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RESEARCH ARTICLE

Novel Smoke-Aware Individual Evacuation and Congestion-Aware Group Evacuation Algorithms in IoT-Enabled Multi-Story Multi-Exit Buildings

HONG-HSU YEN, (Member, IEEE), CHENG-HAN LIN, AND HUNG-WEI TSAO
Department of Information Management, Shih Hsin University, Taipei 11604, Taiwan

Corresponding author: Hong-Hsu Yen (honghsuyen@gmail.com)

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ABSTRACT Because of toxic gases and fast propagation speed, smoke causes the major injuries and deaths than burns in the fire. Deploying IoT enabled smoke sensors not only help to sense, collect, and transmit the smoke data to the control station, but also enable a dynamic and real-time evacuation approach to increase the evacuation success probability. In this paper, two smoke-aware evacuation approaches are proposed. The individual evacuation mathematical model and the associated SIEP algorithm are first devised to identify a fastest smoke toxic safe evacuation path for an evacuee. Next, the group evacuation mathematical model and the associated SGEP algorithm are devised to evacuate as many evacuees as possible in considering the smoke toxicity and flow congestion along the evacuation routes. SGEP circumvents the congestion problem by scheduling the evacuation sequence according to evacuee's accumulated smoke toxicity value, where higher accumulated smoke toxicity value has higher evacuation priority to prevent incapacitation at evacuation. The FDS simulations based on the real layout of Taipei 101 mall are performed to compare the evacuation success probability between SIEP and SGEP at methane fire and PVC fire. The simulation results show that smoke from PVC fire is more toxic than that of methane fire. In addition, enabling sprinklers can reduce the percentage of toxic nodes up to 41% at methane fire and up to 10% at PCV fire, as compared to not enabling them. These results indicate that it is more challenging to evacuate at PVC fire than at methane fire. The simulation results in SGEP and SIEP justify the above conclusions where the success evacuation probability differences between methane fire and PVC fire are up to 39% (i.e., 100% and 61%) and 52.5% (i.e., 82.5% and 30%) for SGEP and SIEP, respectively. The simulation results also show that SGEP outperforms SIEP in terms of evacuation success probability at all simulation settings, especially when large number of evacuees are to be evacuated. At methane fire, the largest evacuation success probability difference between SGEP and SIEP is 68.1% at 1000 evacuees, 0.3 FED threshold and without sprinklers. At PVC fire, the largest difference is 50% at 1000 evacuees, 0.5 FED threshold and with sprinklers. These significant differences in evacuation success probability come from the evacuation congestion in SIEP. The evacuation scheduling approach based on accumulated smoke toxicity policy enables SGEP to circumvent the evacuation congestion, and to get better evacuation success probability. Besides identifying safe evacuation route and evacuation scheduling policy during congestion to evacuate more evacuees, another contribution of this paper is to identify the critical percentage of toxic nodes for safe fire evacuation and rescue operations.

INDEX TERMS Individual evacuation, group evacuation, evacuation congestion, smoke sensors, fire evacuation planning and optimization.

I. INTRODUCTION

There are a lot of reported injuries and deaths in fire every year. According to the newest statistics data from U.S. Fire Administration (USFA), there are 3704 fire deaths and

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16600 injuries at the U.S.A in 2019 [35]. Fire progresses rapidly in minutes. In [11], they show that the critical time for the fire is 5.5 minutes, after this time the fire spread quickly to the other parts of the building. As compared to burns, toxic smoke contributes the major causes of death and injuries. The statistics in [44] show that there has been a progressive shift in cause of death from burns to toxic gases or smoke from 1955-2015 in UK. USFA statistics [36] show that smoke inhalation and breathing difficulty contribute 50% and thermal burns contributes 30% of the primary symptoms resulting in injuries from 2017 to 2019. Smoke is more dangerous than heat in the fire because the smoke will not only block the evacuee's vision, but also causes dizziness, disorientation, and suffocation to incapacitate the evacuees in evacuation. Toxic fire effluents, like carbon monoxide (CO), can incapacitate evacuees in a very short time. When exposed to 0.1% to 0.8% concentration of carbon monoxide within one or two minutes, evacuees will be incapacitated in movement [29]. In addition, the smoke can reduce the visibility below 1 meter to increase the difficulty in evacuation even though the generation of the toxic gases are relatively modest [30].

Existing evacuation approach uses the fixed evacuation sign on the wall to point to the nearest emergency exits. However, the fixed evacuation sign may lead the evacuees to the emergency exit that has a high smoke concentration on the evacuation route. Novel evacuation scheme should adapt to the smoke concentrations in the fire to guide the evacuees to the safe evacuation route in a limited safe evacuation time. Thanks to the rapid progress of IoT sensors technology, the real-time fire information can be acquired. The smoke sensors are deployed to detect and send back the smoke concentration data periodically to the control station. These IoT enabled sensors are connected by wired or wireless networks in monitoring and capturing the fire smoke signal in the buildings. How to leverage on this real-time smoke information to devise a novel evacuation approach is an important research problem.

Basically, smoke spreads in a much faster speed than heat in the fire zone. To quantify the smoke hazard and heat hazard in the fire zone, the fire simulation via Fire Dynamics Simulator (FDS) is performed on the building layout of the three-floored Taipei 101 mall. FDS is a well-known fire simulation software which is developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce [32].

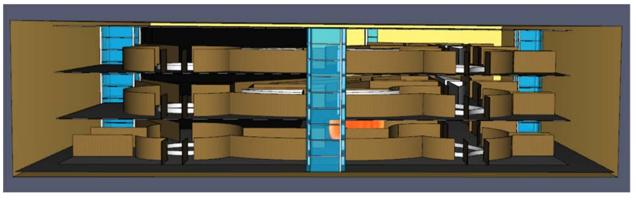


FIGURE 1. Floor layout of the Taipei 101 mall.

Figure 1 shows the layout of the Taipei 101 mall, and the fire colored in red starts at the first floor in the building. The blue color region indicates the staircase to the emergency exit at the first floor. Three escalators are placed in the mall for visitors to move between first, second and to the third floor easily. Unlike emergency exits doors that are always closed, the escalators are in an open space which will become the chimney to spread the fire and smoke in the fire zone. In Figure 2 and Figure 3, we show the visualized heat diagram and visualized smoke diagram at 80 seconds of simulation time in the three-floored Taipei 101 mall by using the FDS. It is shown that the escalator beside the fire origin has higher temperature and higher smoke concentration as shown in Figure 2 and Figure 3.

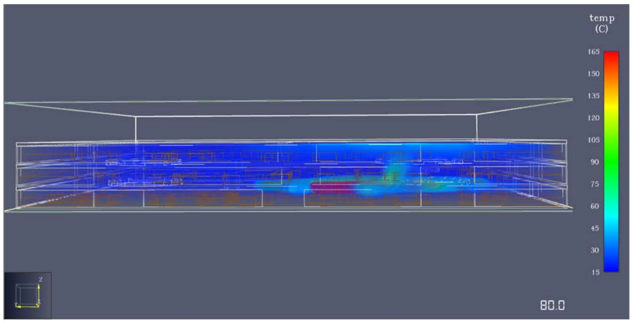


FIGURE 2. Temperature distribution in the Taipei 101 mall.

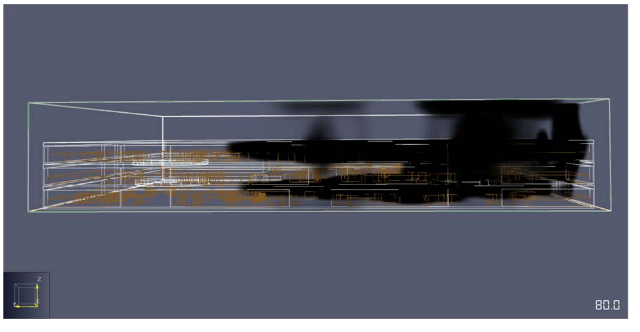


FIGURE 3. Smoke distribution in the Taipei 101 mall.

Figure 2 shows the temperature distribution after 80 seconds of simulation time. Fire starts at the first floor; and after 80 seconds of simulation time, the temperature at the fire origin is about 150 °C. In Figure 2, the neighboring area of the fire origin at the first floor and the escalator from the first floor to the second floor have the higher temperature, between 100 °C to 150 °C. Also, the temperature at the other areas is 25 °C, which do not change in 80 seconds of simulation. Considering the upper limit of human temperature tenability in 100 °C [1], the area with more than 100 °C temperature is the heat danger zone. It can be observed that the heat danger zone is colored from light green to red, which is confined to the nearby area of the fire origin at the first floor and the escalator from first to second floor.

Figure 3 shows the visualized smoke distribution at 80 seconds of FDS simulation time. It is clear to observe that the smoke zone in Figure 3 is much larger than the heat danger zone in Figure 2. In addition, the heat danger zone is a subset of the smoke zone. In Figure 3, the stack effect is observed at the escalator from the first floor to the third. This stack effect comes from the escalator in Taipei 101 mall, which is like a chimney for smoke circulating from the first floor all the way to the third floor. Because of this stack effect, the smoke spreading at the third floor is faster than that of the second floor. Since visualized smoke zone does not mean smoke danger zone, the threshold of the smoke toxicity value must be determined to define the smoke danger zone.

To measure the toxicity of the fire gases, an international standard, Fractional Effective Dose (FED), is documented in International Standards Organization (ISO) document 13571 [38]. In [47], Purser identifies the asphyxiant gases and irritants to calculate the FED value. Basically, the larger concentration of asphyxiant gases and irritants, the bigger the FED value. In [37], it is reported that the elderly, young, and occupants with compromised immune systems, who are 11% of the population, will be incapacitated when staying in the FDS value greater than 0.3. In NFPA 130 [48], 0.5 FED is suggested as the threshold limit for healthy adult population.

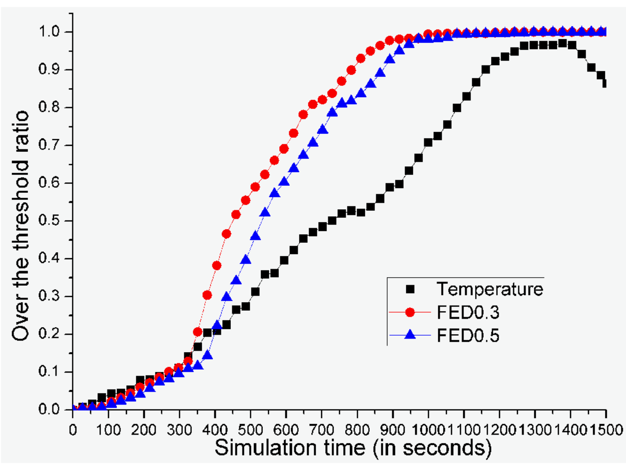


FIGURE 4. Ratio of sensors that report over the threshold value.

In Figure 4, we show the FDS simulation results on the ratio of data captured by the sensors that are over the threshold in terms of temperature and FED values at Taipei 101 mall. We set 100°C as the temperature threshold and two FED threshold values (i.e., 0.3 and 0.5) in Figure 4. According to results in Figure 4, 0.3 FED has the largest over the threshold ratio, followed by 0.5 FED; The temperature over 100°C has the smallest over the threshold ratio. This simulation shows that the area of the smoke danger zone (i.e., the ratio of sensors reporting larger than 0.3 FED value or 0.5 FED value) is larger than heat danger zone (i.e., the ratio of sensors reporting more than 100 °C) at Taipei 101 mall.

Based on Figures 2, 3 and 4, it is evident that smoke hazard has a greater impact on the fire evacuation than heat hazard. Based on this finding, in this paper, we address the smoke-aware evacuation problem in multi-story multi-exit buildings where the smoke toxicity in terms of FED is considered in evacuation. Basically, to evacuate a single evacuee and to evacuate a group of evacuees are different. Single evacuee evacuation is to identify the fastest smoke-safe evacuation path for an evacuee. On the other hand, group evacuation is to safely evacuate as many evacuees as possible. Because the number of evacuees who can pass through a passage is limited at any moment, it is important to consider this flow constraint in group evacuation. Hence, as compared to single evacuee evacuation, evacuees' scheduling in entering the over-capacity passage is important in group evacuation to prevent the tragedy of being crushed or injured in over-crowded areas. It arises an interesting question, which evacuees have higher priority to pass the passage when the number of evacuees violate the flow constraint in the passage.

