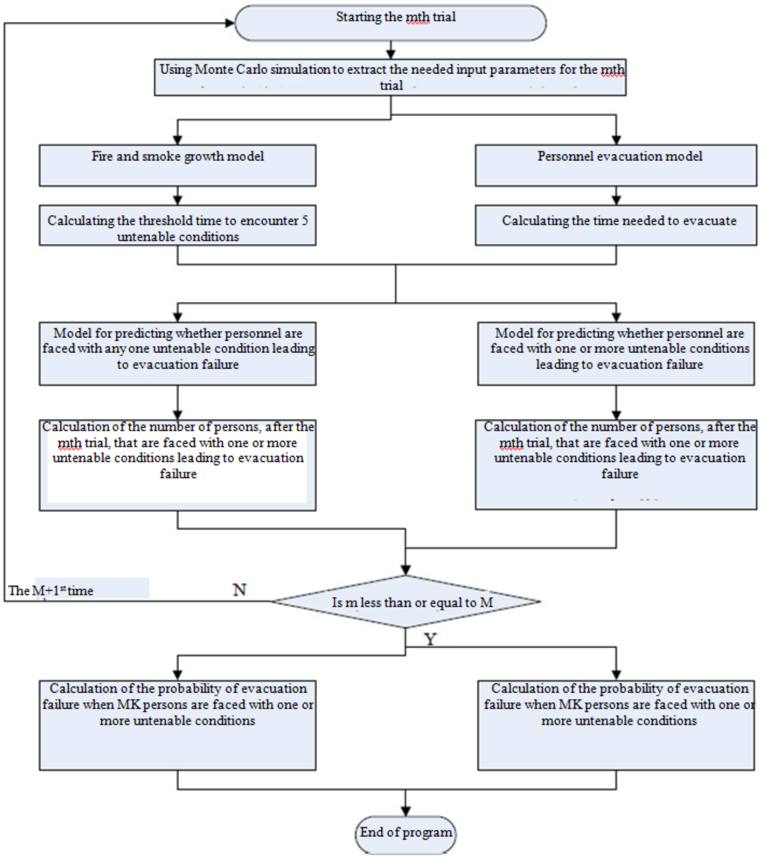

FIG. 3. CALCULATION FLOW CHART USING THE STOCHASTIC MODEL TO PREDICT THE OUTCOME OF PERSONNEL EVACUATION IN SUBDIVIDED SPACE.

6.2 Defining stochastic parameters and simulation methods

In this study, by referencing the research of Nystedt [40] and Williams [41], we used the average values of deterministic parameters as stochastic parameter values to define the standard deviation for all parameters, and assume that all parameter distributions are log normal distributions. Details of the stochastic parameters defined by this study (i.e., input of variables for one or more simulations) and pre-determined probability distributions are presented in Table 6.

TABLE 6
STOCHASTIC PARAMETERS AND PRE-DETERMINED PROBABILITY DISTRIBUTIONS

Random parameter	Mean value	Standard deviation	Parameter distribution
Fire growth rate	0.059 kW/s^2	0.0059 kW/s^2	Lognormal distribution
Combustion heat	23,900 kJ/kg	956 kJ/kg	Lognormal distribution
Combustion efficiency	0.8	0.08	Lognormal distribution
Carbon monoxide production rate	0.03 kg_{CO}/kg_{fuel}	0.006 kg_{CO}/kg_{fuel}	Lognormal distribution
Carbon dioxide production rate	1.5 kg_{CO2}/kg_{fuel}	0.3 kg_{CO2}/kg_{fuel}	Lognormal distribution
Breathing rate per minute for individual persons	25 L/min	5 L/min	Lognormal distribution
Walking speed of the kth person	1.3 m/s	0.2 m/s	Lognormal distribution
Fire detection time of the 4th person	30 s	5.7 s	Uniform distribution
Response time of the kth person	20 s	5.7 s	Uniform distribution
Nominal temperature for activation of fixed temperature detector	57 °C	2 °C	Lognormal distribution

Using the Monte Carlo simulation method, random numbers [42] corresponding to predetermined probability distribution of stochastic parameters can be produced. Substitute the parameters of deterministic models with random numbers to predict the outcome of subdivided space fire evacuation, the results are treated as a set of experimental values. After several simulations, using the stochastic model for predicting the outcome of subdivided space fire evacuation to calculate number of persons failed to evacuate, which is the probability of failure in fire evacuation if some persons are faced with one or more untenable conditions. This model can overcome the uncertainties of deterministic models, and the assessment results are also more objective.

VII. MODEL APPLICATIONS

7.1 Model illustration

The target building is classified under as entertainment quarter (discos, hotels, pubs, etc.) catering to the usage of non-specific people. Since it is of special business in nature, like others it only has one entrance. When a lot of people gather into the quarters and a fire incident breaks out, the situation often leads to heavy casualties, therefore this type of entertainment quarters is chosen as an application model for our study. The total floor area of the entertainment compartment is 200 m^2, and its height is 3 m, and an egress or entrance is located at the opposite corner with a width of 2 m.

