Research on Dynamic Evacuation Simulations in large-scale shopping centers

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Abstract— *This study chose a large-scale shopping center housed in a typical warehouse-style commercial building as an example to review its fire accident history and to conduct an on-site questionnaire survey to determine the features and conditions of the fire and smoke hazards when this type of building is on fire. The features of the distribution of people and the characteristics of their behavior and responses from the literature were quantified into parameters and inputted into the evacuation model. The FDS+Evac computer simulation software of the performance-based analysis was used to dynamically simulate the amount of time required for evacuation. The present study chose two fire scenarios and, depending on the activation of the fire safety equipment, each scenario was further divided into four more scenarios for discussing their impacts on evacuation. Hazardous impacts from the height of the smoke layer, fire temperature, CO concentration, visibility, and radiation intensity on people during evacuation were simulated and analyzed. The present study further verified and validated the hazardous conditions for the shoppers using the FED value and explored the approach for helping people who need assistance during shopping center evacuation at the time of occurrence. The results show that when fire equipment (smoke exhausts and automatic fire sprinklers) is activated, the majority of people can be evacuated safely. If only one of the equipment is activated, then the activation of the smoke exhaust would work better than the automatic fire sprinklers in protecting people's lives. For warehouse store fire safety, it is critical to plan the evacuation routes according to the local conditions and enhance guidance for people who need assistance in an emergency evacuation.*

Keywords— Warehouse-style commercial buildings, large-scale shopping centers, fire accident simulation, FDS+Evac, Dynamic evacuation simulation.

I. INTRODUCTION

In recent years, there have been frequent fire accidents worldwide. Aside from the heavy casualties due to terror attacks, the most serious accidents, in terms of human injuries, deaths and financial losses, often happened at crowded, large-scale shopping centers. For example, the Ycuá Bolaños supermarket fire in Asunción, Paraguay on August 1, 2004 was the most detrimental one; 509 people were killed and 144 injured. Due to industrialization and commercialization, large-scale shopping centers featuring large shopping areas, extensive product lines, and convenient parking have been built in cities to accommodate the needs of consumers. These large-scale shopping centers are filled with not only all sorts of shoppers and but also a lot of combustible goods. Moreover, the many product display racks arranged in the shopping center may block safety routes and sight; not to mention that shoppers can be easily trapped due to the maze-like floor plan inside the large building and the hidden exits and exit indicators. In addition, fire and electricity are frequently used in shopping centers, and when fire happens, they can speed up fire propagation, resulting in not only serious financial losses but also the deaths and injuries of people who fail to find their way out. Therefore, evacuation safety is a critical issue for these types of buildings.

Many evacuation studies such as Shields (1), Ding (2), Cheng (3), Tsai (4), Fang (5), and Hsu (5) are focused on fire prevention strategies, evacuation routes, the analysis of the distribution of people and dynamic flow of people, and evacuation time estimation. Few studies have explored evacuation behavior during fire accidents. Chen and Lin (7) examined the evacuation time required by people in buildings in countries worldwide but they did not take into account the possibility of prolonged evacuation time due to obstructions caused by fire. Neither did these authors assess the evacuation behavior or capability of people. Currently, when architects are designing buildings, they would take building construction and fire prevention-related laws and regulations into consideration, but in a building with crowds, even if the building itself satisfies the laws and regulations, the interior decoration, which normally aims for creating a convenient and aesthetically pleasing environment, as well as the stacks of goods for display or storage, tend to cause the overall layout to deviate from the originally approved architectural design, thereby increasing the risks of fire. The current performance-based fire prevention design tends to deal with evacuation and fire accidents separately in two stages. That is, the evacuation simulation software will first be used for calculating the required evacuation time, and then the value will be compared with the time it takes for the smoke layer to descend and have the concentration reach a hazardous level to determine if everyone can be evacuated on time. Nevertheless, the fire accident simulation does not take into account possible obstructions, physical conditions, evacuation behavior and capability, or mental factors of people, which may influence the amount of time for evacuation. At present, there are evacuation simulation softwares like Building Exodus, Simulex, Exit, and CFD for use, but their simulation results have to be analyzed and compared with results from fire simulation software, such as CFAST, HAZARD I, and FireCAM, to ensure that the design meets the safety evacuation requirements (8). Because the field distribution system (FDS) is open source, the massive validation testing has increased the accuracy of the simulation result (9). Using the FDS+Evac software, Wang et al. (10) successfully restored the fire scene of the KaErhTeng Barber Shop fire. Huang et al. (11) also used the FDS+Evac software to perform a retrospective simulation of the most serious fire disaster in Taiwan, the Wei-Er-Kang Restaurant fire. In the present study, the researchers analyzed the field investigation data of a large-scale shopping center and conducted a quantitative analysis using the performance-based design of computer simulation to assess the evacuation safety of fire accidents in that specific large-scale shopping center by simulating the evacuation with various fire conditions taken into consideration. This study examined two types of fire scenarios and according to whether the fire safety equipment is activated or not, four more scenarios were derived for each scenario. The researchers of this study then explored impacts from these scenarios on evacuation and discussed strategies for helping people who need assistance to evacuate from a shopping center in a fire accident. A safety operation management system was established for large-scale shopping centers to ensure that shoppers can be safely evacuated from a fire accident and to complement the shortcomings of the specification-based laws and regulations.