To answer the above question, the basic idea is to prevent the evacuees from breathing in too much smoke. Smoke is dangerous because there are many kinds of toxic fire effluents in the fire smoke. Common toxic gases like carbon monoxide and other gases, lead to evacuees' incapacitation and causes 60% of the deaths in fire [31]. Basically, the larger amount of smoke an evacuee breathes in, the higher the probability an evacuee will be incapacitated in evacuation. Hence, the evacuee who has already breathed in the largest amount of toxic gases during evacuation should be evacuated first. To be more specific, the evacuees with larger accumulated FED on the travelled evacuation path are given higher priority to pass the over-capacity passage.

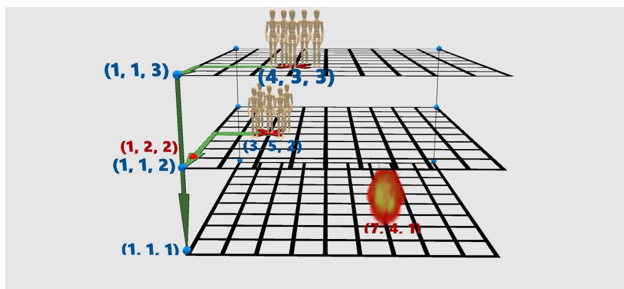


FIGURE 5. Group evacuation in the Taipei 101 mall.

Figure 5 illustrates an example of group evacuation in the Taipei 101 mall with a grid size 10 × 10 deployed smoke sensors at 80 seconds of FDS simulation time. In this example, we assume that the evacuation speed is one hop per one time slot, and one time slot is 30 seconds. The flow constraint at each passage is five. In other words, at most, five evacuees are allowed to pass a node at the same time. Figure 5 has the same fire origin (7, 4, 1) as Figure 2 and 3, which is at the first floor. According to Figure 3, at 80 seconds simulation time, the smoke does not cover the exit (1, 1, 1). Five evacuees starting at (3, 5, 2) and five evacuees starting at (4, 3, 3) will evacuate the exit (1, 1, 1). After six time slots (i.e., 180 seconds), these two groups will all arrive at node (1, 1, 2). Because the flow constraint is five, it can be expected that there is a congestion on the passage from node (1, 1, 2) to node (1, 1, 1). This kind of congestion will slow down the evacuation speed and even causes injuries in evacuation.

In Figure 5, to avoid ten evacuees moving to node (1, 1, 2) at the same time, one group should wait one more time slot before moving to node (1, 1, 2) at the fifth iteration. Hence, either five evacuees starting at (4, 3, 3) wait one more time slot at node (1, 1, 3) or five evacuees starting at (3, 5, 2) wait one more time slot at node (1, 2, 2) before moving to node (1, 1, 2). Then, the next decision will be about the choice of the group to be moved to (1, 1, 2). One good solution is based on the accumulated smoke on the evacuation route.

According to the visualized smoke diagram in Figure 3, smoke spreads at a faster speed at the third floor than at the second. Therefore, the five evacuees starting at (4, 3, 3) breathes in more smoke than the five evacuees starting at (3, 5, 2). Then, by giving higher priority to the five evacuees starting at (4, 3, 3), they can evacuate to the emergency exit (1, 1, 1) with less time to prevent incapacitation from inhaling too much toxic gases. In other words, at the fifth time slot (i.e., 150 seconds), the evacuation group starting at (3, 5, 2) should wait at location (1, 2, 2) for one time slot (i.e., 30 seconds) and the evacuation group starting at (4, 3, 3) can proceed to (1, 1, 2). At the seventh time slot (i.e., 210 seconds), five evacuees starting at (4, 3, 3) can reach the exit node (1, 1, 1) and five evacuees starting at (3, 5, 2) will arrive at node (1, 1, 2). Finally, five evacuees starting at (3, 5, 2) will reach exit node (1, 1, 1) at the eighth time slot (i.e., 240 seconds). With this extra one time slot delay at location (1, 2, 2) for the evacuees starting at (3, 5, 2), the flow constraint is satisfied and the tragedy of being crushed or injured in over-crowded passage (1, 1, 2) to (1, 1, 1) can be avoided.

Based on the above example, the evacuation problem should consider the accumulated smoke injuries of the evacuees so that evacuees will not be incapacitated in evacuation. Because smoke will spread very fast in the fire, the smoke concentrations change dramatically in a very short period, especially in a large multi-story building. Hence, evacuation path should be re-calculated and even be rerouted at every time slot to adapt to the rapid smoke concentration changes in the fire. With the help of existing positioning scheme [33] to identify the physical location of the evacuee and the IoT enabled smoke and chemical sensors [34] to periodically report the sensed smoke data, the accumulated smoke data for each evacuee in evacuation can be traced and calculated.

In this paper, besides identifying the smoke-safe shortest evacuation route for an evacuee, we also develop a smoke-aware group evacuation algorithm to maximize the number of successfully evacuated evacuees. In addition, the scheduling algorithm at over-crowded node is also devised in considering the inhaled toxic gases. In other words, the devised group evacuation algorithm aims to maximize the number of successfully evacuated evacuees, and at the same time reduce the smoke injuries of evacuees in evacuation. From the FDS simulations in Section 5, we show that violating the flow constraints will lead to lesser number of successfully evacuated evacuees.

We summarize the contributions of this paper.

A. NOVEL SMOKE-AWARE EVACUATION MATHEMATICAL MODELS

We propose two mathematical models to capture the smoke-aware evacuation problem in the multi-story multi-exit building. The first one is the Individual's Evacuation Path Planning (IEPP) model, where the objective function is to identify the fastest evacuation path for a single evacuee without violating the smoke toxicity constraint. The second one is the Group's Evacuation Path Planning (GEPP) model, where the objective function is to evacuate the largest number of evacuees in considering the smoke toxicity constraint and the flow constraint.

B. NOVEL SMOKE-AWARE EVACUATION ALGORITHMS

Based on the IEPP model and GEPP model, two evacuation algorithms (called SIEP and SGEP) are devised to evacuate a single evacuee and a group of evacuees. SIEP is a Dijkstra's shortest-path-based algorithm, where the link arc weight setting via the combination of the smoke toxicity value and the hop count, is performed to identify the smoke-aware fastest evacuation route for an evacuee. With the consideration of the flow constraint, the second proposed algorithm SGEP is to evacuate as many evacuees as possible and at the same time reduce the injuries from toxic smoke inhalation in evacuation.

C. FDS SIMULATIONS BASED ON REAL FLOOR LAYOUT OF TAIPEI 101 MALL

FDS simulations are performed to examine the smoke spreading and smoke toxicity progression at the most visited Taipei 101 mall, where the building layout in the FDS is modeled based on the real layout of Taipei 101 mall. The results show that the smoke danger zone is larger than the heat danger zone; therefore, the smoke toxicity value should be addressed in planning the evacuation routes. Based on the FDS's smoke toxicity value at Taipei 101 mall, the SGEP is superior to SIEP in terms of evacuation success probability at all simulation settings in both the methane fire and PVC fire.

D. HELPS TO DETERMINE THE CRITICAL PERCENTAGE OF TOXIC NODES FOR SAFE EVACUATION

We define the critical percentage of the toxic nodes for evacuation as the percentage of toxic nodes at the time of the last evacuee's evacuation time. When the percentage of the toxic nodes is larger than the critical percentage of the toxic nodes, no evacuees can be safely evacuated. From the FDS simulations with SIEP and SGEP, we identify the critical percentage of the toxic nodes in the buildings that can help the rescue team (e.g., fireman) to perform safe evacuation.

II. RELATED WORKS

Thanks to the rapid advancement of sensor technologies and IoT technologies, sensors can sense, capture, and communicate the sensed data via wired links or wireless technologies to detect and issue the fire alarm. Because of the advantages of fast deployment and low deployment cost, wireless sensors have predominated the wired sensors in recent years. Popular wireless technologies for IoT sensors include Wi-Fi [40], Bluetooth [41], Zigbee [39] and LoRa [42].

Occupant localization and positioning problem must be solved before evacuating the occupants to the safe exit. In [2], RFID-based localization scheme is used. Based on the RFID signal from the occupant's RFID tag, occupant's location can be traced to enable emergency evacuation [2]. Another indoor localization system is proposed in [7] by using the Bluetooth to locate and evacuate evacuees.

Several IoT enabled fire detection system prototypes are implemented. In [27], an Arduino board which bundle temperature sensors, flame sensors and ZigBee module is built to facilitate the application of home-based fire detection and alert. Similar home-based fire detection system using the wireless sensors networks and GSM communication module are proposed in [26]. Another IoT prototype in [28] is built to monitor the toxic gases concentration and operate the ventilation system when the level of toxic gases become high in the industrial environment. Large area IoT evacuation support system is proposed in [6] which includes the emergency centers, localization center, smartphone App and wireless backbone networks.

Hazard from toxic gases and smoke has been studied in recent fire engineering studies. In [46], real fire experiments are performed in a real health care center equipped with the sprinkler system. The results show that the sprinkler system suppressed the fire to reduce the risks from burns; however, risks of incapacitation due to toxic gases cannot be eliminated. In [45], by leveraging on the wireless sensor network, the boundary algorithms are proposed to capture the dangerous area of toxic gases in considering the gases leaking and node failure.

Evacuation planning algorithm has been proposed in recent studies. In [7], [8], and [13], shortest-path-based algorithm based on the risk score is proposed to guide the evacuees to the safe exit. The risk score is the weighted sum of risk factors (including temperature, visibility, CO density etc.). Based on the risk score on each link, Dijkstra's shortest path algorithm is performed to identify the best route. In [24], they compare the safest and shortest path and found out that the safest route is longer than the shortest route in the majority of the tested scenarios. Leveraging on the swarm intelligence of ants and bees, ant colony evacuation algorithm [3], [4] and bee colony evacuation algorithm [18] are proposed to search for safe emergency exit based on the cooperative behavior of the evacuees. In [5], first congestion-aware multi-exit evacuation algorithm is presented to avoid the congestion at the exit. Their approach is to partition the evacuees into groups and calculate the departure time of each group to avoid congestion. The first fire evacuation environment to train reinforcement learning agents for evacuation planning is proposed in [15]. Our earlier work in [43] proposes an evacuation algorithm in multi-exits and multi-floor building based on the timely sensed temperature data from the temperature sensors.

Evacuee's behavior plays an important role in evacuation. Basically, acquiring more fire environment information provided by the IoT devices can help to reduce the evacuee's degree of panic [14]. In [10], they also found out that occupants will not immediately evacuate after the fire alarm. However, occupants will speed-up the evacuation process when they are informed with the fire locations and evacuation path. The spreading of fire smoke will seriously affect the moving speed of the evacuees. In [19], they show that the evacuees' movement behaviors change from normal walk, bent-over walk, to crawl, as fire smoke keeps spreading. In [20], computational experiments are performed to identify the influence of the evacuee density, age, and gender on evacuation strategies in different fire scenarios. Environmental knowledge in an evacuation is another key factor in determining the evacuation speed. In [25], they show the environment information from the IoT devices can significantly help visitors to speed-up the evacuation process. In [12], evacuation path choice model is proposed and simulated by assuming that the evacuees can predict both the spreading of fire and the crowdedness of the exits. The results show that timely fire spread information and passage density information is essential to efficient evacuation.

Fire simulation models have been proposed in recent research. The most well-known fire simulation tool is the Fire Dynamics Simulator (FDS). FDS is developed by the NIST of the United States Department of Commerce [32], which is widely used in fire engineering to simulate the fire scenarios. In [17], FDS are used to simulate the evacuation time in various environment scenarios. Another FDS simulations are performed in [22] to capture the movement of occupants with considering the fire spread. Fire and evacuation simulations done in [16] are used to reconstruct a fatal fire that occurred in Pusan, Korea in 2009. The simulation results show that the occupants' response time is the most important factor in determining the evacuation success probability. Since the architecture of historical buildings cannot be altered, fire and evacuation simulations are done at historical museum [21] and historical theaters [23] in Italy to increase the evacuation efficiency.

