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# Modeling and simulation of large crowd evacuation in hazard-impacted environments

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**Abstract.** Every year, many people are severely injured or lose their lives in accidents such as fire, chemical spill, public pandemonium, school shooting, and workplace violence. Research indicates that the fate of people in an emergency situation involving one or more hazards depends not only on the design of the space (e.g., residential building, industrial facility, shopping mall, sports stadium, school, concert hall) in which the incident occurs, but also on a host of other factors including but not limited to (a) occupants' characteristics, (b) level of familiarity with and cognition of the surroundings, and (c) effectiveness of hazard intervention systems. In this paper, we present EVAQ, a simulation framework for modeling large crowd evacuation by taking into account occupants' behaviors and interactions during an emergency. In particular, human's personal (i.e., age, gender, disability) and interpersonal (i.e., group behavior and interactions) attributes are parameterized in a hazard-impacted environment. In addition, different hazard types (e.g., fire, lone wolf attacker) and propagation patterns, as well as intervention schemes (simulating building repellent systems, firefighters, law enforcement) are modeled. Next, the application of EVAQ to crowd egress planning in an airport terminal under human attack, and a shopping mall in fire emergency are presented and results are discussed. Finally, a validation test is performed using real world data from a past building fire incident to assess the reliability and integrity of EVAQ in comparison with existing evacuation modeling tools.

**Keywords:** emergency mapping; crowd simulation; human behavior; architecture for safety; cellular-automata

## 1. Introduction

Improper crowd management and evacuation planning can lead to an increase in casualties during an emergency (Kobes *et al*. 2010, Sagun *et al*. 2013). An emergency situation may arise as a result of natural (e.g., flood, hurricane, tornado, earthquake) or manmade (e.g., fire, chemical spill, toxic gas release, radiological accident, explosion, civil disturbance, workplace violence) causes. One of the best practices for crowd management is to create emergency action plans based on a thorough investigation of emergency mapping and egress route assignment (i.e., workplace layout, position of exits, floor plans, and safe or refuge areas) during all stages of design, construction, and operation of a building or facility (Kobes *et al*. 2010, Wright 2007).

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Among all causes of accidents in the built environment, fire-related accidents claim a large number of lives and property loss both in residential and commercial buildings. In 2015, the Federal Emergency Management Agency (FEMA) reported 2,565 deaths, 11,475 injuries, and $7 billion in damage from 380,900 fire incidents in residential buildings. During the same period, 104,600 fire incidents were reported in commercial buildings and facilities with 70 deaths, 1,325 injuries, and $2 billion in damage. According to the National Fire Incident Reporting System (NFIRS), 32% of all such fatalities are caused by ineffective egress and escape-related planning (FEMA 2017) which is often caused by large crowd density in a confined space, human interactions, limited number of exits, nonfunctional exits or egress routes, improper use of exits, physical obstacles, unfamiliarity with the layout, insufficient time due to long distance to the nearest clear exit and selecting a suboptimal exit route.

In addition to fire, other causes of the loss of life include lone wolf attacks and home-grown terrorism (knife stabber, shooter, suicide bomber). According to the Federal Bureau of Investigation (FBI) (2016) crime data, the number of people killed by knives or cutting instruments was four times more than that by rifles. An average of 1,190 knife-related injuries was treated every day by emergency management system (EMS) units in the U.S. from 1999-2008 (Smith 2013). Therefore, it is imperative that proper attention be drawn to studying and characterizing emergency action planning for crowd evacuation under different scenarios.

Previous research has developed evacuation models mostly to understand the human and social behavior of a crowd during the evacuation process (Zheng *et al.* 2009). The physical characteristics (i.e., building floorplan, room layout, presence of glass doors, firewalls, flame retardant system) of a hazard-affected environment (i.e., building on fire) can influence the behavior of occupants. In a literature review conducted as part of this research, it was found that the majority of existing evacuation tools only model crowd movements in hazard-free environments, overlooking the influence of hazard(s) in steering crowd behavior. Moreover, the value of intervention systems (i.e., fire extinguishers, sprinklers) to evacuation in a deteriorating environment has been, at best sparsely studied. Therefore, an inclusive simulation platform capable of capturing all key components (e.g., environment, hazard, intervention, and people) of an emergency can significantly reinforce the egress analysis.