II. METHOD

2.1 Description of stadium and surroundings

According to the definition provided in 2009, convenience stores, supermarkets, warehouse stores, department stores, and shopping centers are all under the class of large-scale warehouse-style commercial buildings. Because of the small surface area and small number of people in convenience stores and supermarkets, it is less likely for these places to encounter evacuation difficulties. In the present study, warehouse-style commercial buildings are defined as those housing warehouse stores, department stores, and shopping centers, and a large-scale shopping center was chosen as the study target here because of its unique floor plan. The floor plan of large-scale shopping centers are designed to provide shoppers with a great variety and a big quantity of affordable products, and compared with that of department stores or common shopping centers, the floor plan of large-scale shopping centers is designed to realize the consumers' wish for one stop shopping. The arrangement of the product display racks in the space can affect the shopper's evacuation direction. There are two major types of floor plan configurations: dispersed core and bilateral core; the former is the most popular kind. The present study analyzed questionnaire survey results and images recorded by security cameras to obtain information related to the characteristics of shopper flow, evacuation time, and pre-movement time of evacuation. Spatial information (the width and height of the exits, the dimensions of each zones, and the arrangement of evacuation routes, fire evacuation equipment, and fire safety equipment) of the building was collected by field measuring, while fire scenarios as well as the characteristics of people's evacuation behavior presented in the literature were analyzed as well. Then FDS+Evac, a fire simulation software, was used for the dynamic simulation of fire scenarios, including the propagation of fire and evacuation. Evacuation safety simulation was performed for various fire scenarios to assess the results of evacuating people from the shopping center. The simulation is described below.

2.2 Information of the Research Target

A large-scale shopping center in New Taipei City was chosen as the research target. The primary part of the building is a two-story steel-reinforced concrete building. According to the architectural blueprint of the approved building permit from the authorities, the total surface area is 12,019m^2, and the fire-resistant level is 2. Inside the building, there are spaces for warehouse stores and retail shops, offices, and storage for lease. The surface areas of the first and second floors are 11,257.92m^2 and 761.08m^2 respectively. The present study was focused on first floor evacuation. The second floor was excluded because firstly, there is only one office on the second floor, meaning not many people will be on the second floor, and secondly, it has an independent staircase to outside.This study conducted numerous investigations on the warehouse store during the month of the Chinese New Year to collect data related to the walls, columns, product racks, tables and chairs, sprinklers (n = 1,492), and smoke dampers (n = 49). The collected data was entered into the computer simulation model.

2.3 Fire situation

For the twelve fire accident-generated hazardous factors, including the descending height of the smoke layer, the temperature in the fire, smoke and other toxic gases, visibility, and radiation heat (12), their impacts on fire emergency evacuation were summarized in Table 2-1 (13). For fire protection engineering and building fire prevention and evacuation safety design, the time when the maximum tolerable condition for the human body is reached is treated as the limit. Regarding the time that the upper tolerable limit by humans is reached in the fire in this study, t_1 is the time for the smoke to descend to 1.8m, t_2 is the time for the fire temperature to reach 60°C, t_3 is the time for CO concentration to reach 1,200ppm, t_4 is the time for visibility to drop to 10m, and $t_5$is the time for radiation intensity to increase to 2.5kW/m.

TABLE 2-1
CRITERIA FOR HAZARDOUS CONDITION REACHING HUMAN UPPER TOLERABLE LIMITS

Time Reaching Hazardous Condition		Upper Tolerable Limit of Human Body				
		BSI standards	Buchanan	NFPA 130	Takayoshi Tanaka	The study's parameters
Smoke level height t_1		—	—	≥Floor height 1.8m	≥Floor height 1.8m	≥Floor height 1.8m
Fire temperature t_2		Skin burn @44˚C	—	<60º C	Nociception @45˚C	<60º C
Smoke and toxic gases t_3	CO	6000ppm	<1400ppm	<1500ppm	<1200ppm	<1200ppm
	CO_2	<7%	<5%	—	<20%	—
	HCN	—	<80ppm	—	<270ppm	—
	O_2	≧13%	≧12%	—	≧6%	—
Visibility t_4		≧2m	≧2m	≧10m	—	≧10m
Radiation intensity t_5		<2.5kW/m^2	<2.5kW/m^2	<6.3kW/m^2	Nociception in 10 sec. @ <4kQ/m^2	<2.5kW/m^2

Most of the interior decorations of the warehouse store studied here had an interior decoration of fire-resistant level 2. According to the fire incident data from Commissioning Guidelines (16) and Holborn (17), the fire growth rate (α_{fm}) of various areas of the warehouse store, causes of fire, and spread paths are shown in Table 2-2.

TABLE 2-2
FIRE GROWTH RATE OF VARIOUS WAREHOUSE STORE AREAS, FIRE CAUSES, AND FIRE SPREAD PATHS

Source:	Store type		Cause of fire	Spread path	α_{fm}	Growth pattern
Commissioning Guidelines	Warehouse stores	Furniture store	—	—	0.257	Extremely fast
		Bookstore	—	—	0.257	Extremely fast
		Other retail stores	—	—	0.905	Fast
		Restaurants	—	—	0.905	Fast
Fire Incidents	Warehouse stores	Restaurants	Lack of awareness; temperature Temperature adjusting machine machine failure induced vegetable oil overheating in the pot	Propagated to the ceiling or the entire restaurant	0.078 ∫ 0.309	Fast to extremely fast
		Electrical appliance retailer	Electrical appliance failure	Igniting other electrical appliances	0.108	Fast
		Bookstore & furniture store	Arson	Propagated to the upper floor	0.085	Fast
		Automobile repair shop	Engine starting igniting vapor of leaked petrol	Propagated to the entire shop	0.057	Fast
		Apparel stores	Arson	Propagated to the piles of clothes	0.027	Average speed

2.4 Spatial Constraints

There are a 44 fireproof iron rolling door sets. The location of the door sets and the related fire prevention zones are shown in Figure 2-3. When investigating the rolling doors of the warehouse store, it was found that if there were a fire accident causing the fireproof rolling doors to close, Stores 16, 17, and 18 would be partitioned into to area C & D (Stores 16-1, 17-1, and 18-1 of Fire Prevention Zone C and Stores 16-2, 17-2, and 18-2 of Fire Prevention Zone D). As for Stores 16-1 and 17-1, they would be blocked by fireproof rolling door cd2 and the 1.5m high wood wall; meaning that people during evacuation would have to climb up the 1.5m high wood wall to leave the area successfully. In this case, people in Stores 16-1 and 17-1 have to take Passage 7 between Stores 16-2 and 17-2 to escape before fireproof rolling door cd2 was put down. The present study examined if people from Stores 16-1 and 17-1 can be evacuated successfully before the fireproof rolling door cd2 was put down.