To summarize, even though there are many evacuation algorithms proposed in the literature, toxic smoke aware evacuation and congestion aware evacuation have not been fully addressed. In this paper, two toxic smoke aware evacuation algorithms (SIEP and SGEP) are proposed where the idea of evacuation priority scheduling based on evacuee's accumulated smoke toxicity value is devised in SGEP to circumvent the congestion in over-crowded fire evacuation.

III. MATHEMATICAL MODEL FOR SMOKE-AWARE EVACUATION IN MULTI-STORY MULTI-EXIT BUILDINGS

A. FRACTIONAL EFFECTIVE DOSE (FED) INDEX

Most fire deaths are caused by toxic gases inhalation and depletion of the oxygen. Quantifying toxicity in fire gases is important in planning safe fire evacuation route. In research [49], they indicate that the toxic gases that impact occupants the most are carbon monoxide (CO) and hydrogen cyanide (HCN). Exposure to either gas can cause incapacitation and deaths in a very short period of time. Basically, there are two types of fire toxic gases, namely asphyxiant gases and irritants. In [47], Purser identifies the common asphyxiant gases in fire gases, which include carbon monoxide (CO), hydrogen cyanide (HCN) and nitrogen oxides (NO_x). Purser also identifies the common irritants in fire gases, which include hydrogen chloride (HCL), hydrogen bromide (HBr), hydrogen fluoride (HF), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), acrolein (C_3H_4O) and formaldehyde (CH_2O). Considering these two types of fire toxic gases, a well-known incapacitating dose called Fractional Effective Dose (FED) index is developed in Equation 1 [47].

$$FED = (FED_{CO} + FED_{CN} + FED_{NO_x} + FLD_{irr}) \, HV_{CO_2} + FED_{O_2} \quad (1)$$

where

$$FED_{CO} = \int_0^t 2.764\times10^{-5} \left(\chi_{CO}(t)\right)^{1.036} dt \quad (2)$$

$$FED_{CN} = \int_0^t \left(\frac{1}{220} exp\left(\frac{\chi_{CN}(t)}{43}\right) - 0.0045\right) dt \quad (3)$$

$$FED_{NO_x} = \int_0^t \left(\frac{\chi_{NO}(t) + \chi_{NO_2}(t)}{1500}\right) dt \quad (4)$$

$$FLD_{irr} = \int_0^t \left(\frac{\chi_{HCl}(t)}{114000} + \frac{\chi_{HBr}(t)}{114000} + \frac{\chi_{HF}(t)}{87000} + \frac{\chi_{SO_2}(t)}{12000} + \frac{\chi_{NO_2}(t)}{1900} + \frac{\chi_{C_3H_4O}(t)}{4500} + \frac{\chi_{CH_2O}(t)}{22500}\right) dt \quad (5)$$

$$HV_{CO_2} = \frac{exp\left(0.1903\chi_{CO_2}(t) + 2.0004\right)}{7.1} \quad (6)$$

$$FED_{O_2} = \int_0^t \frac{dt}{exp\left(8.13 - 0.54\left(20.9 - \%_{O_2}(t)\right)\right)}. \quad (7)$$

In Equations (2)~(6), t is time in minutes and $\chi_i(t)$ means the concentration of gas i at given time in ppm. For example, $\chi_{CO}(t)$ means the concentration of carbon monoxide (CO) at given time in ppm. Because CO has higher affinity to NO_x than O_2, then considering the protective effects of NO and NO_2 from hydrogen cyanide poisoning. In Equation (3), $\chi_{CN}(t) = \chi_{HCN}(t) - \chi_{NO}(t) - \chi_{NO_2}(t)$. In Equation (7), $\%_{O_2}(t)$ means the concentration of oxygen in percentage. In Equation (5), the denominator for each irritant gas is lethal exposure doses to half of the population in (ppm×minute). Equation (6) captures the hyperventilation from carbon dioxide. Equation (7) captures the incapacitating does of low oxygen hypoxia. In this paper, we adopt this FED value as the main index to quantify the toxicity of the fire gases.

Because toxic gases and smoke spread very fast in fire, the gas concentration can increase dramatically in a very short time. Instead of one-shot sensing, smoke and gas data should be periodically sensed and transmitted back to the control station. Then the evacuation path should be calculated, and evacuees guided to the safe exit based on the current sensed data. In this paper, two mathematical models are proposed to capture the smoke-aware evacuation path planning problem for a single evacuee and a group of evacuees, based on the gases data periodically captured by the sensors in the multi-story multi-exit buildings. For evacuating a single evacuee, the proposed single evacuation path algorithm identifies a path that can safely evacuate as fast as possible. When considering evacuating a group of evacuees, the proposed group evacuation path algorithm is to identify the evacuation paths to safely evacuate as many evacuees as possible with considering the flow constraint on the evacuation route. In the Section 3.2, we first propose the mathematical formulation (IEPP) to identify a safe and quick evacuation route for a single evacuee. In Section 3.3, the mathematical formulation (GEPP) is devised to evacuate as many evacuees as possible.

B. INDIVIDUAL'S EVACUATION PATH PLANNING (IEPP) MODEL

First, we give the notations used in the formulation as follows.

Input values:

L: the set of possible links on the graph;

E: the set of emergency exit nodes on the graph;

M_{FED} : the tenability limit of human's FED value (e.g., 0.3);

δ_{pl} : the indication function, $\delta_{pl} = 1$ when the link l is on the evacuation path p; $\delta_{pl} = 0$, otherwise;

ζ_{pe} : the indication function, $\zeta_{pe} = 1$ when the node e is on the evacuation path p; $\zeta_{pe} = 0$, otherwise;

T: the set of time slots during evacuation;

FED_{lt} : the calculated FED value based on Equation (1) on link $l \in L$ at time slot $t \in T$;

Decision variables:

x_p := 1 if evacuation path p is selected where $p \in P_u$, $u \in U$; =0, otherwise;

y_l := 1 if link l is on the selected evacuation path where $l \in L$; =0, otherwise;

z_{lt} := 1 if link l$\in L$ is on the selected evaculation path at time slot t $\in T$; =0, otherwise.

The IEPP mathematical model is proposed as follows.

Problem (P_1):

$$Z_{p1} = \min \sum_{l \in L} \sum_{t \in T} FED_{lt} \times z_{lt} \quad (8)$$

$$\text{Subject to}: \sum_{p \in P_u} x_p = 1 \quad \forall u \in U \quad (9)$$

$$\sum_{p\in P_u}\sum_{e\in E} x_p\zeta_{pe} \geq 1 \quad \forall u \in U \tag{10}$$

$$x_p\times\delta_{pl} \leq y_l \quad \forall p \in P_u,\ u \in U,\ l \in L \tag{11}$$

$$y_l \leq \sum_{t\in T} z_{lt} \quad \forall l \in L,\ t \in T \tag{12}$$

$$\sum_{t\in T} z_{lt} \leq 1 \quad \forall l \in L \tag{13}$$

$$x_p = 0 \text{ or} 1 \quad \forall p \in P_u,\ u \in U \tag{14}$$

$$y_l = 0 \text{ or} 1 \quad \forall l \in L \tag{15}$$

$$z_{lt} = 0 \text{ or} 1 \quad \forall l \in L, t \in T \tag{16}$$

$$z_{lt}\times FED_{lt} \leq M_{FED} \quad \forall l \in L,\ t \in T. \tag{17}$$

Basically, the evacuation path should not select the risk links with higher smoke concentration. In the fire zone, smoke concentration might change rapidly. By assuming that sensors periodically report the sensed gases' concentrations back to sink node, the link cost FED_{lt} is introduced to capture the timely risk cost in terms of toxic smoke at time slot $t \in T$ on link $l \in L$ in the objective function. In addition, the decision variable, z_{lt}, is to identify the selected link $l \in L$ on the evacuation path at a time slot $t \in T$. Then, the objective function is to minimize the total risk cost of the selected links on the evacuation path.

In Problem (P_1), Constraint (9) enforces that an evacuation path should be identified for each evacuee $u \in U$. Constraint (10) enforces at least one emergency exit is on the evacuation path. Constraints (11) enforces that $y_l = 1$ for every link $l \in L$ on the selected evacuation path. Constraint (12) enforces that if a link $l \in L$ on the evacuation path (i.e., y_l =1), then the evacuee should traverse on that link at least one time slot, (i.e., $1 \leq \sum_{t\in T} z_{lt}$). Constraint (13) is to ensure an evacuee can only traverse every link $l \in L$ on the evacuation path at most one time slot. Hence, Constraints (11), (12) and (13) guarantee that there is no loop on the evacuation path by enforcing that an evacuee can only traverse exactly one time slot for every link $l \in L$ on the evacuation path. Constraints (14), (15) and (16) define the feasible solutions for the decision variables. Constraints (9)~(16), they ensure that if any link $l \in L$ on the evacuation path is traversed by an evacuee at a time slot $t \in T$, then z_{lt} is 1 (i.e., z_{lt} =1). Then the objective function is to identify the evacuation path for an evacuee with the minimum aggregate FED value on the evacuation route. Constraint (17) enforces that the calculated FED value based on Equation (1) cannot exceed M_{FED} when an evacuee traverse on link $l \in L$ at time slot $t \in T$. This is to ensure that an evacuee will not traverse on a dangerous link during evacuation. This constraint is to prevent the evacuee from the toxic smoke injuries in evacuation.

C. GROUP'S EVACUATION PATH PLANNING (GEPP) MODEL

Besides the notations given in Section 3.2, the additional notations used in the GEPP model are listed as follows.

Input values:
U : the set of occupants to be evacuated;
K: the maximum number of evacuees can be evacuated on a link in one time slot;
Decision variables:
$A_u := 1$ if occupant $u \in U$ is evacuated successfully; =0, otherwise;
$r_{ul} := 1$ if link $l \in L$ is on the selected evaculation path for occupant $u \in U$; =0, otherwise;
$s_{ult} := 1$ if link $l \in L$ is on the selected evaculation path for occupant $u \in U$ at time slot $t \in T$; =0, otherwise.

The Group's Evacuation Path Planning (GEPP) mathematical model is proposed as follows.

Problem (P_2):

$$Z_{p2} = \max \sum_{u\in U} A_u \tag{18}$$

$$\text{Subject to: } A_u \leq \sum_{p\in P_u} x_p \quad \forall u \in U \tag{19}$$

$$\sum_{p\in P_u} x_p \leq 1 \quad \forall u \in U \tag{20}$$

$$\sum_{p\in P_u}\sum_{e\in E} x_p\zeta_{pe} \geq A_u \quad \forall u \in U \tag{21}$$

$$x_p\times\delta_{pl} \leq r_{ul} \quad \forall p \in P_u, u \in U, l \in L \tag{22}$$

$$r_{ul} \leq \sum_{t\in T} s_{ult} \quad \forall u \in U, l \in L, t \in T \tag{23}$$

$$\sum_{t\in T} s_{ult} \leq 1 \quad \forall u \in U, l \in L \tag{24}$$

$$\sum_{u\in U} s_{ult} \leq K \quad \forall l \in L, t \in T \tag{25}$$

$$A_u = 0 \text{ or} 1 \quad \forall u \in U \tag{26}$$

$$x_p = 0 \text{ or} 1 \quad \forall p \in P_u, u \in U \tag{27}$$

$$r_{ul} = 0 \text{ or} 1 \quad \forall u \in U, l \in L \tag{28}$$

$$s_{ult} = 0 \text{ or} 1 \forall u \in U, l \in L, t \in T \tag{29}$$

$$s_{ult}\times FED_{lt} \leq M_{FED} \quad \forall u \in U, l \in L, t \in T. \tag{30}$$

As compared to identifying the minimum cost evacuation path for a single evacuee in the IEPP model, the main objective of GEPP model is to evacuate as many evacuees as possible. In the GEPP model, besides identifying the smoke safe evacuation path for each successfully evacuated evacuee, flow constraint is also considered in the GEPP model. Flow constraint specifies that the number of concurrent evacuees on a link should not exceed its maximum capacity. This is an important constraint in evacuating a group of occupants in the fire zone to prevent the tragedy of being crushed or injured in over-crowded area.