Considering the current state of knowledge, the main objective of this research is to design and validate EVAQ, an end-to-end simulation environment for modeling large crowd emergency evacuation capable of capturing the key events occurring during the evacuation process, as well as the dynamics between evacuees, hazards, and intervention systems. EVAQ has been developed in Python and allows modelers to describe key events of an evacuation process in a hazard-affected environment while incorporating information on evacuees' attributes. An EVAQ model considers four principal factors of emergency evacuation, all of which influence the fate of evacuees, namely (i) layout of the affected environment (e.g., building plan, exit layout), (ii) dynamics of the hazard (e.g., hazard type, propagation speed and pattern), (iii) dynamics of the potential intervention (e.g., repellent type, propagation speed and pattern), and (iv) evacuees' personal (e.g., age, gender, disability) and interpersonal a.k.a., behavioral (e.g., group behavior) characteristics. Accordingly, the main building blocks of EVAQ include the (i) environment module (for modeling building plan, exit layout, and construction materials), (ii) hazard module (for modeling hazard propagation and ramification), (iii) intervention module (for modeling repellent propagation and effectiveness), and (iv) evacuee module (for modeling personal and interpersonal characteristics of evacuees', and subsequent exit strategies). This modular architecture provides maximum modeling flexibility by allowing users to revise the parameters and content of each module independently. For example, modelers can incorporate random hazard movement patterns in the hazard module to imitate social disturbance or workplace violence cases, or simulate evacuees' behavioral traits (e.g., herding, altruistic, leader-follower) in the agent module.

## 2. Literature review

With the increasing use and acceptance of performance-based codes, simulation modeling has become an essential tool for verifying building design, construction, operation, and maintenance. As related to this research, evacuation models are used to perform safety design assessment and safe egress analysis during emergency due to different hazards (Ronchi and Nilsson 2013). Previously, researchers categorized existing evacuation models based on modeling principles (Gwynne *et al*. 1999), methodological approaches (Zheng *et al*. 2009), occupant movements, their behavior, route choice, user availability, and validation procedure (Kuligowski *et al*. 2010).

Gwynne *et al*. (1999) reviewed 22 evacuation models and categorized them into three modeling principles. *Optimization models* consider occupant's optimal path to exit without considering their personal and interpersonal characteristics (Xie *et al*. 2003, Yuan *et al*. 2009). On the other hand, *simulation models* try to realistically represent occupants' exit strategies considering their unique characteristics (Fahy 1999, Owen *et al*. 1996, Thompson *et al*. 2003). Additionally, *risk assessment models* quantify risks associated with safe egress of occupants from a hazard-affected environment (Fraser-Mitchell 1994, Shestopal and Grubits 1994).

According to the methodological approaches, evacuation models can be classified into microscopic and macroscopic models (Zheng *et al*. 2009). *Microscopic models* where pedestrian dynamics are modeled as a particle are further divided into five different types, namely *cellular automata models* (Fu *et al*. 2015, Kirchner and Schadschneider 2002, Wei *et al*. 2014), *multi-lattice models* (Guo and Huang 2008, Guo *et al*. 2013), *social force models* (Yang *et al*. 2014), *agent-based models* (Bonabeau 2002, Goldstone and Janssen 2005), and *game theory models* (Lo *et al*. 2006). *Macroscopic models*, on the other hand, model pedestrian dynamics similar to a body of fluid, thus ignoring individuals' distinctive behaviors during evacuation (Guo *et al*. 2011, Lee 2012).

Given the complex nature of crowd behavior, researchers have also recently started to combine the basic principles of these approaches to develop hybrid evacuation models. Examples of such models include the cellular automata model combined with lattice gas approach (Yamamoto *et al*. 2007) or social force approach (Yang *et al*. 2005, Wei-Guo *et al*. 2006), lattice gas model based on social force (Song *et al*. 2006), agent-based models (ABMs) in combination with cellular automata (Bandini *et al*. 2005, Toyama *et al*. 2006) or social force (Braun *et al*. 2005, Pelechano *et al*. 2007).