Figure 2-3 shows the location of the fire prevention zones, fireproof iron rolling doors, and exits of the warehouse store. Aside from the fireproof iron rolling doors, there were other spatial constraints in the warehouse store affecting evacuation. These constraints were the external walls, internal wood walls, columns, counters, tables, chairs, supermarket product display racks, and in-store product racks. They were found to be at the evacuation routes, and therefore, they may affect the evacuation flow and speed. The present study investigated the spatial constraints in the warehouse and the results are shown in Figure 2-4.

TABLE 2-3

Constraints	Structure	Length (m)	Width (m)	Height (m)	Description	Illustration
Wood wall	Wood panel	—	0.1	15	Stores 16.1, 16.2, 17-1, and 17-2 were blocked into an evacuation Obstruction area	
Fireproof iron rolling doors	Iron sheets	—	0.1	1.5	Fire prevention zones ABand CD were blocked, making Store 19 an evacuation obstruction area	
Columns	Concrete	0.6	0.6	4.75	Columns at the evacuation route affects the direction of evacuation and slows down the speed of evacuation.	
Store product display racks	Iron racks	1.2-1.8	0.6-1.2	0.2-2	Blocking the evacuation	

2.5 Exits and Passages

The exits and passages of the warehouse stores are also critical factors affecting evacuation. The results from investigating the dimensions and conditions (i.e., closed or blocked) of the exits of the warehouse are shown in Table 2-5.

TABLE 2-4
DIMENSIONS AND CONDITIONS (BLOCKED OR CLOSED) OF EXITS OF THE WAREHOUSE STORE

Type	Name		Width (m)	Height (m)	Potentially hazardous conditions	Illustration
Exits	Non-emergency exits	a4 and b5	2.4	235	—	
	Emergency exits	a1, a2, a3, b1, b2, b3, b4, c1, c2, c4, c5, d1, d2, d3, d4, d5, d6	1.8	2.1	Emergency exits a1, a2, b2, b3, b4, c1, c2, d1, d2, d3, d4, and d5 were locked or closed, resulting Restaurant 20 and Store 20 forming an evacuation obstruction area when closing the fireproof iron rolling door.	
	General exit	f2	2.4	2.95	—	
Door	Fireproof door	ab, cd, de, eg, fg, fh, gh, ij	1.2	2.05	Fireproof Door eg was blocked by the interior decoration	

Note: Prepared by this study.

2.6 Density of People

This study chose the Chinese New Year period to conduct its field investigation. Chinese New Year is a time when many people would rush to shopping centers to buy goods for ancestor veneration, god welcoming, and family gathering. Therefore, during the month of Chinese New Year, the researchers of this study went to the warehouse store every morning and evening to perform unannounced emergency evacuation behavior analysis and to determine shopper flow characteristics, evacuation, and pre-movement time of the warehouse store according to shopper flow images recorded by security cameras and referring to the density of people at locations listed by Chen (2008) (18). Because only staff worked at the cashier's office, security office, interrogation room, and control room during normal hours, the density of the people at these areas was set to 0.3 people/m^2. For the areas around the shopping carts, the density of people was set to 0. For the rest of the warehouse store, the density of the people was set to 0.55 people/m^2.As for the storage area and fire prevention zone I of the warehouse, the density of the people was set to 0.03 people/m^2. In the warehouse shopping area, the E-2 zone was blocked by product racks, and therefore the density of the people was set to be 0. In the warehouse store, the average density of shopping carts was 0.11 cart/m^2. The average walking speed of people was 0.79m/s. The ratio among healthy people, shopping carts, and people who need assistance for evacuation was 1:0.34:0.17.The average number of people during weekends and holidays was 1.8-fold higher than during weekdays.

2.7 Fire Prevention Safety Equipment

The warehouse store had fire extinguishers, indoor fire hydrant equipment, automatic fire sprinklers, automatic fire alarms, emergency broadcasting equipment, labeling equipment, evacuation equipment, emergency lighting, smoke exhausts, and other fire safety equipment. Another piece of fire prevention and evacuation equipment of the warehouse store was the detector-geared fireproof iron rolling door. The fire safety equipment and fire evacuation facilities are shown in Table 2-6.

TABLE 2-6
FIRE SAFETY EQUIPMENT AND FIRE EVACUATION FACILITIES IN THE WAREHOUSE STORE

Fire Safety Equipment and Fire Evacuation Facilities	Name	Quantity
Extinguishers	10P (lb) dry powder extinguishers	84
Labeling equipment	Exit indicator lights	38
	Evacuation direction indicator lights	75
Emergency lighting equipment	Emergency lamps	109
Emergency broadcasting equipment	Emergency broadcasting mainframe	1
	Speakers	119
Fire alarm equipment	Fire fiduciary switchboard	1
	Fire alarm complexes (PBL)	16
	Smoke detectors	400
Smoke exhaust equipment	Smoke exhausts	4
	Smoke dampers	49
	Activation devices	49
Indoor fire hydrant equipment	Indoor fire hydrant boxes	4
	Fire pump	1
Automatic fire sprinkler system	Automatic sprinkler pump	1
	Automatic sprinkler water dispensing port	3
	Sprinklers	1492
	Buzzers	14
	Ending checking valves	6
Fire evacuation facilities	Fireproof iron rolling doors	44
Emergency power source	Emergency power generator	1