In the objective function of GEPP model, the objective function is to maximize the number of occupants that are successfully evacuated. In Constraints (19) and (20), they specify that if an evacuee is successfully evacuated, then an evacuation path should be identified for this evacuee. Constraint (21) enforces at least one emergency exit is on the evacuation path if an evacuee is successfully evacuated. Constraints (22), (23) and (24) guarantee that there is no loop on the evacuation path by enforcing that an evacuee can only visit a link once for every link $l \in L$ on the evacuation path. Constraint (25) is the flow constraint that enforces that the number of evacuees on a link in one time slot cannot exceed the link's maximum evacuation capacity K. Constraints (26), (27), (28) and (29) define the feasible solutions for the decision variables. Constraint (30) specify that the identified evacuation path must be smoke safe.

In the next section, we propose the algorithms to tackle the IEPP and GEPP mathematical models.

IV. SOLUTION APPROACHES

Problem (P_1) is basically a constrained shortest path problem where the objective is to identify a shortest evacuation path with considering the smoke safe evacuation path constraint. By relaxing the flow constraint in Problem (P_2), identifying the shortest evacuation path for each evacuee with considering the smoke safe evacuation path constraints can maximize the number of successfully evacuated evacuees. In other words, by relaxing the flow constraint, Problem (P_2) is to identify several constrained shortest paths for each evacuee. However, the constrained shortest path problem is proven to be a NP-hard problem in [9]. In other words, Problem (P_1) and (P_2) are all NP-hard problem and there is no existing polynomial time algorithm to optimally solve Problem (P_1) and Problem (P_2). In the following, we devise the novel heuristic algorithms to tackle Problem (P_1) and Problem (P_2).

A. SMOKE-AWARE INDIVIDUAL EVACUATION PLANNING (SIEP) ALGORITHM

In the following, we first present the SIEP algorithm to identify good evacuation path for an evacuee in Problem (P_1). The basic idea of SIEP algorithm is to leverage on Dijkstra's algorithm to identify the path to every exit based on the link arc weight $(1 + FED_{lt})$ for each link $l \in L$ at time slot $t \in T$, where the FED_{lt} is calculated based on Equation (1) and the gas concentration data in Equation (1) are acquired by sensors at each time slot t. Basically, there are two parts in link arc weight setting. The first part (i.e., one) is the hop-count and the second part is the smoke danger index—FED as defined in Equation (1). With the hop count in the link arc weight setting, the Dijkstra's algorithm identifies the route with the smallest hop count to the emergency exit. With the FED in the link arc weight setting, the Dijkstra's algorithm identifies the route with smallest accumulated smoke danger index. Hence, by combining the hop count and the smoke danger index in the arc weight, the Dijkstra's algorithm identifies the fastest smoke safe path to the emergency exit.

Among these shortest paths to every exit, identify the exit (say $\tilde{\lambda}$) with the minimum path cost and let exit $\tilde{\lambda}$ be the destination node of the evacuation path at this time slot. As the number of hops a user can move is limited in one time slot (e.g., 30 seconds), an evacuee can only move a few hops towards the exit $\tilde{\lambda}$. Let Λ be the number of hops an evacuee can move in one time slot. Two scenarios should be considered to determine an evacuee's location at the next time slot. When the hop distance between the evacuee's current position and exit $\tilde{\lambda}$ is not greater than Λ, the evacuee can be evacuated successfully at emergency exit $\tilde{\lambda}$ and SIEP algorithm stops. Otherwise, the evacuee moves Λ hops along this evacuation path towards the exit$\tilde{\lambda}$ and the algorithm repeats until the evacuee finally reach an emergency exit.

SIEP Algorithm

Begin
Initialize the value of all the decision variables to be zero;
Construct the nodes and links in the 2-D planar graph;
Let the node position of an evacuee be the source node;
Let $\Omega = 0$;
Let $\rho = 0$;
Let $t = 0$;
While $((t \leq |T|)$ and $(\rho == 0)$ and $(\Omega \leq N))$//looping at each time slot t
Begin
Collect the sensed smoke data at each link at time slot t;
Calculate $(1 + FED_{lt})$ based on Equation (1) as the link arc weight for each link l at time slot t;
Remove the link l from set L if the FED value is over the upper limit M_{FED}; //ensures that all the links on the evacuation path are smoke-safe
Calculate the shortest path from the source node to every exit node by using the Dijkstra's algorithm; //Step 3
Let $\sigma = 0$;
For every exit $e \in E$
Begin
If there is a best path to exit $e \in E$
Begin
Let λ_e = the best path cost to exit $e \in E$;
Let $\sigma = 1$;
End//if
End//For
If $(\sigma == 0)$//cannot find any best path to all the exits
Begin
Report no feasiblesolutions;
Break from the **While** loop;
End// If $(\sigma == 0)$
Else//at least there is a shortest path to exit
Let $\tilde{\lambda} = \text{Min}Arg_{e \in E} \lambda_e$; //the exit number that has the smallest shortest path cost, exit $\tilde{\lambda}$ is the destination node
If (the hop distance from the source node to the exit number $\tilde{\lambda}$ on the evacuation path $\leq \Lambda$) //reach the exit

Begin
Let Π be set of the links from the source node to the exit $\tilde{\lambda}$ on the evacuation path;
Report the evacuation path; //report the evacuation route;
Let $\rho = 1$; //evacuate successfully, exit from the "While" loop
End // If (the hop
Else // haven't reached the exit, then move the source node Λ hop distance closer to exit $\tilde{\lambda}$ on the emergency path
Begin
Let Π be set of the links from the source node to the node with hop distance Λon the evacuation path;
Move the source node to the new position with Λ hop distance on the evacuation path;
End// Else, haven't reached the exit
Let $t = t + 1$; //proceed to next time slot
End;//While loop
If $(\rho == 0)$
Report no feasible solutions;
End

In the SIEP algorithm, the time complexity is bounded at the "While" loop for each time slot. In the worst case, "While" loop is looped for $|T|$ times. Inside the "While" loop, Dijkstra's shortest path algorithm is to be performed for every emergency exit. The time complexity of Dijkstra's shortest path algorithm is $O\left(|N|^2\right)$ where N is the set of nodes in the networks. The time complexity for the SIEP algorithm is $O\left(|T| \times |E| \times |N|^2\right)$, where $|T|$ is the maximum number of time slots and $|E|$ is the maximum number of exits in the networks.

B. SMOKE-AWARE GROUP EVACUATION PLANNING (SGEP) ALGORITHM

Next, we show the SGEP algorithm. As compared to the SIEP algorithm to identify the minimum cost evacuation path for an evacuee, the goal in SGEP is to evacuate evacuees as many as possible. In every time slot t, first remove the unsafe links with the smoke concentration that are over the upper limit of human tenability (i.e., M_{FED}) from the set L. Like the link arc weight setting in SIEP algorithm, the arc weight for the remaining links is also setting as $(1 + FED_{lt})$ for each link $l \in L$ at each time slot $t \in T$. Next, performing the Dijkstra's algorithm to identify the shortest evacuation path to every emergency exit. Among these emergency exit nodes, identify the emergency exit node that has the smallest path cost and let the evacuee move towards the identified emergency exit.

When the flow constraint is violated, an interesting question is how to select K evacuees to go through this link. The idea is to choose the evacuees with more suffering in the fire zone. Considering the case in choosing only one from two evacuees, one traverses a harsh evacuation path with larger accumulated FED and the other traverses a relatively good evacuation path with smaller accumulated FED; then, it is better to evacuate that evacuee with larger accumulated FED because s/he has already breathed in too much smoke. Based on this idea, we calculate the accumulated travelled path cost of each evacuee, and then put the evacuee's ID in set Ψ in descending order with respect to the accumulated path cost. When the flow constraint is violated at a link, the first K evacuees in set Ψ can traverse on this link and the other evacuees in set Ψ must wait until the next time slot. In other words, besides the number of successfully evacuated evacuees, SGEP algorithm also tries to reduce the injuries from toxic smoke in evacuation. This is especially important in over-crowded fire evacuation.

As compared to SIEP, an evacuee's next time slot position is not only determined from the number of hops an evacuee can move to the emergency exit in one time slot, but also determined by the flow constraint along the evacuation path. Four scenarios should be considered to determine an evacuee's location at the next time slot. When the hop distance between an evacuee u's current position and exit $\widetilde{\mu^u}$ is not greater than Λ and the flow constraint is not violated on the travelled links, an evacuee u can be evacuated successfully at emergency exit $\widetilde{\mu^u}$. When the hop distance between an evacuee u's current position and exit $\widetilde{\mu^u}$ is not greater than Λ and the flow constraint is violated on the travelled links, the evacuee can be evacuated to the node before violating the flow constraint. When the hop distance between the evacuee's current position and exit $\widetilde{\mu^u}$ is greater than Λ and the flow constraint is not violated on the travelled links, the evacuee can be evacuated to the new location with Λ hop distance along the evacuation path closer to exit $\widetilde{\mu^u}$. When the hop distance between the evacuee's current position and exit $\widetilde{\mu^u}$ is greater than Λ and the flow constraint is violated on the travelled links, the evacuee can be evacuated to the node before violating the flow constraint. Otherwise, the evacuee moves Λ hops on this evacuation path towards the exit $\tilde{\lambda}$ and the algorithm repeats until the evacuee finally reaches an emergency exit. The SGEP algorithm iterates at most $|T|$ time slots or evacuate all the evacuees that can be evacuated.

SGEP Algorithm

Begin
Initialize the value of all the decision variables (A_u, r_{ul}, s_{ult})to be zero;
Construct the nodes and links in the 2-D planar graph;
Let the node position of an evacuee be the source node;
Let$\Delta_u = 0 \; \forall u \in U$;
Let $\rho = 0$;
Let $t = 0$;
While $((t \leq |T|)$ and $(\rho == 0)$ and $(\Omega \leq N))$//looping at each time slot t
Begin
Collect the sensed smoke data at each link at time slot t;
Calculate $(1 + FED_{lt})$ based on Equation (1) as the link arc weight for each link l at time slot t;
Remove the link l from set L if the FED value is over the upper limit M_{FED}; //ensures that all the links on the evacuation path are smoke-safe