Of note, most of the abovementioned simulation tools are commercial products or available only through consultation services. Moreover, ambiguities in model development and the lack of an open source platform may cause challenges for simulation practice, research, or training. In addition, most tools (e.g., STEPS, ASERI) do not incorporate the key components (e.g., environment, hazard, intervention, agent) of an emergency scenario in one single framework. Most importantly, all these tools only focus on fire hazards and leave out the scenarios involving human attackers in the built environment. Also, after an extensive review, no documented work was found on simulating the effect of an intervention system in evacuation from a hazard-affected environment. Lastly, to the authors' best knowledge, none of the existing evacuation simulation

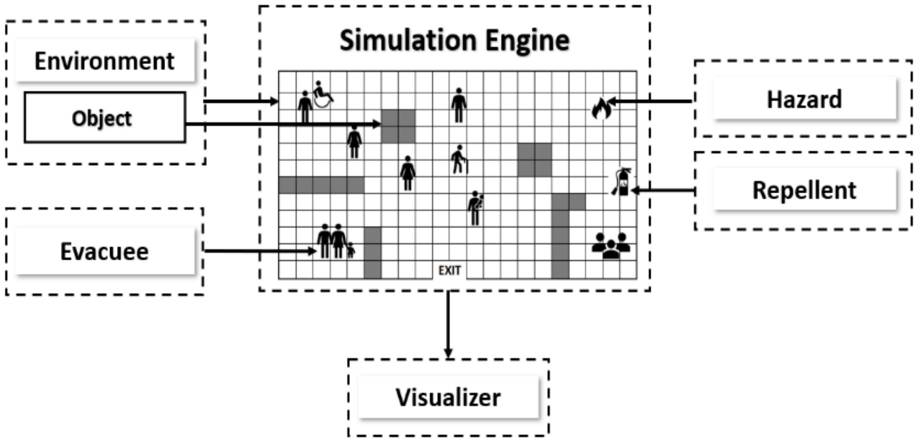


Fig. 1 Overall architecture of EVAQ

models (e.g., EVACNET4, MASSEgress, Simulex) is able to simultaneously simulate hazard propagation (i.e., fire) and movement (i.e., human attacker) cases in a deteriorating environment and their impact on egress route selection and evacuees' movement drifts. These gaps in the state-of-art of evacuation simulation modeling served as the main motivation of the research presented in this paper. In the following Subsections, a comprehensive discussion is presented about the development, implementation, and validation of EVAQ using data from multiple scenarios involving several types of hazards.

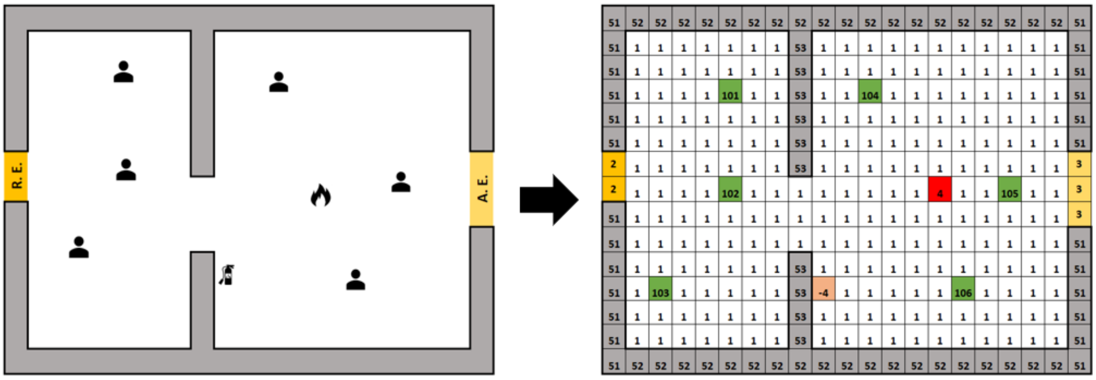
## 3. EVAQ framework architecture

The main building blocks of EVAQ are the *Environment* module, *Hazard* module, *Intervention* module, and *Evacuee* module. All four modules interact with each other via the *Simulation Engine* and the generated results are animated or visualized through the *Visualizer*. Fig. 1 depicts the overall architecture of EVAQ.