III. RESULTS

Fire Simulation Using FDS

3.1 Hazardous Situation Criteria

In this section, the evacuation routes and FED values were combined for the performance-based evaluation of a building fire in hopes of more correctly reflecting the evacuation process and to avoid relying only on the height of the smoke layer, temperature, toxicity, visibility, and radiation intensity

3.2 Fire Accident Scenario Simulation

When investigating the spatial arrangement inside the warehouse store, it was found that usually no one would access the fire engine room, the electric room, or the electric engine room, and moreover, these areas have independent exits to the outside. Therefore, these places were excluded from the discussion. The present study divided the remaining space into the retail space for lease, warehouse store, and storage as the three main areas for evacuation validation. Because in the warehouse store there are various combustible products placed in different areas, each of these areas has its own potential fire risk. From the field investigation, it was found that the bookstore and the furniture store were areas with a relatively high risk compared to other areas, and therefore, this area was chosen to be the fire starting point when designing fire accident scenarios (Figure 3-1).

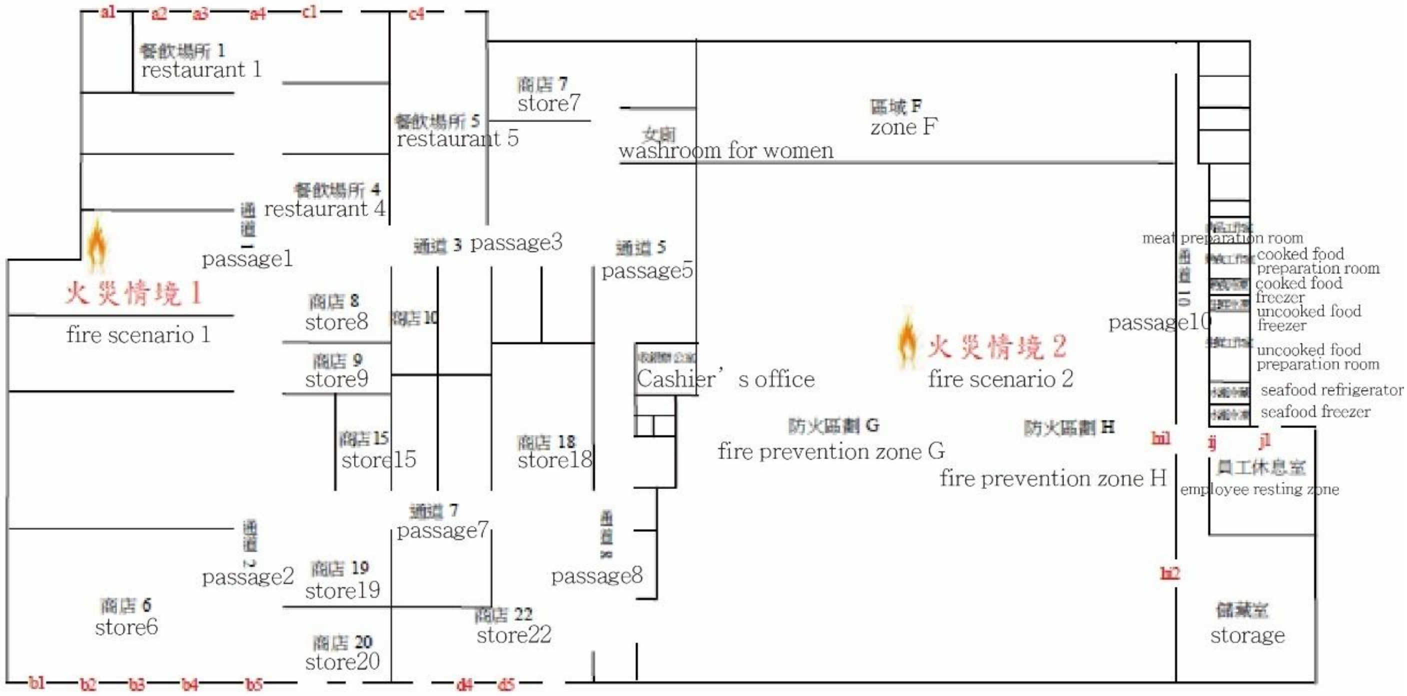
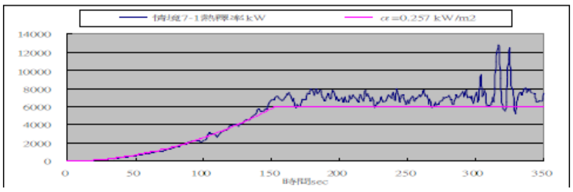
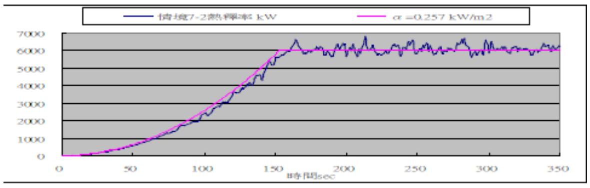
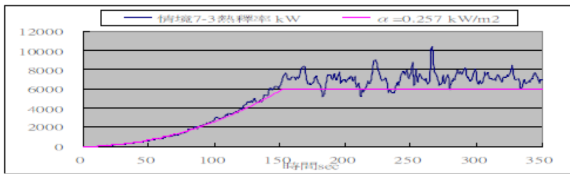
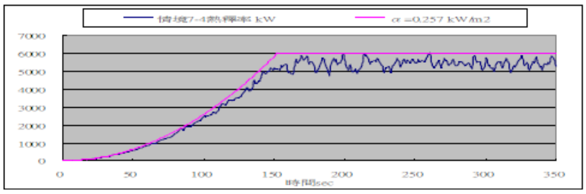
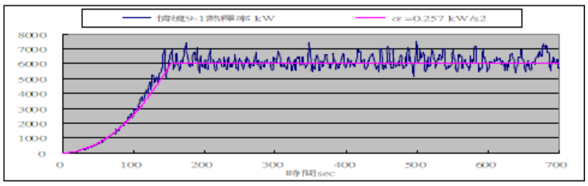
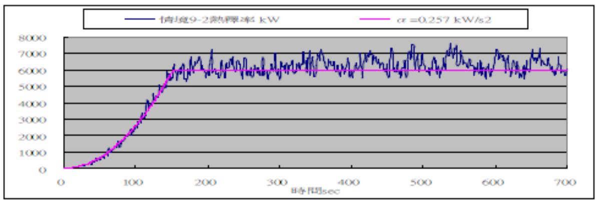
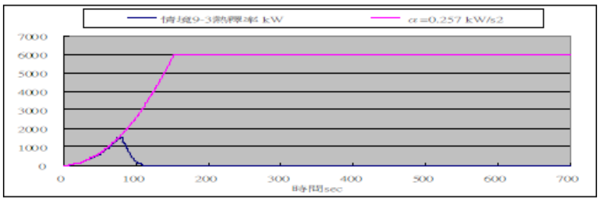
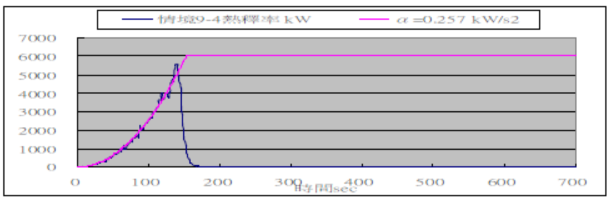