For each un-evacuated evacuee u where ($A_u == 0$) //first For loop
Begin
Calculate the shortest path for evacuee u from the current position to every exit node $e \in E$ by using the Dijkstra's algorithm; //Step 3
If shortest path can be identified by evacuee u to exit $e \in E$
Let μ_e^u = the shortest path cost for evacuee u to exit $e \in E$;
ElseIf
Let $\mu_e^u = \infty$; //no path to exit e, infinite path cost to exit e
If ($\mu_e^u \geq \infty \forall e \in E$) //no path to every emergency exit
Begin
Let $\alpha_u = \infty$; // evacuee u cannot be evacuated, infinite number of hops to the emergency exit
End//If
Else//can find evacuation path
Begin
Let $\widetilde{\mu^u} = \text{Min}Arg_{e \in E}\mu_e^u$; //identify the emergency exit $\widetilde{\mu^u}$ that has the smallest evacuation path cost
Let $\alpha_u$be the number of hops to the emergency exit $\widetilde{\mu^u}$;
End//Else
End//For
Sorting Δ_u for each un-evacuated evacuee u in descending order and put the associated evacuee ID to evacuation list Ψ for those evacuee u with ($\alpha_u < \infty$); // the data element in Ψ is the evacuee ID
For each data element u in evacuation list Ψ // an evacuee in set Ψ with larger FED value can be evacuated first
Begin
If (($\alpha_u \leq \Lambda$) and (flow constraint is not violated)) //can reach the exit at the next time slot
and the flow constraint is not violated
Begin
Let $s_{ult} = 1$ for all the links from the current location of u to the exit number $\widetilde{\mu^u}$;
Let Γ_u be the set of links from
the current location of u to the exit number $\widetilde{\mu^u}$
Let $\Delta_u = \Delta_u + \sum_{l \in \Gamma_u} FED_{lt} \times s_{ult}$;
Let A_u= 1;
Report A_u, $\Delta_u r_{ul}$, s_{ult}; // evacuate successfully, report the decision variables and total cost on the evacuation path
End// If (($\alpha_u \leq \Lambda$)
ElseIf(($\alpha_u \leq \Lambda$) and (flow constraint is violated)) //can reach the exit at the next time slot but the flow constraint is violated, then move the location of u to the node before violating the flow constraint
Begin
Let $s_{ult} = 1$ for all the links from the current location of u to the node before violating the flow constraint;
Let Γ_u be set of the links from the current location of u to the node before violating the flow constraint;
Let $\Delta_u = \Delta_u + \sum_{l \in \Gamma_u} FED_{lt} \times s_{ult}$;
Move evacuee u to the node before violating the flow constraint;
End// ElseIf
ElseIf (($\alpha_u > \Lambda$) and (flow constraint is not violated)) //cannot reach the exit at the next time slot and the flow constraint is not violated, then move the location of u to Λ hop distance closer along the evacuation path to exit $\widetilde{\mu^u}$
Begin
Let $s_{ult} = 1$ for all the links from the current location of u to the new location with Λ hop distance closer to exit $\widetilde{\mu^u}$;
LetΓ_u be set of the links from the current location of u to the new location with Λ hop distance closer to exit $\widetilde{\mu^u}$;
Let $\Delta_u = \Delta_u + \sum_{l \in \Gamma_u} FED_{lt} \times s_{ult}$;
Move evacuee u to the new location with Λ hop distance along the evacuation path closer to exit $\widetilde{\mu^u}$;
End// ElseIf
ElseIf (($\alpha_u > \Lambda$) and (flow constraint is violated)) //cannot reach the exit at the next time slot and the flow constraint is violated, then move the location of u at most Λ hop counts
along the evacuation path to the node before violating the flow
constraint
Begin
Let $s_{ult} = 1$ for all the links from the current location of u at most Λ hop counts along the evacuation path to the node before violating the flow constraint;
LetΓ_u be set of the links from the current location of u at most Λ hop counts along the evacuation path to the node before violating the flow constraint;
Let $\Delta_u = \Delta_u + \sum_{l \in \Gamma_u} FED_{lt} \times s_{ult}$;
Move evacuee u at most Λ hop counts along the evacuation path to the node before violating the flow constraint;
End// ElseIf
Ifthere are no more elements in list Ψ //finish evacuation process
Let ρ= 1; //evacuate all the evacuees that can be evacuated, terminate the While loop
End// For each data element u
Let $t = t + 1$; //proceed to next time slot
End;//While loop
Calculate the total evacuees that are successfully evacuated (i.e., $\sum_{u \in U} A_u$);
End

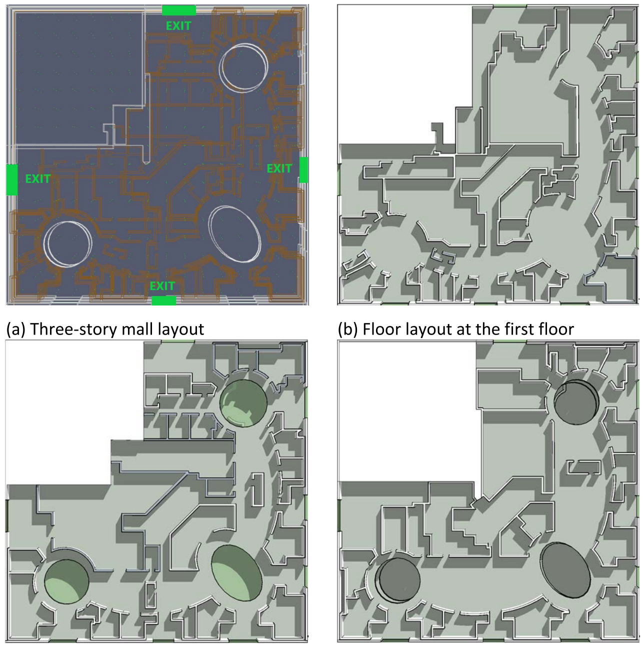
In the above SGEP algorithm, the time complexity is bounded at the "While" loop for each time slot. In the worst case, "While" loop is looped for $|T|$ times. Inside the "While" loop, for each evacuee, Dijkstra's shortest path algorithm is to be performed for every emergency exit. The time complexity of Dijkstra's shortest path algorithm is $O\left(|N|^2\right)$ where N is the set of nodes in the networks. Since there are total $|U|$ number of evacuees to be evacuated, then the time complexity for the SGEP algorithm is $O\left(|U| \times |T| \times |E| \times |N|^2\right)$, where $|T|$ is the maximum number of time slots and $|E|$ is the maximum number of exits in the networks.

Basically, the design philosophy of SGEP is different from SIEP. SIEP is an individualized evacuation approach and SGEP is a group evacuation approach. To be more specific, based on the most recent smoke data acquired by the sensors, SIEP algorithm is to identify the fastest smoke-safe evacuation path for an evacuee and SGEP algorithm is to identify the smoke-safe group evacuation plan (including identifying evacuation paths and evacuees' scheduling at the over-crowded passages) to evacuate as many evacuees as possible. Because flow constraint is not addressed in SIEP, it can be expected that evacuating a group of evacuees by using the SIEP algorithm will lead to poor results as compared to the SGEP algorithm, especially in over-crowded fire evacuation. In the simulations, we will examine the solution quality comparisons between individualized evacuation approach (i.e., SIEP) and group evacuation approach (i.e., SGEP) in different fire settings.

V. FIRE SIMULATIONS AND COMPUTATIONAL EXPERIMENTS

To capture the fire and smoke spreading in the fire zone, we conduct the fire simulations by adopting the well-known Fire Dynamics Simulator (FDS), which is developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce [32]. We choose Taipei 101 mall as the fire simulation site because Taipei 101 building is not only the tallest building in Taiwan, but also it attracts more than one million visitors every year [50]. To get accurate simulation results, we use AutoCAD to re-construct the three-story Taipei 101 mall based on the real layout in Taipei 101 mall. Figure 6(a) is the bird view of the layout of the three-story Taipei 101 mall with four exits, Figure 6(b) to Figure 6(d) captures the layout at each floor of Taipei 101 mall. Note that at each floor, one-fourth (blank layout area) is the office area, and this office area is inaccessible to the people in the mall. There are three escalators connecting the first, second and third floor in the Taipei 101 mall. The design of escalators is to help visitors shop between floors. However, the escalators will be a chimney to spread fire and smoke during fire.

In the FDS model, the length and width of Taipei 101 mall at each floor are the same with 160 meters, and the height is 6.5 meters. The height of the partition wall between shops is 2.5 meters. The width of the partition wall is one meter, which is composed of 0.6 meters of wood, 0.3 meters of calcium silicate and 0.1 meters of polyvinyl chloride (PVC). There are 256 (=16 × 16) sensors deployed at each floor, where the distance between each sensor is 10 meters, and the sensors are deployed at 4 meters high at each floor. In total, there are 768 (=256 × 3) sensors deployed in the building where these deployed sensors are shown as the green dots in Figure 6(a). Note that about one-fourth of the deployed sensor nodes are at the office area, making the total number of deployed sensor nodes in the Taipei 101 mall to be 586. Sprinklers are installed at the Taipei 101 to spray water when detecting smoke. There are 64 (=8 × 8) sprinklers deployed at each floor, where the distance between each sprinkler is 20 meters. Also, the sprinklers are deployed at 4 meters high at each floor. In total, there are 192 (=64 × 3) sprinklers deployed at these three floors in the building. In the following simulations, we assume that the evacuees are uniformly distributed in the Taipei 101 mall.



(a) Three-story mall layout (b) Floor layout at the first floor (c) Floor layout at the second floor (d) Floor layout at the third floor

FIGURE 6. Floor layout at the three-story Taipei 101 mall.

According to the report in Taipei city fire department [51], the top two fire causes are cooking fires (40.2%) and electrical fires (29.6%) in 2021. Methane is the main energy source in cooking, whereas PVC conduit is used to protect the electrical wires in the building. Two fire ignitors (methane and PVC) are simulated in Taipei 101 mall, and the configuration files of two fire ignitors in FDS are shown in Table 1. Note that the fire origin at the first floor and the location of the fire origin is shown in Figure 1.

Based on Table 1, we simulate two fire ignitors, methane and PVC, in Taipei 101 mall to calculate the FDS value at each sensor node based on Equation (1) under methane fire smoke and PVC fire smoke, respectively. To calculate the percentage of the toxic nodes in different FED values, we define FED_0.3 and FED_0.5 as the percentage of the sensor nodes that the calculated FED value is greater than 0.3 and 0.5, respectively. In Figure 7, we show the ratio of the sensors that are over the FED 0.3 threshold and FED 0.5 threshold at methane fire smoke and PVC fire smoke for 30 minutes simulation time in Taipei 101 mall.

There are two observations from Figure 7.

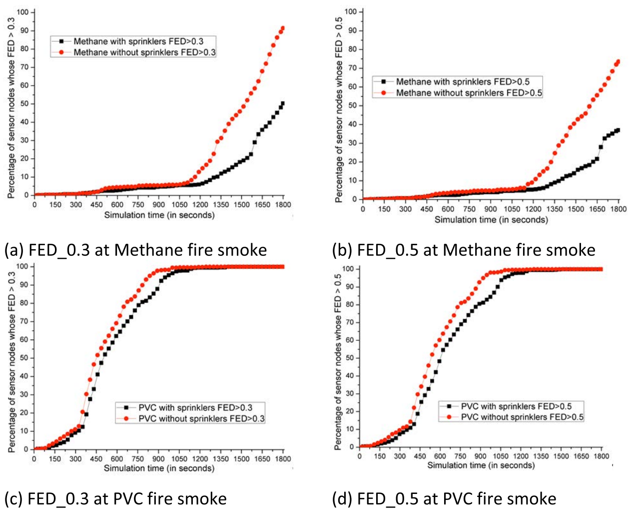
1) Sprinkler can help to reduce the smoke toxicity, especially at methane fire smoke. When enabling the sprinklers, both methane and PVC have lower FED_0.3 and FED_0.5 as compared to the simulation

TABLE 1. **The configuration fire of two fire ignitors in Taipei 101 mall.**

(a) Methane ignitor configuration	(b) PVC ignitor configuration
&REAC ID='METHANE', FYI='AFT NIST Multi-Floor FDS5 Validation', FUEL='REAC_FUEL', FORMULA='C1H4', RADIATIVE_FRACTION=0.35 &MATL ID='WOOD', SPECIFIC_HEAT=1.36, CONDUCTIVITY=0.13, DENSITY=369.6/ &MATL ID='CALCIUM SILICATE', FYI='NBSIR 88-3752 - NBS Multi-Room Validation', SPECIFIC_HEAT_RAMP='CAL CIUM SILICATE_SPECIFIC_HEAT_RA MP', CONDUCTIVITY=0.12, DENSITY=720.0, EMISSIVITY=0.83/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_R AMP', T=20.0, F=1.25/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_R AMP', T=200.0, F=1.25/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_R AMP', T=300.0, F=1.33/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_R AMP', T=600.0, F=1.55/ &MATL ID='PVC', FYI='NISTIR 1013-1 - NIST NRC Validation', SPECIFIC_HEAT_RAMP='PVC _SPECIFIC_HEAT_RAMP', CONDUCTIVITY_RAMP='PVC _CONDUCTIVITY_RAMP', DENSITY=1380.0, EMISSIVITY=0.95/ &RAMP ID='PVC_SPECIFIC_HEAT_RA MP', T=23.0, F=1.29/ &RAMP ID='PVC_SPECIFIC_HEAT_RA MP', T=50.0, F=1.35/ &RAMP	&SPEC ID='AIR', BACKGROUND=.TRUE., SPEC_ID(1)='NITROGEN', SPEC_ID(2)='OXYGEN', VOLUME_FRACTION(1)=5.76, VOLUME_FRACTION(2)=1.53/ &REAC ID='PVC', HEAT_OF_COMBUSTION=1.64 E4, FUEL='PVC', SPEC_ID_NU='AIR','PVC','PRO DUCTS', NU=-1.0,-1.0,1.0/ &MATL ID='WOOD', SPECIFIC_HEAT=1.36, CONDUCTIVITY=0.13, DENSITY=369.6/ &MATL ID='CALCIUM SILICATE', FYI='NBSIR 88-3752 - NBS Multi-Room Validation', SPECIFIC_HEAT_RAMP='CAL CIUM SILICATE_SPECIFIC_HEAT_ RAMP', CONDUCTIVITY=0.12, DENSITY=720.0, EMISSIVITY=0.83/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_ RAMP', T=20.0, F=1.25/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_ RAMP', T=200.0, F=1.25/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_ RAMP', T=300.0, F=1.33/ &RAMP ID='CALCIUM SILICATE_SPECIFIC_HEAT_ RAMP', T=600.0, F=1.55/ &MATL ID='PVC', FYI='NISTIR 1013-1 - NIST NRC Validation', SPECIFIC_HEAT_RAMP='PVC _SPECIFIC_HEAT_RAMP', CONDUCTIVITY_RAMP='PVC _CONDUCTIVITY_RAMP', DENSITY=1380.0, EMISSIVITY=0.95/