In this study, following the guiding principles for special business quarter, we set an accommodating capacity limit of 200 for special business quarters. We also considered whether the quarter has installed automatic fire alarms and emergency broadcast equipment. We then used a stochastic model for predicting the outcome of subdivided space fire evacuation to estimate the probability of failure in personnel evacuation under the above two test conditions respectively.

7.2 Evacuation modeling results, analysis, and discussions

After 100 trials under the above two test conditions, we calculated the probability of failure in personnel evacuation when fire victims are faced with one or more untenable conditions, that is $P_{fail\_i,[100]}$, $i \in [5]$ and $P_{fail,[100]}$, where personnel refers to 20,000 persons remaining in the quarter. Detailed numbers relating to the model are displayed in Table 7.

From the probability statistics given in Table 7.1, it can be seen that when the entertainment quarters (discos) are installed with automatic fire alarms and emergency broadcast equipment, the probability of failure in personnel evacuation when fire victims are faced with one or more untenable conditions is close to 0; however, if the entertainment quarters (discos) are not installed with automatic fire alarms and emergency broadcast equipment, the first untenable condition that personnel are most likely to encounter is "visibility", which may reach the tolerance limit of 5 m, followed by "radiant heat flux", which may reach the tolerance limit of 2.5 kW/m², and then "smoke layer temperature", which may reach the tolerance limit of 200°C, followed by "carbon monoxide content in blood", which may reach the tolerance limit of 30%, and the final untenable condition "concentration of carbon monoxide in smoke layers", which may reach the tolerance limit of 1,400 ppm.

TABLE 7
PROBABILITY OF FAILURE IN PERSONNEL EVACUATION WHEN FIRE VICTIMS ARE FACED WITH ONE OR MORE UNTENABLE CONDITIONS UNDER THE ABOVE TWO TEST CONDITIONS

Test condition	$P_{fail\_1,[100]}$	$P_{fail\_2,[100]}$	$P_{fail\_3,[100]}$	$P_{fail\_4,[100]}$	$P_{fail\_5,[100]}$	$P_{fail,[100]}$
w/ fire equipment	0.00005	0.00010	0.00005	0.00010	0.00005	0.00015
w/o fire equipment	0.00095	0.12640	0.00010	0.00015	0.04765	0.13395

Note: "with or without fire equipment" means whether the place is installed with automatic fire alarms and emergency broadcast equipment.

Furthermore, regardless of test conditions, if the probability of failure of individual persons in personnel evacuation faced with any untenable condition are added together, it is greater than the probability of evacuation failure when fire victims are faced with one or more untenable conditions. This indicates that personnel may be faced with up to 5 untenable conditions simultaneously leading to evacuation failure. No matter what kind of test conditions, the probability of failure with the third untenable condition is less than the probability of failure with the second untenable condition. However, this does not necessarily mean that the second untenable condition must have occurred before the third one. Overall speaking, it only implies that the probability of occurrence of the second untenable condition is higher than the third one. If the average threshold time to the second untenable condition 2 is deducted by 3 standard deviations, it may be less than the average threshold time to the third untenable condition added with 3 standard deviations, but such probabilities are very small. Nevertheless, the third untenable condition could occur before the second one. The statistics of threshold time for various untenable conditions listed can be referred in Table 8.

TABLE 8
STATISTICAL DATA RELATING TO PERSONNEL EVACUATION AFTER 100 TRIALS, INCLUDING THRESHOLD TIME TO ENCOUNTER 5 UNTENABLE CONDITIONS AND TIME NEEDED FOR SAFE EVACUATION.

Test condition	Statistical data	$t_{critical\_1,m,k}$	$t_{critical\_2,m,k}$	$t_{critical\_3,m,k}$	$t_{critical\_4,m,k}$	$t_{critical\_5,m,k}$	$t_{escape,m,k}$
w/ equipment	Mean value	158.0 s	133.1 s	174.3 s	181.3 s	140.4 s	61.8 s
	Standard deviation	6.1 s	13.0 s	7.9 s	6.8 s	6.9 s	24.1 s
w/o equipment	Mean value	158.2 s	131.1 s	173.8 s	181.4 s	140.6 s	92.9 s
	Standard deviation	5.4 s	18.3 s	7.7 s	7.2 s	6.3 s	28.8 s

Note: "with or without equipment" refers to the condition whether the quarter is installed with automatic fire alarms as well as emergency broadcast equipment.

After 100 trials, this study had collected evacuation statistics relating to 20,000 persons that may stay in the quarters, including the threshold time to untenable conditions $t_{critical\_i,m,k}, i \in [5], m \in [100], k \in [200]$, time needed for safe evacuation （$t_{escape,m,k}, m \in [100], k \in [200]$） , average values, and standard deviations. The detailed numbers are shown in Table 8.

From the mean time values listed in 7.2, it can be seen that regardless of test conditions, if the risks of one or more untenable conditions are sorted according to the mean values of threshold time to encounter untenable condition, the above listing order is similar to the order of life threat proposed by Purser [43]. Purser has conducted an analysis with respect to fire in a single quarter (using a sofa containing PU materials as furniture), and listed the order of life threats in the first six minutes of fire. The life threats listed in order are fractional smoke visibility dose(abbreviated as FSVD), fractional radiation heat(abbreviated as FRH), convective heat dose (abbreviated as CHD), temperature, carbon monoxide concentration, and finally fractional asphyxiating gas dose (asphyxiating gas refers to carbon monoxide).