### *3.1 Environment representation*

The *Environment* module represents the physical geometry or layout of a hazard-affected environment (e.g., residential building, stadium, shopping mall) in a 2D grid system. This module discretizes a floor plan into cells of 0.5m by 0.5m in size (i.e., average human shoulder-to-shoulder width = 0.5 m), where each cell can accommodate one person (Still 2000). At any given time, the state of each environment component (e.g., position and status of exits, objects, evacuees, hazards, and repellents) is captured and stored by this module. The module also contains a sub-module named *Object* to describe the material types of different objects (e.g., wall or ceiling finishes) in the environment, particularly their fire resistance properties (Milke *et al*. 2002). All these components within the 2D grid cells are represented using the following notations:

0 = Cell is not accessible to evacuees due to the presence of an obstacle (e.g., wall, furniture).
1 = Cell is accessible to evacuees (each cell can only hold one person at a time).




**(a) Typical floorplan** **(b) Converted floorplan for EVAQ simulation**

Fig. 2 Example of a simple floor layout discretized into square cells for EVAQ simulation

2 = Cell is a regular exit, primarily intended for able people.
3 = Cell is an accessible exit, primarily intended for disabled people.
4 = Cell is affected by hazard, and thus not accessible to evacuees.
-4 = Cell is occupied by repellent and remains accessible to evacuees.
51 = Class A material for object in the cell.
52 = Class B material for object in the cell.
53 = Class C material for object in the cell.
>101 = Cell is occupied by a person whose ID is the same as the marked integer.

Fig. 2(a) shows an example of a simple floor layout which is discretized into square cells in Fig. 2(b) to create the environment for EVAQ simulation. In Fig. 2(b), cells marked as 101 through 106 represent people, while those marked as 4 and -4 represent hazard (e.g., fire) and repellent (e.g., fire extinguisher), respectively. Also, regular exit (2-cells wide) is marked as 2 and accessible exit (3-cells wide) is marked as 3. As a general rule, disabled people cannot use regular exits, and able people can use accessible exits. Exits are considered the final destinations for evacuees trapped in a hazard-affected environment and as such, the egress strategy of each person involves reaching one of these cells. As a convention, an exit that is *n*-cells wide can accept at most *n* number of people at the same time. This parameter is referred to as exit capacity.

Time and space granularity plays a pivotal role in designing the environment in the simulation framework (Guo *et al*. 2012). In general, time and space granularity in a simulation environment can be different from the real time and space; although an easy conversion exists. In EVAQ, time granularity is specified such that all event times including human and hazard movements are integer multiples of this time granularity. Therefore, if one simulation step is taken as being equivalent to 0.11s, all events will occur at multiples of 0.11s (0.11s, 0.22s, 0.33s, 0.44s, …). Accordingly, space granularity is specified such that no entity (i.e., human, hazard) moves more than one cell in any given simulation time step; however, an entity can move one cell in several time steps. To avoid precision loss (and capture all movements of hazards and people), in the current implementation of EVAQ, each simulation time step (herein, SS) is defined as 0.25s, and space granularity is taken as, 1 cell = 0.5m x 0.5m. Using these conventions, evacuees' movement speeds can be converted from real world space (expressed in m/s) to simulation space (expressed in cells per SS).

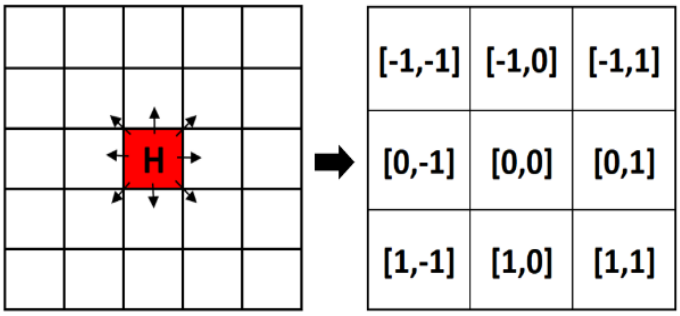



Fig. 3 Adjacency of hazard cell

## 3.2 Hazard modeling

The Hazard module initiates hazards by specifying their position in the environment. It models different hazard characteristics such as propagation (e.g., for fire) or movement (e.g., for attacker) patterns, as well as propagation or movement direction, initiation time, speed, and deceleration over time. The current implementation of EVAQ allows two types of hazard modeling, namely fire and human attacker models as discussed in the following Subsections. For the purpose of hazard propagation and/or movement, the adjacency (neighborhood) of a cell is defined as the eight surrounding cells on top, bottom, left, right, top-left, top-right, bottom-left, and bottom-right as shown in Fig. 3.