TABLE 1. ***(Continued.)*** **The configuration fire of two fire ignitors in Taipei 101 mall.**

ID='PVC_SPECIFIC_HEAT_RA MP', T=75.0, F=1.41/ &RAMP ID='PVC_SPECIFIC_HEAT_RA MP', T=100.0, F=1.47/ &RAMP ID='PVC_SPECIFIC_HEAT_RA MP', T=125.0, F=1.53/ &RAMP ID='PVC_SPECIFIC_HEAT_RA MP', T=150.0, F=1.59/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=23.0, F=0.192/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=50.0, F=0.175/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=75.0, F=0.172/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=100.0, F=0.147/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=125.0, F=0.141/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=150.0, F=0.134/ &SURF ID='Ignitor', RGB=204,127,102, HRRPUA=1200.0, BURN_AWAY=.TRUE., BACKING='VOID', MATL_ID(1,1)='WOOD', MATL_ID(2,1)='CALCIUM SILICATE', MATL_ID(3,1)='PVC', MATL_MASS_FRACTION(1,1) =1.0, MATL_MASS_FRACTION(2,1) =1.0, MATL_MASS_FRACTION(3,1) =1.0, THICKNESS(1:3)=0.02,0.01,5.0 E-3, GEOMETRY='CARTESIAN', LENGTH=0.0, WIDTH=0.0/	&RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=23.0, F=1.29/ &RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=50.0, F=1.35/ &RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=75.0, F=1.41/ &RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=100.0, F=1.47/ &RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=125.0, F=1.53/ &RAMP ID='PVC_SPECIFIC_HEAT_R AMP', T=150.0, F=1.59/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=23.0, F=0.192/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=50.0, F=0.175/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=75.0, F=0.172/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=100.0, F=0.147/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=125.0, F=0.141/ &RAMP ID='PVC_CONDUCTIVITY_R AMP', T=150.0, F=0.134/ &SURF ID='Ignitor', RGB=204,127,102, HRRPUA=1200.0, BURN_AWAY=.TRUE., BACKING='VOID', MATL_ID(1,1)='WOOD', MATL_ID(2,1)='CALCIUM SILICATE', MATL_ID(3,1)='PVC', MATL_MASS_FRACTION(1,1) =1.0, MATL_MASS_FRACTION(2,1) =1.0, MATL_MASS_FRACTION(3,1) =1.0,
	THICKNESS(1:3)=0.02,0.01,5.0E -3, GEOMETRY='CARTESIAN', LENGTH=0.0, WIDTH=0.0/



(a) FED_0.3 at Methane fire smoke (b) FED_0.5 at Methane fire smoke

(c) FED_0.3 at PVC fire smoke (d) FED_0.5 at PVC fire smoke

FIGURE 7. **FED_0.3 and FED_0.5 at methane and PVC fire smoke.**

results without enabling the sprinklers. At methane fire smoke, enabling sprinklers can reduce the percentage of toxic nodes more than in PVC fire smoke. For instance, there is a 41% difference on FED_0.3 at 1800 seconds of simulation time for methane fire smoke. On the other hand, there is only 10% difference on FED_0.3 at 800 seconds of simulation time for PVC fire smoke.

2) The smoke from PVC is more toxic than methane. As can be observed from Figure 7, FED_0.3 and FED_0.5 at PVC fire smoke is always higher than the methane fire smoke. At 1200 seconds of simulation time, the FED_0.3 is 100% for PVC fire smoke with/without enabling sprinklers. FED_0.5 is 100% without enabling sprinklers and 98% with enabling sprinklers. It indicates that almost every place in the mall is full of fatal toxic gases after twenty minutes at PVC fire and there is no chance for safe evacuation. On the other hand, at 1200 seconds of simulation time, the FED_0.3 is 6.5% for methane fire smoke with sprinklers and 15% without sprinklers. FED_0.5 is 5.5% with enabling sprinklers and 11% without enabling sprinklers. It indicates that there are still plenty of rooms for safety evacuation at twenty minutes in methane fire.

Next, based on the FED value computed at each sensor node, the proposed SIEP and SGEP algorithms are performed to identify the evacuation route for a single evacuee and a group of evacuees with respect to Problem (P_1) and Problem (P_2), respectively. Before we present the simulation results of SIEP and SGEP algorithms, the evacuation time during congestion needs to be addressed. When the flow constraint is violated, it needs more time to evacuate the evacuees on a link because of congestion. Congestion will not only slow down the evacuation speed but also increase the probability of injuries during evacuation. According to the reports from United States Department of Transportation [52], delay is a superlinear function with respect to the traffic intensity. To be more specific, the growth of delay time is much higher than the growth of the traffic intensity when in congestion. Next, we propose the Equation (31) to capture this superlinear function.

$$\Xi = \left(\left\lceil 2^{\epsilon/K} - 1 \right\rceil\right) \times 27 \tag{31}$$

In Equation (31), ϵ is the number of evacuees on a link and K is the maximum number of evacuees that can be evacuated on a link in one time slot. In the following simulation results, we set $K = 5$ and one time slot are 27 seconds. When $\epsilon > K$, flow constraint is violated and the number of time slots to evacuate all the ϵ evacuees on this link is the ceiling function of $\left(2^{\epsilon/K} - 1\right)$. For example, when $\epsilon = 6$, $\left(\left\lceil 2^{\epsilon/K} - 1 \right\rceil\right) = 2$; when $\epsilon = 12$, $\left(\left\lceil 2^{\epsilon/K} - 1 \right\rceil\right) = 5$. When $\epsilon \leq K$, flow constraint is not violated, and it requires only one time slot to evacuate all the ϵ evacuees on this link. For example, when $\epsilon = 5$, $\left(\left\lceil 2^{\epsilon/K} - 1 \right\rceil\right) = 1$; when $\epsilon = 1$, $\left(\left\lceil 2^{\epsilon/K} - 1 \right\rceil\right) = 1$. Note that one time slot is 27 seconds in the FDS, then Ξ calculates the evacuation time (in seconds) to evacuate these ϵ evacuees on this link. In Figure 8, we show the evacuation time (i.e., Ξ) with respect to the number of ϵ evacuees on a link based on Equation (31).

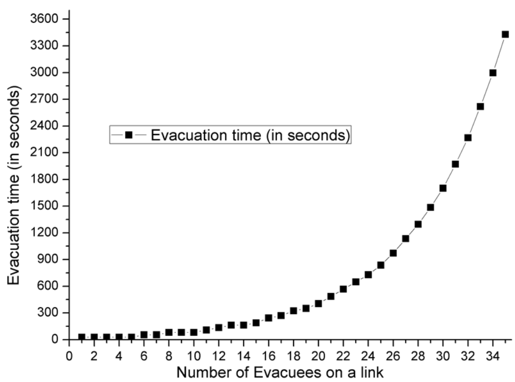
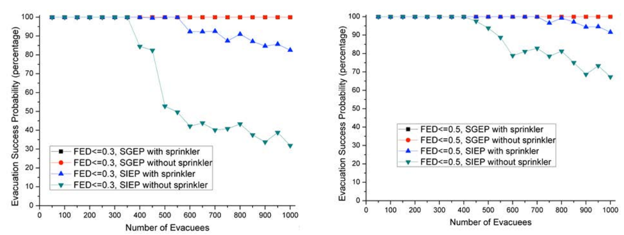


FIGURE 8. **The evacuation time (Ξ) with respect to the number of evacuees (ϵ).**

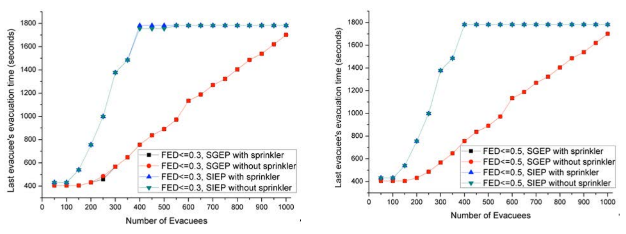


(a) M_{FED}=0.3 (b) M_{FED}=0.5

FIGURE 9. **Evacuation success probability at methane fire smoke under $M_{FED} = 0.3$ and $M_{FED} = 0.5$.**

In Figure 9, we show the evacuation success probability comparisons between SGEP algorithm and SIEP algorithm at methane fire smoke under $M_{FED} = 0.3$ (i.e., tenability limit of human's FED value is 0.3) and $M_{FED} = 0.5$ (i.e., tenability limit of human's FED value is 0.5), where the evacuation success probability is defined as the number of evacuees successfully evacuated divided by the total number of evacuees. The $M_{FED} = 0.3$ is a more stringent constraint than the $M_{FED} = 0.5$ and we can expect that the success probability is higher at $M_{FED} = 0.5$. SGEP algorithm can evacuate all the evacuees both at $M_{FED} = 0.3$ and $M_{FED} = 0.5$. On the other hand, SIEP algorithm does get lower success probability at $M_{FED} = 0.3$, especially at larger number of evacuees (e.g., 1000 evacuees). In addition, sprinklers do help to reduce the toxicity of the smoke so that SIEP algorithm can evacuate more evacuees than without sprinklers. For example, when the number of evacuees is one thousand, sprinklers can improve the evacuation success probability from 32% to 83% when $M_{FED} = 0.3$ and from 67% to 92% when $M_{FED} = 0.5$.

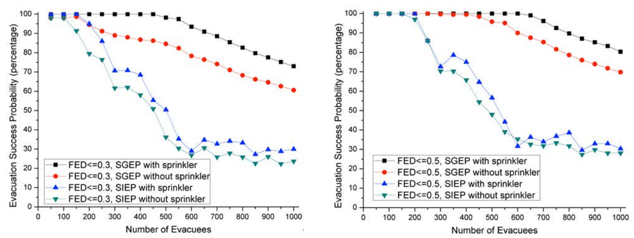
Figure 9 shows that SIEP algorithm gets low evacuation success probability at larger number of evacuees. This low evacuation success probability comes from the evacuation congestion. Recall that when the flow constraint is violated, SGEP algorithm identifies the K evacuees with larger accumulated FED value to move, and the other evacuees must stay at the same place so that the flow constraint is not violated. SIEP algorithm identifies the smallest accumulated FED path for each evacuee without considering the flow constraint. It increases the probability of directing the evacuees to the same node at the same time slot at large number of evacuees (e.g., 1000 evacuees). In this case, based on Equation (31), it takes longer evacuation time to evacuate, and more toxic smoke will decrease the possibility of safely evacuation. In the case of no sprinklers and the number of evacuees is more than 500, tragedy will result when the evacuation success probability is below 50% for SIEP algorithm under $M_{FED} = 0.3$.