FIGURE 3-1 SHOWS FIRE SCENARIOS 1 AND 2

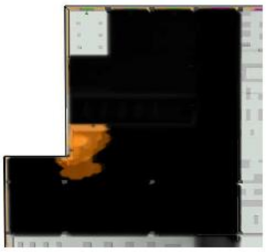
Figure 3-1 shows fire scenarios 1 and 2 (both with a maximum heat release rate 6MW). According to whether the smoke exhaust equipment and the automatic fire sprinkler equipment are activated or not, each scenario can be further divided into four more scenarios, resulting in eight fire scenarios in total. αfm of 0.257 was used for the furniture store and the bookstore; it was chosen according to Table 2-2 and the Commissioning Guidelines and were used as the fire growth rate of the fire scenarios. The conditions of the eight fire scenarios are presented in Table 3-2.

TABLE 3-2
EIGHT FIRE SCENARIOS AND THEIR CONDITIONS

Fire scenarios		Smoke exhaust equipment	Fire sprinkler equipment	Heat release speed
Scenario 1	Scenario 1-1	No action	No action	
	Scenario 1-2	Action	No action	
	Scenario 1-3	No action	Action	
	Scenario 1-4	Action	Action	
Scenario 2	Scenario 2-1	No action	No action	
	Scenario 2-2	Action	No action	
	Scenario 2-3	No action	Action	
	Scenario 2-4	Action	Action	

It can be found from the heat release speed plots of various fire scenarios that when the sprinklers were activated in fire scenarios1-3 and 1-4, there would be no effect on suppressing the growth of fire. It is because in scenarios 1-3 and 1-4, the source of fire was set to be near the wall, and the smoke from combustion will move up along the wall to the ceiling, creating ceiling jet flows. In this case, water from sprinklers cannot easily reach and extinguish the fire. As for fire scenarios 2-3 and 2-4, when the sprinklers are activated, there would be no such obstacle mentioned above preventing the water from reaching the ceiling jet flows, hence fire can be quickly controlled. Consequently, people are more likely to be evacuated successfully. As for fire scenario 2-4 (both the smoke exhaust equipment and automatic fire sprinkler equipment are activated), its heat release rate (5.5MW) was actually bigger than the heat release rate of fire scenario 2-3(1.5MW), which had the sprinklers activated only. The major reason is that in scenario 2-3, the automatic sprinklers were activated but the smoke exhausts were not. Consequently, the heat flow from the combustion would not be expelled by the exhausts but the sprinklers would quickly spray the water (74.7 sec). As for scenario 2-4, both the sprinklers and the smoke exhausts were activated, which means that the expelling of smoke would delay the action of the sprinklers (104.3 seconds). Putting the information together it can be found that scenario 2-4 is not as good as scenario 2-3 in extinguishing fire. It is also shown in Table 3-2 that the activation of smoke exhausts or not has little or no effect on the heat release rate. According to the heat release speed plot of fire scenario 1-1, it is clear that the heat release rate surges at 316.10 seconds (12.5MW). This is because the surface area of fire prevention zone A is relatively smaller than others, and moreover, the interior decoration of the leased retail space has a lower ceiling. These two conditions resulted in a small smoke accumulation capacity. Aside from the poor ventilation and heat dissipation associated with a lack of vents, neither the smoke exhausts nor the automatic sprinklers were activated. As a result, the fire can grow without hindrance, and when the fireproof iron rolling doors were lowered down, the smoke concentration would be high, creating a condition promoting the tumble phenomenon. The fire and smoke of the tumble phenomenon are shown in Table 3-3.

TABLE 3-3
TUMBLE PHENOMENON OF FIRE SCENARIO 1-1

Fire scenario	Fire and smoke before tumble phenomenon	Fire and smoke during tumble phenomenon	Fire and smoke after tumble phenomenon
7-1	 Simulation time: 314.00 sec	 Simulation time: 316.10 sec	 Simulation time: 318.10 sec

In this section, the focus is on the effect of the activation of the smoke exhaust equipment and automatic fire sprinkler equipment on the evacuation in the eight fire scenarios shown in Table 3-2.The distribution of people (the ratio of men, women, children, and elderly) in the warehouse store before the evacuation and the distribution of the them when a fire accident happens are compared to determine which type of people are relatively more disadvantaged in an evacuation and if there is any strategy to help them.