VIII. CONCLUSION

8.1 Brief results and discussion

(A) This study used the "stochastic subdivided space personnel evacuation prediction model", supplemented by the Monte Carlo simulation method, to assess the probability of personnel evacuation failure. Personnel may be faced with untenable conditions in entertainment quarters (discos) during evacuation process. The fire is initiated from PU (polyurethane) furniture in the quarters (where fire growth rate is according to the t^2 fire growth model, while the average fire growth rate is 0.059 kW/s². The untenable conditions faced by personnel include visibility less than 5 m, radiant heat flux greater than 2.5 kW/m², smoke layer temperature higher than 200 °C, fractional incapacitating dose of carbon monoxide in blood 30%, and lastly the concentration of carbon monoxide over 1,400 ppm.

(B) In this study, setting the accommodating capacity control limit for the entertainment quarter (discos) to 200 persons, equipped with automatic fire alarm and emergency broadcast equipment, the probability of failure in personnel evacuation due to one or more untenable conditions will be decreased by 13.3%. Such a decrease is close to the result of Nystedt [44]. Nystedt made a simulation with residential quarters equipped with smoke detectors, in which the risk of fire death was decreased by 11%. The apparent difference may be due to several factors. The fire growth model used by this study is different from Nystedt; the accommodating capacities for the business quarters are different; the personnel behavior and detector types used are different; and the standards for untenable conditions are also different. However, the installation of automatic fire alarms and emergency broadcast equipment will indeed reduce the probability of fire casualties overall.

(C) The personnel evacuation model developed by this study has made several assumptions. The fire is flaming combustion; people remaining in the compartment will listen to the automatic fire alarms and follow instructions from the emergency broadcast equipment to escape; no one stays behind to fight the fire, or opens the windows to release smoke. In fact, if considering the smoldering effect or that some people will not observe the fire warning and escape but choose to stay behind to assist the fire fighting or open the windows to release smoke, such circumstances should be discussed and elucidated separately with another research topic to analyze the probability of evacuation failures due to the above conditions.

8.2 Recommendations

(A) In the past, fire protection systems have been designed based on prescriptive codes and requirements which have been proven to be effective and adequate for traditional building developments. Nevertheless, prescriptive approach often fails to provide satisfactory and safer fire engineering designs and systems for modern buildings [45], where fire scenarios can be far more complicated by the possible involvement of a wide variety of combustible items and interactions of compartment surfaces with fire.

It is recommended the fire authority should enforce the "Fire Protection and Safety Equipment Set-up Standard for Various Buildings" (hereinafter referred to as "Installation Standards"). Based on Article 4 of the Installation Standards relating to floor characteristics (floors without outside opening), and Article 12 of the Installation Standards relating to building usage classification (category A buildings), total floor area provided for such usage, and control limit on accommodating capacity (reaching or exceeding the control number), the fire authorities should determine what types of buildings are difficult for fire rescue operations. For category buildings without wide-open floors and where control limit on accommodating capacity is often exceeded, such buildings should be selected and targeted as a high priority for fire fighting and rescue exercises.

(B) At this stage, only the Taipei City Government and Taoyuan City Government have their own regulations for the accommodating capacity control limit to be applied on various buildings. These regulations are currently enforced by the authorities. Taichung City Government has drawn up its own regulations and has sent it to the municipal council for review. The Ministry of Interior (MOI) (Taiwan) has recently sent a letter to autonomous regions or cities, asking local governments to reference the guiding rules relating to accommodate capacities of special business quarters, and urges them to formulate their own regulations for direct enforcement, which needs to be sent to local municipal councils for review. The MOI also invited other counties and city governments to review their local needs. If relevant regulations are necessary in their administrative regions, they should follow suit. Therefore, this study suggests that, in addition to regulating the accommodating capacity control limits of special business quarters, the local authorities could also play documentary films of major fire incidents on official websites in connection with personnel evacuation, so that the public can view the documentary and enhance their safety awareness in buildings and places with special business. Furthermore, for special business quarters where the accommodating capacity control limit is often exceeded, owners of such buildings should be required to install automatic fire alarms and emergency broadcast equipment. When an emergency situation occurs, using a linked manner to stop the loud music and broadcast fire alarms to remind or warn people in the compartment to escape immediately.

(C) This study was experimental in nature, as there are rooms for further improvements. For instance, parameters' setting for outside openings, capacity of exhaust equipment, linking of several closed compartments, and so on. However, under this experiment, the present model for predicting various untenable conditions is created for closed and small compartments, and the fire scene is initiated in such an environment. If the experimental conditions are to include outside openings, capacity of exhaust equipment, linking of several quarter space, smoke layer flow, and threshold time for various untenable conditions, it is feared that the new scenario may not be compatible with the actual situation, so that further investigations are needed with these additional factors.

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