(a) M_{FED}=0.3 (b) M_{FED}=0.5

FIGURE 10. Last evacuee's evacuation time at Methane fire smoke under $M_{FED} = 0.3$ and $M_{FED} = 0.5$.

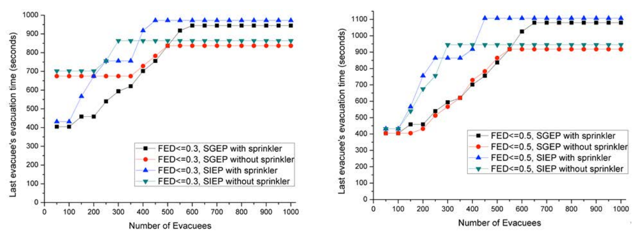
In Figure 10, we show the last evacuation time at methane fire smoke. It shows that the last evacuee's evacuation time is almost a linear function with respect to the number of evacuees for SGEP algorithm with or without sprinklers. In addition, when there are 1000 evacuees to be evacuated, the last evacuee's evacuation time is still less than 1800 seconds for SGEP algorithm with or without sprinklers. This explains why the success evacuation probability for SGEP algorithm is always 100% with or without sprinklers. On the other hand, at the SIEP algorithm, when the number of evacuees is above 400, the last evacuee's evacuation time is 1800 seconds. This indicates that, when the number of evacuees is more than 400, evacuation congestion problems arise for the SIEP algorithm.



(a) M_{FED}=0.3 (b) M_{FED}=0.5

FIGURE 11. Evacuation success probability at PVC fire smoke $M_{FED} = 0.3$ and $M_{FED} = 0.5$.

In Figure 11, we show the evacuation success probability comparisons between SGEP algorithm and SIEP algorithm at PVC fire smoke. At 1000 evacuees and $M_{FED} = 0.3$, the evacuation success probability for SGEP algorithm is 73% with sprinklers and 61% without sprinklers. At 1000 evacuees and $M_{FED} = 0.5$, the evacuation success probability for SGEP algorithm is 80% with sprinklers and 70% without sprinklers. These results are much lower than the methane fire smoke in Figure 9, where the evacuation success probability is all 100% for SGEP algorithms. The biggest difference is 39% at 1000 evacuees, $M_{FED} = 0.3$ and without sprinklers. Similar results are also observed in SIEP algorithm. All the evacuation success probability is lower than the methane fire smoke in Figure 9. At 1000 evacuees and $M_{FED} = 0.3$, the evacuation success probability for SIEP algorithm is 30% with sprinklers and 24% without sprinklers. At 1000 evacuees and $M_{FED} = 0.5$, the evacuation success probability for SIEP algorithm is 30% with sprinklers and 28% without sprinklers. As compared to Figure 9, the biggest difference is 61.6% at 1000 evacuees, $M_{FED} = 0.5$ and with sprinklers. To conclude, the evacuation success probability at PVC fire smoke is significantly reduced for both SGEP algorithm and SIEP algorithm. The reason is because PVC is more toxic than methane, which is consistent with the results in Figure 7.



(a) M_{FED}=0.3 (b) M_{FED}=0.5

FIGURE 12. Last evacuee's evacuation time at PVC fire smoke under $M_{FED} = 0.3$ and $M_{FED} = 0.5$.

In Figure 12, we show the last evacuation time at PVC fire. The last evacuee's evacuation time for both SGEP algorithm and SIEP algorithm is much smaller than the methane fire in Figure 10. When the last evacuee's evacuation time is smaller than the simulation time (i.e., 1800 seconds), the last evacuee's evacuation time is the evacuation window time for the evacuees. For instance, when $M_{FED} = 0.3$ at SIEP algorithm, the last evacuee's evacuation time is 972 seconds with sprinklers. This indicates that no evacuee can be successfully evacuated after this evacuation window time. This result is consistent with the result at 972 seconds in Figure 7, where FED_0.3 = 95% at PVC fire smoke with sprinkler. FED_0.3 = 95% means only 5% of the sensor nodes whose FED value is smaller than 0.3 so that it is almost no chance to find a safe evacuation route. In the case of without enabling the sprinklers, the evacuation window time is 864 seconds when $M_{FED} = 0.3$ at SIEP algorithm. This result is also consistent with the result at 864 seconds in Figure 7, where FED_0.3 = 96% at PVC fire smoke without sprinkler.

Note that evacuation window time for SIEP is slightly larger than the evacuation window time for SGEP. For instance, at $M_{FED} = 0.3$ and with sprinklers, the evacuation window time for SIEP algorithm and SGEP algorithm is 972 seconds and 945 seconds, respectively. At $M_{FED} = 0.3$ and without sprinklers, the evacuation window time for SIEP algorithm and SGEP algorithm is 864 seconds and 837 seconds, respectively. Note that, according to Figure 11, the evacuation success probability for SGEP is higher than SIEP. This shows that SGEP algorithm can not only evacuate more evacuees, but also evacuate faster than the SIEP algorithm.

Note that evacuation window time depends on the total number of evacuees. Since the number of occupants in the building changes frequently and it is hard to get the exact number of occupants in the building during fire, evacuation window time does not provide enough useful information for safe rescue operations. The percentage of the toxic nodes (e.g., FED_0.3) at the last evacuee's evacuation time, named as critical percentage of the toxic nodes, is another safe evacuation indicator. Recall that no evacuee can evacuate successfully after 972 seconds at both SGEP and SIEP in PVC fire with sprinklers. And at 972 seconds, FED_0.3 = 95% where only 5% of the sensor nodes whose FED value is smaller than 0.3. In other words, when FED_0.3 > 95%, no evacuees can be safely evacuated even adopting the SGEP. As compared to evacuation window time, the value of FED_0.3 is a better indicator to be used by the rescue team (e.g., fireman) for safe evacuation at Taipei 101 mall. To be more specific, FED_0.3 = 95% is a critical point at Taipei 101 mall that the rescue team or evacuation plan should either evacuate the evacuees before FED_0.3 = 95% or extinguish the fire and smoke so that FED_0.3 < 95%.

VI. CONCLUSION

Smoke is the deadliest factor in fire evacuation because of fast smoke spreading and smoke toxicity. From the fire simulations at Taipei 101 mall by using the FDS, we show that smoke danger zone is larger than the heat danger zone and this explains why smoke injuries is higher than the burn injuries in the historical fire accidents. In this paper, two smoke aware mathematical models and two smoke aware evacuation algorithms are devised. This first model is to identify the safe evacuation route with the fastest evacuation time for an evacuee. SIEP algorithm is proposed to tackle this individual evacuation problem. The second model is to safely evacuate as many evacuees as possible with considering the evacuation congestion. Congestion aware SGEP algorithm is proposed not only to identify the evacuation routes, but also to schedule the evacuation sequence of passing through a congested place.

Based on the real floor layout of the Taipei 101 mall, the FDS simulations are first performed to compare smoke toxicity between two most common fire sources, methane and PVC. At 20 minutes (i.e., 1200 seconds) of simulation time, the percentage of the sensor nodes with FED value over 0.3 is 6% (i.e., FED_0.3 = 6%) with enabling sprinklers, and 12.8% (i.e., FED = 12.8%) without enabling sprinklers for methane fire smoke. However, FED_0.3 = 100% for PVC fire smoke with/without sprinklers at 1200 seconds of simulation time. It indicates that PVC fire smoke is more toxic than methane fire smoke. In addition, enabling sprinklers do help to reduce smoke toxicity. The smoke toxicity reduction is more significant at methane fire smoke (41% at FED = 0.3, 1800 seconds) than at PVC fire smoke (12% at FED = 0.3, 837 seconds). This indicates that it is more challenging to evacuate in PVC fire smoke than in methane fire smoke.

From the simulation results, SGEP algorithm has a higher evacuation success probability than SIEP algorithm both at methane fire and PVC fire. In particular, the evacuation success probability for SGEP is 100% at methane fire with/without sprinklers. On the other hand, the evacuation success probability for SIEP at $M_{FED} = 0.3$ is 82.5% with sprinklers and 31.9% without sprinklers at methane fire. Hence, congestion aware evacuation can increase up to 68.1% evacuation success probability at methane fire. At PVC fire, the evacuation success probability for SGEP at $M_{FED} = 0.3$ is 73% with sprinklers and 61% without sprinklers. For SIEP at $M_{FED} = 0.3$ is 30% with sprinklers and 24% without sprinklers. Hence, congestion aware evacuation can increase up to 43% evacuation success probability at PVC fire.

The last evacuee's evacuation time in the simulation results implies the evacuation window time, where no evacuees can be evacuated after the last evacuee's evacuation time. From the results in Figure 10 and Figure 12, evacuation window time depends on the total number of evacuees. The number of occupants in the Taipei 101 mall is random and it is difficult to tell exactly how many occupants are still in the building when on fire. This implies evacuation window time is not a good safe evacuation indicator for the rescue operation. On the other hand, the critical percentage of the toxic nodes is a good safe evacuation indicator because the percentage of toxic nodes can be collected and calculated at a timely basis. According to the simulation results, FED_0.3 = 95% is a safe evacuation indicator that no evacuees can be safely evacuated when FED_0.3 > 95% at Taipei 101 mall. Via the FDS simulations, the proposed algorithms can be extended and applied to other buildings to identify their critical percentage of the toxic nodes for the rescue team (e.g., fireman) to perform safe evacuation and rescue operations.

REFERENCES

[1] S. Marsar, "Survivability profiling: How long can victims survive in a fire?" *Fire Eng.*, vol. 163, no. 7, pp. 77–82, 2010. [Online]. Available: https://www.fireengineering.com/2010/07/01/302841/survivability-profiling-how-long-can-victims-survive-in-a-fire-2/

[2] S. Gokceli, N. Zhmurov, G. K. Kurt, and B. Ors, "IoT in action: Design and implementation of a building evacuation service," *J. Comput. Netw. Commun.*, vol. 2017, pp. 1–13, Jan. 2017.

[3] B. Wang, L. B. J. Zhou, D. Hu, M. Pawęska, L. Šimák, J. Ristvej, and M. Jánošíková, "Emergency evacuation route choice based on improved ant colony algorithm," *Logistics Transp.*, vol. 44, no. 4, pp. 33–39, 2019.

[4] H. Jiang, "Mobile fire evacuation system for large public buildings based on artificial intelligence and IoT," *IEEE Access*, vol. 7, pp. 64101–64109, 2019.

[5] L. Han, H. Guo, H. Zhang, Q. Kong, A. Zhang, and C. Gong, "An efficient staged evacuation planning algorithm applied to multi-exit buildings," *ISPRS Int. J. Geo-Inf.*, vol. 9, no. 1, p. 46, Jan. 2020, doi: 10.3390/ijgi9010046.

[6] G. Eggly, J. Finochietto, M. Micheletto, R. Centelles, R. Santos, S. Ochoa, R. Meseguer, and J. Orozco, "Evacuation supporting system based on IoT components," *Proceedings*, vol. 31, no. 1, p. 38, 2019, doi: 10.3390/proceedings2019031038.

[7] J. Zhang, J. Guo, H. Xiong, X. Liu, and D. Zhang, "A framework for an intelligent and personalized fire evacuation management system," *Sensors*, vol. 19, no. 14, p. 3128, Jul. 2019.

[8] Y. Hu and X. Liu, "Optimization of grouping evacuation strategy in high-rise building fires based on graph theory and computational experiments," *IEEE/CAA J. Autom. Sinica*, vol. 5, no. 6, pp. 1104–1112, Nov. 2018.

[9] Z. Wang and J. Crowcroft, "Quality-of-service routing for supporting multimedia applications," *IEEE J. Sel. Areas Commun.*, vol. 14, no. 7, pp. 1228–1234, Sep. 1996.

[10] M. Gerges, S. Penn, D. Moore, C. Boothman, and C. Liyanage, "Multi-storey residential buildings and occupant's behaviour during fire evacuation in the U.K.: Factors relevant to the development of evacuation strategies," *Int. J. Building Pathol. Adaptation*, vol. 36, no. 3, pp. 234–253, Jun. 2018, doi: 10.1108/IJBPA-08-2017-0033.