3.3 Activation of Fire Prevention Safety Equipment

When performing the FDS-Evac fire and evacuation simulation, impacts from the automatic fire sprinkler equipment and the smoke exhaust equipment for fire safety and the fireproof iron rolling doors for fire prevention evacuation on fire accidents and evacuation were examined. In the warehouse store, 156 sets of detecting points were set to obtain the smoke height, fire temperature, CO concentration, visibility, and radiation intensity and to validate whether the time of occurrence of untenable conditions of people inside the warehouse store for evacuation were reached. For the setup of activation of the above-mentioned fire safety equipment and fire evacuation facilities, see Table 3-8.

TABLE 3-8
ACTIVATION SETUP OF FIRE SAFETY EQUIPMENT AND FIRE EVACUATION FACILITIES

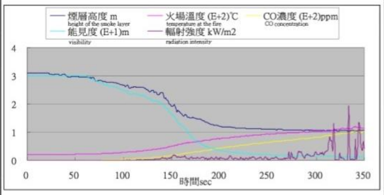
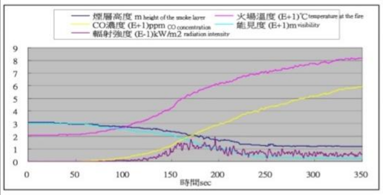
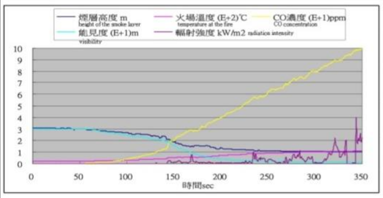
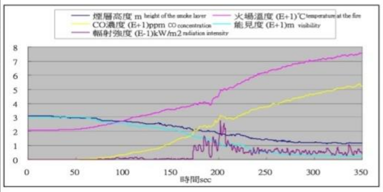
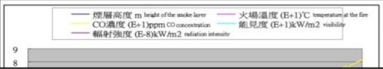
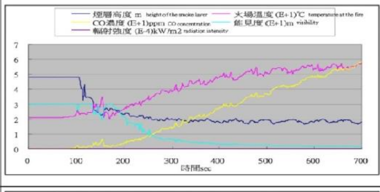
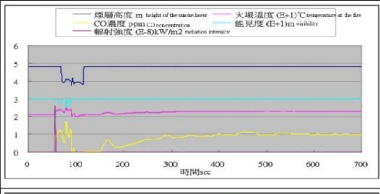
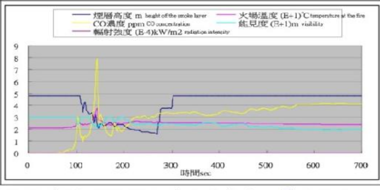
Equipment	Activation	Quantity	Illustration
Automatic fire sprinkler equipment: sprinklers	Activated at 74°C	1492 each	
Smoke exhaust equipment: Smoke dampers	The activation of the smoke detector will activate the smoke dampers, and in 5 seconds, the speed of the wind will reach to and be stabilized at 10m/s. The speed was maintained until the end of the simulation.	49 sets	
Fire evacuation facility: Fireproof iron rolling doors	The fireproof iron rolling doors will be lowered down ten seconds after the activation of the fire detector.	44 sets	
Detection points	Detection points are set for smoke layer height, temperature at the fire, CO concentration, visibility, and radiation intensity	156 sets	

IV. RESULTS AND DISCUSSIONS

4.1 Evacuation Safety Analysis of the Warehouse Store Building

In this section, the warehouse store fire simulation and evacuation simulation were combined and performance-based fire prevention design concepts were proposed for setting up new performance-based decision-making criteria. FDS+Evac fire and evacuation simulation software were used in combination for carrying out an dynamic evacuation study with the effects from the fire environment in real-time. Compared to the currently adopted performance-based design approach, this study chose the performance-based design evaluation method of the FED value, which can more comprehensively reflect the evacuation process and provide a more scientific and real evaluation result than the performance-based design approach. The time of the occurrence of untenable conditions and the evacuation time of fire scenarios 1 and 2 obtained from the computer evacuation software are shown in Table 4-1.