### 3.2.1 Fire hazard model

Currently, a forest-fire inspired model (Bak *et al*. 1990) is used to represent sequential hazard propagation in EVAQ. Primarily, for each fire hazard, an initiation point and a propagation time $t_H$ is specified as input which represents the pace of fire spread. Propagation time refers to the time by which adjacent cells of a fire-affected cell also become affected. For instance, a $t_H = 5$ implies that fire propagates to its adjacent cells at every 5SS (i.e., 5SS, 10SS, 15SS, 20SS, …) until the entire environment is affected. Using this notation, a smaller $t_H$ means a faster spread of fire and vice versa. For example, for $t_H = 10$, fire propagates to its adjacent cells at every 10SS (i.e., 10SS, 20SS, 30SS, 40SS, …) which indicates a slower pace than a fire with $t_H = 5$.

Using this criterion, fire is modeled to propagate from its initial position in either symmetrical or eight different directional pattern, as shown in Fig. 4. In this figure, for each fire propagation pattern (cases 0 through 9), three-time steps are demonstrated including the initiation point at time 0 (left grid in each case), first step in propagation at time $t_H$ (middle grid in each case), and second step of propagation at time $2t_H$ (right grid in each case). The area affected by fire after each step of the propagation is termed *blockage area*. EVAQ supports the inclusion of several hazards in different directions within the same environment, a feature that is largely missing in many existing frameworks (Tang and Ren 2008, Guo *et al*. 2013, Nguyen *et al*. 2013).

In reality, however, fire growth (temperature or energy) does not follow a constant pace; rather it can be represented as a function of time, as shown in Fig. 5 (NIST 2010). In this research, it is considered that $t_H$ continues to increase after the ignition until it reaches to the decay phase of fire growth. After the decay phase, it follows a maximum predefined $t_H$ until the entire environment is consumed by fire. To incorporate the variation in propagation time, two more attributes are incorporated into the fire model, namely maximum fire propagation time and fire deceleration rate.

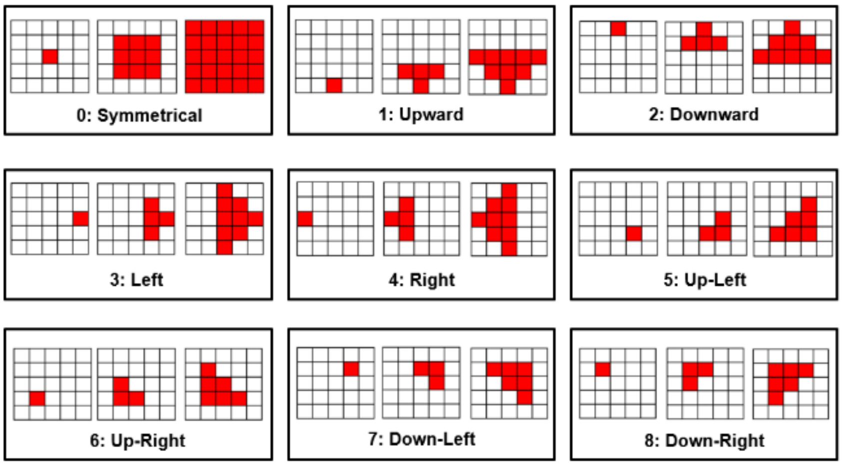



Fig. 4 Symmetrical and directional fire propagation at times 0, $t_H$, and $2t_H$