[11] E. Hulida, I. Pasnak, O. Koval, and A. Tryhuba, "Determination of the critical time of fire in the building and ensure successful evacuation of people," *Periodica Polytechnica Civil Eng.*, pp. 308–316, Feb. 2019, doi: 10.3311/PPci.12760.

[12] M. M. Shuaib, "Incorporating intelligence for typical evacuation under the threat of fire spreading," *Saf. Sci.*, vol. 106, pp. 1–9, Jul. 2018, doi: 10.1016/j.ssci.2018.02.022.

[13] J.-J. Li and H.-Y. Zhu, "A risk-based model of evacuation route optimization under fire," *Proc. Comput. Sci.*, vol. 211, pp. 365–371, 2018, doi: 10.1016/j.proeng.2017.12.024.

[14] T. T. Liu, Z. Liu, M. Ma, R. Xuan, T. Chen, T. Lu, and L. Yu, "An information perception-based emotion contagion model for fire evacuation," *3D Res.*, vol. 8, no. 1, Mar. 2017, doi: 10.1007/s13319-017-0120-4.

[15] J. Sharma, P.-A. Andersen, O.-C. Granmo, and M. Goodwin, "Deep Q-learning with Q-matrix transfer learning for novel fire evacuation environment," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 51, no. 12, pp. 7363–7381, Dec. 2021, doi: 10.1109/TSMC.2020.2967936.

[16] Z. Wang, F. Jia, E. R. Galea, and J. H. Choi, "A forensic analysis of a fatal fire in an indoor shooting range using coupled fire and evacuation modelling tools," *Fire Saf. J.*, vol. 91, pp. 892–900, Jul. 2017, doi: 10.1016/j.firesaf.2017.03.029.

[17] E. A. Khan, M. A. Ahmed, E. H. Khan, and S. C. Majumder, "Fire emergency evacuation simulation of a shopping mall using fire dynamic simulator (FDS)," *J. Chem. Eng.*, vol. 30, no. 1, pp. 32–36, Dec. 2017, doi: 10.3329/jce.v30i1.34795.

[18] C. Wang, L. C. Wood, H. Li, Z. Aw, and A. Keshavarzsaleh, "Applied artificial bee colony optimization algorithm in fire evacuation routing system," *J. Appl. Math.*, vol. 2018, pp. 1–17, Apr. 2018, doi: 10.1155/2018/7962952.

[19] Y. Zheng, B. Jia, X.-G. Li, and R. Jiang, "Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading," *Saf. Sci.*, vol. 92, pp. 180–189, Feb. 2017, doi: 10.1016/j.ssci.2016.10.009.

[20] Y. Hu, X. Wang, and F. Wang, "A quantitative study of factors influence on evacuation in building fire emergencies," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 2, pp. 544–552, Jun. 2018, doi: 10.1109/TCSS.2018.2823869.

[21] C. Caliendo, P. Ciambelli, R. Del Regno, M. G. Meo, and P. Russo, "Modelling and numerical simulation of pedestrian flow evacuation from a multi-storey historical building in the event of fire applying safety engineering tools," *J. Cultural Heritage*, vol. 41, pp. 188–199, Jan. 2020, doi: 10.1016/j.culher.2019.06.010.

[22] J. Lee, M. Lee, and C. Jun, "Fire evacuation simulation considering the movement of pedestrian according to fire spread," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 42, pp. 273–281, Oct. 2018.

[23] G. Bernardini, M. Azzolini, M. D'Orazio, and E. Quagliarini, "Intelligent evacuation guidance systems for improving fire safety of Italian-style historical theatres without altering their architectural characteristics," *J. Cultural Heritage*, vol. 22, pp. 1006–1018, Nov. 2016, doi: 10.1016/j.culher.2016.06.008.

[24] H. Bayat, M. R. Delavar, W. Barghi, S. A. EslamiNezhad, P. Hanachi, and S. Zlatanova, "Modeling of emergency evacuation in building fire," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 43, pp. 312–327, Aug. 2020.

[25] O. Richardson, A. Jalba, and A. Muntean, "Effects of environment knowledge in evacuation scenarios involving fire and smoke: A multiscale modelling and simulation approach," *Fire Technol.*, vol. 55, no. 2, pp. 415–436, Mar. 2019, doi: 10.1007/s10694-018-0743-x.

[26] F. Saeed, A. Paul, A. Rehman, W. Hong, and H. Seo, "IoT-based intelligent modeling of smart home environment for fire prevention and safety," *J. Sensor Actuator Netw.*, vol. 7, no. 1, p. 11, Mar. 2018.

[27] F. Idris, N. Hashim, A. F. Kadmin, Ahmad, and L. B. Yee, "Intelligent fire detection and alert system using LabVIEW," *Int. J. Elect. Comput. Eng.*, vol. 9, no. 3, pp. 1842–1849, 2019.

[28] A. A. Jaber, F. K. I. Alaa Abdulhady; Al-Mousawi, and H. S. Jasem, "Internet of Things based industrial environment monitoring and control: A design approach," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 6, pp. 4657–4667, 2019.

[29] D. A. Purser, "Toxicity assessment of combustion products," in *SFPE Handbook of Fire Protection Engineering*, 2nd ed. Quincy, MA, USA: NFPA, 1995.

[30] J. A. Milke, "Evaluating the smoke hazard from fires in large spaces," *Int. J. Eng. Perform.-Based Fire Codes*, vol. 2, no. 3, pp. 94–103, 2000.

[31] J. Giebultowicz, M. Rużycka, P. Wroczynski, D. A. Purser, and A. A. Stec, "Analysis of fire deaths in Poland and influence of smoke toxicity," *Forensic Sci. Int.*, vol. 277, pp. 77–87, Aug. 2017.

[32] (2021). *FDS and Smokeview*. [Online]. Available: https://www.nist.gov/services-resources/software/fds-and-smokeview

[33] X. Guo, N. Ansari, F. Hu, Y. Shao, N. R. Elikplim, and L. Li, "A survey on fusion-based indoor positioning," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 566–594, 1st Quart., 2020, doi: 10.1109/COMST.2019.2951036.

[34] J. Fonollosa, A. Solórzano, and S. Marco, "Chemical sensor systems and associated algorithms for fire detection: A Review," *Sensors*, vol. 18, no. 2, p. 553, 2018, doi: 10.3390/s18020553.

[35] *Data Sets and Statistics About Fires, Fire Risk, Firefighters and Fire Departments in the United States*. Accessed: Nov. 14, 2022. [Online]. Available: https://www.usfa.fema.gov/statistics/

[36] U.S. Fire Administration, "Civilian fire fatalities in residential buildings (2017–2019)," *Top. Fire Rep. Ser.*, vol. 21, no. 3, pp. 1–13, Jun. 2021.

[37] *SFPE Guide to Human Behavior in Fire*. Gaithersburg, MD, USA: Society of Fire Protection Engineers, 2019.

[38] *Life-Threatening Components of Fire—Guidelines for the Estimation of Time to Compromised Tenability in Fires*, Standard ISO 13571:2012, [Online]. Available: https://standards.iteh.ai/catalog/standards/iso/b7d0e694-6603-42e6-8422-83cefc90a39e/iso-13571-2012

[39] Q. Wu, J. Cao, C. Zhou, J. Huang, Z. Li, S.-M. Cheng, J. Cheng, and G. Pan, "Intelligent smoke alarm system with wireless sensor network using ZigBee," *Wireless Commun. Mobile Comput.*, vol. 2018, pp. 1–11, Mar. 2018, doi: 10.1155/2018/8235127.

[40] U. Singh, J.-F. Determe, F. Horlin, and P. D. Doncker, "Crowd forecasting based on WiFi sensors and LSTM neural networks," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 9, pp. 6121–6131, Sep. 2020, doi: 10.1109/TIM.2020.2969588.

[41] J.-S. Chou, M.-Y. Cheng, Y.-M. Hsieh, I.-T. Yang, and H.-T. Hsu, "Optimal path planning in real time for dynamic building fire rescue operations using wireless sensors and visual guidance," *Autom. Construction*, vol. 99, pp. 1–17, Mar. 2019.

[42] H.-C. Lee and K.-H. Ke, "Monitoring of large-area IoT sensors using a LoRa wireless mesh network system: Design and evaluation," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 9, pp. 2177–2187, Sep. 2018, doi: 10.1109/TIM.2018.2814082.

[43] H.-H. Yen, C.-H. Lin, and H.-W. Tsao, "Time-aware and temperature-aware fire evacuation path algorithm in IoT-enabled multi-story multi-exit buildings," *Sensors*, vol. 21, no. 1, p. 111, Dec. 2020, doi: 10.3390/s21010111.

[44] A. A. Stec, "Fire toxicity—The elephant in the room?" *Fire Saf. J.*, vol. 91, pp. 79–90, Jul. 2017.

[45] L. Shu, Y. Chen, Z. Sun, F. Tong, and M. Mukherjee, "Detecting the dangerous area of toxic gases with wireless sensor networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 8, no. 1, pp. 137–147, Jan. 2020, doi: 10.1109/TETC.2017.2700358.

[46] S. Hostikka, E. Veikkanen, T. Hakkarainen, and T. Kajolinna, "Experimental investigation of human tenability and sprinkler protection in hospital room fires," *Fire Mater.*, vol. 45, no. 6, pp. 823–832, Oct. 2021.

[47] D. A. Purser, "Combustion Toxicity," in *SFPE Handbook of Fire Protection Engineering*, 5th ed. New York, NY, USA: Springer, 2016.

[48] *NFPA 130: Building Construction and Safety Code*, 2014th ed., Nat. Fire Protection Assoc., Quincy, MA, USA, 2013.

[49] A. Gager and G. Dominguez, "Tenability criteria in unique situations and atypical buildings," presented at the 3rd Fire Evacuation Model. Tech. Conf. (FEMTC), 2016. [Online]. Available: https://www.thunderheadeng.com/files/com/FEMTC2016/files/d1-14-gager/gager-paper.pdf

[50] *A Taste of Taiwan*. Accessed: Nov. 14, 2022. [Online]. Available: https://www.taipei-101.com.tw/en/food

[51] *Cooking Fires and Electrical Fires are The Top Two Fire Causes in Taipei City*. Accessed: Nov. 14, 2022. [Online]. Available: https://eoc.gov.taipei/News_Content.aspx?n=C0A67897F6E64EA6&sms=72544237BBE4C5F6&s=06E45B8CC80E2737

[52] C. Systematics, "Traffic congestion and reliability: Trends and advanced strategies for congestion mitigation," Tech. Rep., FHWA-HOP-05-064, Washington, DC, USA: Federal Highway Administration, 2005.

HONG-HSU YEN (Member, IEEE) received the B.S. degree in industrial engineering from the National Tsing Hua University, in 1990, and the M.S. degree in electrical engineering and the Ph.D. degree in information management from the National Taiwan University, in 1995 and 2001, respectively. He joined the Faculty of the Department of Information Management, Shih Hsin University, in 2001, where he is currently a Professor. He is the author of one book, more than 50 articles, and holds two patents. His research interests include the IoT, healthcare technologies, wireless sensor networks, and optimization. He was awarded the "Outstanding Research Award" from Shih Hsin University, in 2006, 2011, 2015, and 2020. He serves as a Lead Guest Editor for *International Journal of Distributed Sensor Networks*: Special Issue on Recent Advances in Wireless Visual Sensor Networks, in 2013.

CHENG-HAN LIN received the bachelor's degree in information management from Shih Hsin University, in 2022. He published one article in 2020 when he is pursuing his bachelor's degree. His research interests include algorithm design and optimize, artificial intelligence, and computer vision processing. In 2022, he was awarded the "Outstanding Graduates" from Shih Hsin University.

HUNG-WEI TSAO received the bachelor's degree in information management from Shih Hsin University, in 2022. He published one article in 2020 when he is pursuing his bachelor's degree. His research interests include algorithm design and optimization, machine learning, and scientific visualization. He was awarded the Undergraduate Research Fellowship from the Ministry of Science and Technology (MOST) in Taiwan.