TABLE 4-1
THE TIME OF OCCURRENCE OF UNTENABLE CONDITIONS AND THE EVACUATION TIME OF FIRE SCENARIOS 1 AND 2

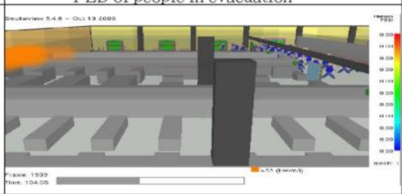
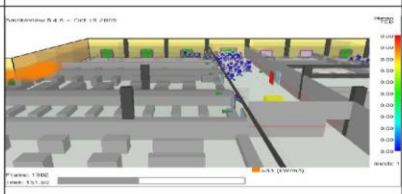
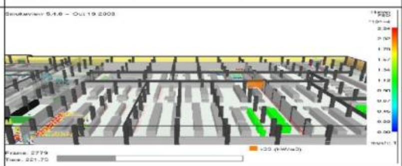
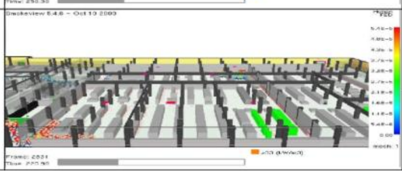
情境 (Scenario)	各種危險情境居臨時間圖 (Times of occurrence of untenable conditions of various hazardous situations)			危險居避難逃生臨及時間 (Time of occurrence of untenable condition and evacuation time)		危害區域 (Hazardous zone)	危害人數 (Number of people at risk)
1-1		t_1	154.79	T	154.79	防火區劃A fire prevention zone A	73人
		t_2	163.14				
		t_3	—				
		t_4	166.69				
		t_5	—				
		t_{escape}			222.09		
1-2		t_1	191.11	T	191.11	—	—
		t_2	193.25				
		t_3	—				
		t_4	197.42				
		t_5	—				
		t_{escape}			188.03		
1-3		t_1	152.00	T	152.00	防火區劃A fire prevention zone A	77人
		t_2	185.62				
		t_3	—				
		t_4	167.40				
		t_5	348.00				
		t_{escape}			198.04		
1-4		t_1	205.81	T	204.43	—	—
		t_2	240.12				
		t_3	—				
		t_4	204.43				
		t_5	—				
		t_{escape}			181.01		
2-1		t_1	288.48	T	222.64	防火區劃G fire prevention zone G	413人
		t_2	445.23				
		t_3	—				
		t_4	222.64				
		t_5	—				
		t_{escape}			415.07		
2-2		t_1	334.72	T	250.66	防火區劃G fire prevention zone G	289人
		t_2	—				
		t_3	—				
		t_4	250.66				
		t_5	—				
		t_{escape}			400.11		
2-3		t_1	—	T	—	—	—
		t_2	—				
		t_3	—				
		t_4	—				
		t_5	—				
		t_{escape}			398.07		
2-4		t_1	236.79	T	236.79	防火區劃G fire prevention zone G	354人

—：在模擬時間 (700秒)內未造成危害人員的狀況。 Without injuring or killing people during the simulation period (700 sec)

It can be found from Table 4-1 that if both the smoke exhaust equipment and the automatic fire sprinkler equipment are activated, all fire scenarios, except fire scenario 2-4, can meet the safety evacuation requirements. If either the smoke exhaust equipment or the automatic fire sprinkler equipment is activated, as in fire scenarios 1-2, 1-3, 2-2, and 2-3, then no scenario attained the safety goal except for fire scenario 2-3 (only the automatic sprinkler is activated). Moreover, activating the smoke exhaust equipment was only sufficient for attaining safe evacuation, but activating the automatic fire sprinkler equipment alone (fire scenario 1-3) was not enough for safe evacuation. The above finding may be because that the time of occurrence of untenable conditions is primarily determined by the height of the smoke layer and visibility. That is, quickly expelling the smoke is more important than quickly activating the automatic fire sprinkler equipment because it can substantially improve the height of the smoke layer and visibility. Therefore, at the early stage of fire, it is critical to activate the smoke exhaust equipment, instead of the automatic fire sprinkler equipment as early as possible. As for the fire sprinkler equipment, it is more effective in delaying fire propagation or extinguishing fire. It can be found in Tables 3-2 and 4-1 that if neither the smoke exhaust equipment nor the automatic fire sprinkler equipment is activated (as in fire scenarios 1-1 and 2-1), many people would be at risk. Therefore, when the fire is big, the smoke exhaust equipment and the automatic fire sprinkler equipment should be used. The result here also shows the importance of maintaining the equipment from time to time.

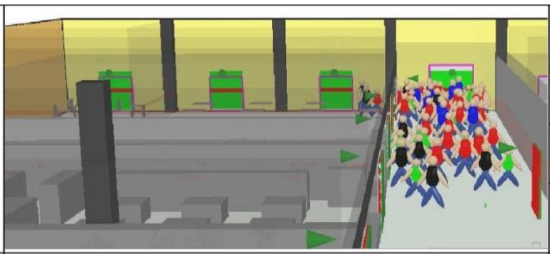
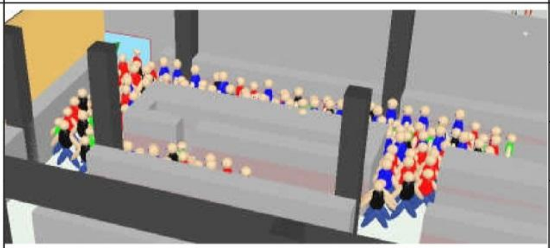
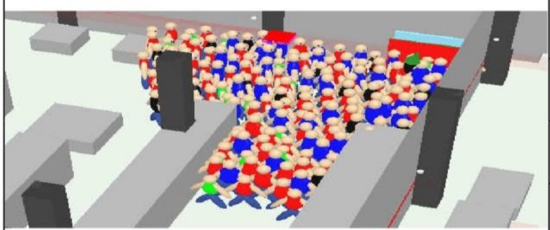
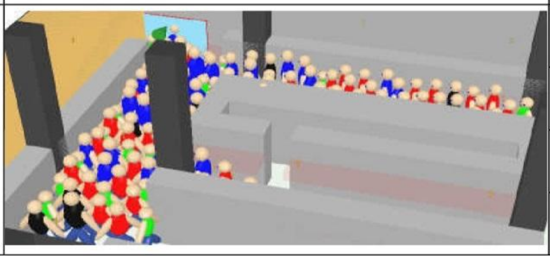
It can be found from Table 4-1 that in fire scenarios 1-2, 1-3, and 2-3, no people in evacuation was at risk. In other words, everyone could escape the fire zone before the occurrence of the hazard. As for other fire scenarios, because there were still people at risk, the present study further explored those people at risk from the time of the occurrence of untenable conditions to everyone escaping from the fire zone. The FED values of people in evacuation from the beginning of the hazardous situation to everyone escaping the fire zone were shown in Table 3-5. It can be found from the table that all FED values of people for evacuation were less than 0.5, and this means that everyone could escape from the fire zone safely.