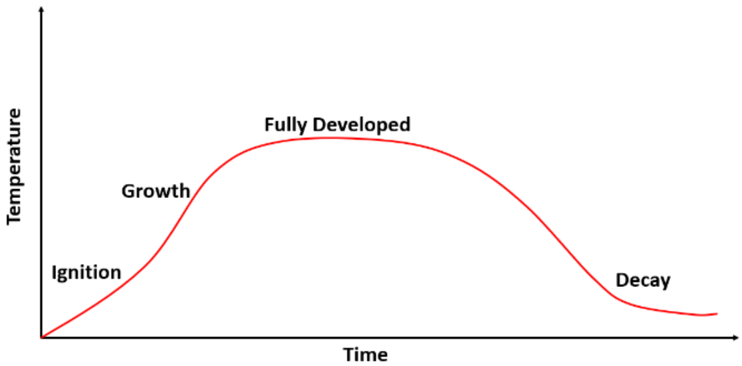



Fig. 5 Classic fire development curve

Maximum fire propagation time is defined as the constant propagation time at which fire propagates after the decay phase. Similarly, fire deceleration rate refers to the rate at which fire propagation time gradually increases after its ignition until it reaches the decay phase. These hazard attributes thus provide maximum flexibility in simulating different scenarios.

All fire attributes are linked to the hazard position and stored in a `hazard_position_descriptors` dictionary developed in Python. In a cell-based system such as EVAQ, this dictionary defines the cell characteristics occupied by fire hazards in a matrix form, as shown below,

```
hazard_position_descriptors [(x position, y position)] = [direction,
propagation time, maximum fire propagation time, fire deceleration
rate]
```

For example, considering the scenario illustrated in Fig. 6, `hazard_position_descriptors = {(2, 1): [8, 5, 7, 2]}` implies that fire initiates from position (2, 1) in the grid (marked as 4) and at simulation time step 5, hazard will propagate from (2, 1) to two adjacent cells in down-right direction (coded as 8), (3, 1) and (2, 2), respectively. Next, new cell descriptors are created for cells (3, 1) and (2, 2). These new cell descriptors inherit the properties of the source cell (i.e., same propagation time, direction, deceleration rate, maximum fire propagation time).

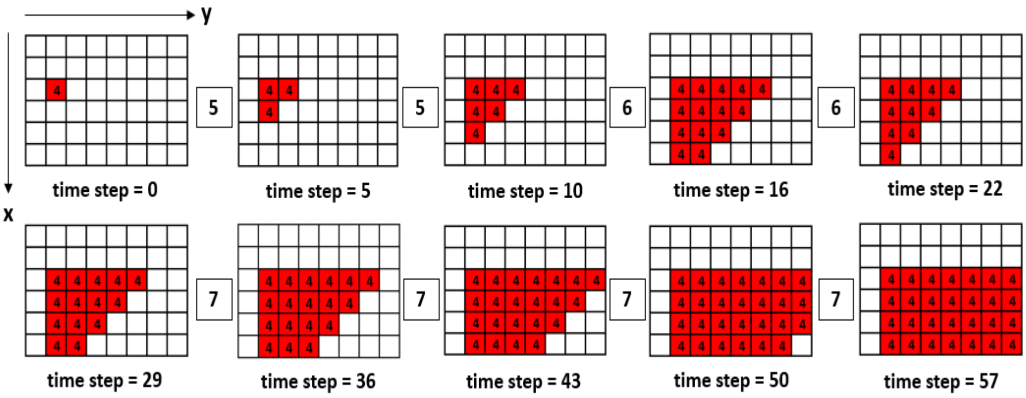



Fig. 6 Schematic representation of a sample directional propagation of fire hazard in EVAQ

Fire propagation time increases by 1 unit at every 2 propagation steps (since deceleration rate is 2) until it reaches the maximum fire propagation time of 7. As shown in Fig. 6, fire starts propagating at 5SS, then again at 10SS, and thereafter (16SS, 22SS, 29SS, 36SS, 43SS, …). This means that $t_H$ = 5 for the first two steps of fire propagation (i.e., 5SS and 10SS), increasing to $t_H$ = 6 in the next two steps (16SS, 22SS), and finally to $t_H$ = 7 (29SS, 36SS, 43SS, …) as the fire reaches its maximum propagation time or decay phase.

### *3.2.2 Human attacker model*

In the current implementation of EVAQ, two types of human threat movement patterns are modeled to provide flexibility in describing life-threatening situations involving lone wolf attackers (e.g., suspect carrying a knife, shooter wandering in a crowded area). The key idea behind the two types of movement patterns is to capture the limits of an attacker's effectiveness which are mainly (i) a random movement provides an average bound on casualty (converges to expected value with sufficient runs), and (ii) a targeted movement allows an attacker to reach and harm maximum possible civilians (thus providing an upper bound on casualty).