TABLE 4-2
FED VALUES OF PEOPLE UNDER RISK AT THE TIME OF THE OCCURRENCE OF UNTENABLE CONDITIONS IN FIRE SCENARIOS 1 AND 2

情境 (Scenario)	逃生人員之FED值 (FED of people in evacuation)	危害開始時間最高FED值 (Hazard beginning time / Max FED)	全部逃離時間最高FED值 (Time required for completing evacuation / Max FED)
1-1		154.79 秒	222.09 秒
		7.61×10^{-4}	1.41×10^{-3}
1-3		152.00 秒	198.04 秒
		8.16×10^{-4}	1.13×10^{-3}
2-1		222.64 秒	415.07 秒
		2.51×10^{-4}	2.26×10^{-3}
2-2		250.66 秒	400.11 秒
		4.06×10^{-4}	1.04×10^{-3}
2-4		236.79 秒	405.20 秒
		1.95×10^{-4}	2.69×10^{-4}

For scenarios 1 and 2, the researcher then made the assumption that people in the warehouse store are composed of 30% men, 45% women, 15% children, and 10% elderly. At the time of the occurrence of untenable conditions, the ratios of men, women, children, and elderly people at risk are shown in Table 4-3. In the picture, men are marked by blue, women by red, children by green, and elderly people by black.

TABLE 4-3
RATIOS OF PEOPLE AT THE TIME OF THE OCCURRENCE OF UNTENABLE CONDITIONS

Scenario	People at the time of the occurrence of untenable condition	Ratio of men, women, children, and elderly people in the warehouse store		Ratio of men, women, children, and elderly people at the time of the occurrence of untenable condition	
1-1		男人 men	0.30	男人 men	0.13
		女人 women	0.45	女人 women	0.53
		小孩 children	0.15	小孩 children	0.20
		老人 elderly people	0.10	老人 elderly people	0.14
1-3		男人 men	0.30	男人 men	0.13
		女人 women	0.45	女人 women	0.45
		小孩 children	0.15	小孩 children	0.24
		老人 elderly people	0.10	老人 elderly people	0.18
2-1		男人 men	0.30	男人 men	0.21
		女人 women	0.45	女人 women	0.46
		小孩 children	0.15	小孩 children	0.19
		老人 elderly people	0.10	老人 elderly people	0.14
2-2		男人 men	0.30	男人 men	0.23
		女人 women	0.45	女人 women	0.46
		小孩 children	0.15	小孩 children	0.18
		老人 elderly people	0.10	老人 elderly people	0.13
2-4		男人 men	0.30	男人 men	0.24
		女人 women	0.45	女人 women	0.46
		小孩 children	0.15	小孩 children	0.18
		老人 elderly people	0.10	老人 elderly people	0.12

It can be found from Table 4-3 Ratios of People at the Time of the Occurrence of Untenable Conditions that during the evacuation, women, children, and elderly people were more likely to be at the back. At the time of the occurrence of untenable conditions, they would be more likely to be trapped than men. Physically weaker than men, women, children, and elderly people are at an unfavorable condition in evacuation; they are more likely to be left in fire. Aside from the physical factor, it is also important to take social force into consideration. Taiwan is a male-dominated society, and influenced by the social force, men are therefore more likely to rush to the front, including during evacuation. Therefore, it is necessary to have specific personnel to guide and direct women, children, and elderly people during a fire evacuation.

V. CONCLUSION

To create a safe shopping environment, the present study established effective evacuation safety guidelines for warehouse stores that business owners and architects can refer to in building fire prevention design and fire evacuation safety drill planning. Here are the major conclusions based on the findings of the present study.

1. It is important to pay attention to the regional tumble phenomenon and to control combustible items at each area. It is especially critical to avoid putting too many combustible items at fire prevention zones or placing combustible items near these zones in order to prevent the flashover phenomenon, which may push burning to its peak state.
2. At the beginning of a fire accident, it is more important to activate the smoke exhaust equipment, instead of the automatic fire sprinkler equipment as early as possible to better protect people’s lives. As for the automatic fire sprinkler equipment, it is more effective in slowing down fire propagation and fire extinguishment. Because of the competing conditions between the smoke exhaust equipment and the automatic fire sprinkler equipment, it is important to have professionals conduct routine maintenance to make sure that the equipment functions effectively during fire accidents.
3. During a fire evacuation, women, children, elderly people, and other people who need assistance are more likely to be trapped in the fire. They need special guidance during evacuation. For self-protection fire prevention training, evacuation drills should be a focus.
4. During the design stage, the accuracy of the fire safety and fire evacuation equipment safety inspection and performance assessment results should be improved.

The conventional performance-based design is composed of two parts: fire development and evacuation of people. Nonetheless, fire accidents may block evacuation, forcing some people to change their evacuation routes. Furthermore, fire may also prolong the evacuation time because it may reduce the use rate of certain exits, causing other exits to be congested by crowds trying to escape. This study took the distribution characteristics of evacuation pre-movement time into consideration and combined route selection and fire accident together in performance-based evaluation for building fires. This approach is different from the conventional approach, which only uses the height of the smoke layer, visibility, and temperature in the evaluation. The present study also combined evacuation and fractional effective dose (FED) for the performance-based evaluation for building fires. It is a new attempt and has eliminated the shortcomings of the conventional performance design, which only uses the time of the occurrence of untenable conditions to determine the hazardous condition. In contrast, the new approach developed by this study has quantified the performance-based design, thereby making the approach more scientific. Through the evacuation safety performance design, alternative design plans can be adopted to make the evacuation safety design of large-scale commercial buildings more flexible and reasonable. The information here can be used to improve the evacuation safety criteria in the performance-based design. For a good building design project, the performance-based concept and approach should be adopted at the design stage, and computer simulation software, such as the evacuation software, the structure computation software, day light analysis software, and energy-savings software, can be employed to inspect or correct those natural shortcomings of the design project to ensure safe building evacuation and to prevent serious injuries and causalities in an emergency situation. The above ideas are especially crucial and urgent for the initial building permit validation of large-scale public buildings or places in lots of people gather.A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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