In the first model, the attacker is assumed to not follow any predictable movement pattern, and rather to randomly move in the environment. In EVAQ, such pattern is termed *random walk* model. To model random walk, an attacker cell is initiated using a starting position and a movement time $t_H$. At every multiple of $t_H$, the attacker randomly moves from its current cell to any one of the eight adjacent cells without following any particular pattern. This random movement continues until the fate (i.e., death or survival) of all evacuees is determined. A schematic representation of a random-walking hazard (i.e., attacker) is illustrated in Fig. 7.

In the second model, the attacker's goal is to maximize damage, and as such, s/he adjusts his/her movement pattern in accordance with the density of people in the environment. For example, an attacker carrying a knife may target as many people as possible by moving in the direction that allows reaching more people. To model such targeted attack, an attacker is described by a starting position (cell) and a movement time $t_H$, similar to the random walk model. However, at each multiple of $t_H$, the attacker moves from its current cell to the adjacent cell that allows reaching the targets in the shortest possible time. Specifically, for each adjacent cell to the attacker's current position, the distance of all targets to that cell is first computed. Next, an overall (sum) distance is obtained by adding all such individually calculated values. Finally, the adjacent

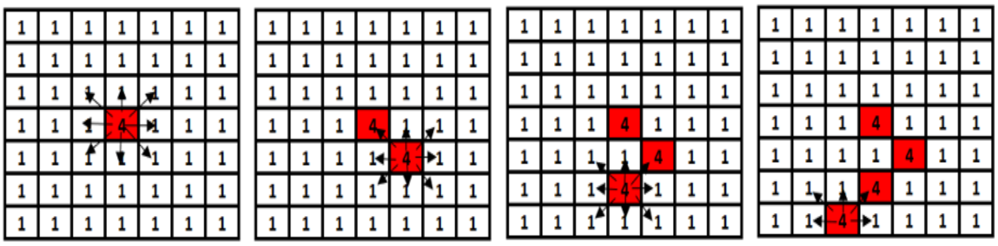



Fig. 7 Schematic representation of random hazard movement in EVAQ

cell with the smallest overall distance is selected as the attacker's next position. It is observed that under this model, more evacuees are likely to be injured than under the random walk model.

### *3.3 Intervention modeling*

As explained earlier, an added modeling feature that distinguishes EVAQ from its predecessors and helps create more realistic results is the ability to incorporate intervention systems. The *Intervention* module initiates fire repellents (e.g., sprinkler system, fire extinguisher) and targeted repellents (e.g., police, security personnel for human attacker) by specifying their positions and characteristics such as initiation time, lifetime, propagation pattern and direction, speed, and deceleration over time.

#### *3.3.1 Repellents to fire hazards*

Fire extinguisher and sprinkler systems are two widely used repellent mechanisms for fire hazards (Hurley *et al*. 2015). In buildings, fire extinguishers are often installed in hallways or passageways or by the side of stairs, so they can be easily reached and used in the time of emergency (Schmidt 1974). Home fire sprinklers, on the other hand, include a network of piping filled with water under pressure installed behind the walls and ceilings (Alpert and Ward 1984). If a fire breaks out, the air temperature above the fire rises (Cao *et al*. 2014), and higher air temperature activates the sprinkler (Hoffmann and Galea 1993). In the current implementation of EVAQ, the fire extinguisher element is modeled such that it propagates toward the direction of fire, while the water sprayed from a sprinkler system can propagate in both symmetrical and directional patterns. Therefore, patterns of repellent propagation (symmetrical or directional) follow the same fire propagation patterns introduced in Subsection 3.2.1. All key attributes of a given repellent such as its effectiveness and the variation of its propagation time are stored and updated in a repellent_position_descriptors dictionary developed in Python, as shown below,

```
repellent_position_descriptors [(x position, y position)] =
[direction, repellent propagation time, maximum propagation time,
repellent deceleration rate, initiation time, duration]
```

The only difference between hazard and repellent cell descriptors is that repellent cell descriptors includes two more static variables, namely initiation time and duration. While the former indicates the time at which the repellent initiates in the environment and prevents a hazard from propagating to the adjacent cells, the latter is a measure of time during which the repellent

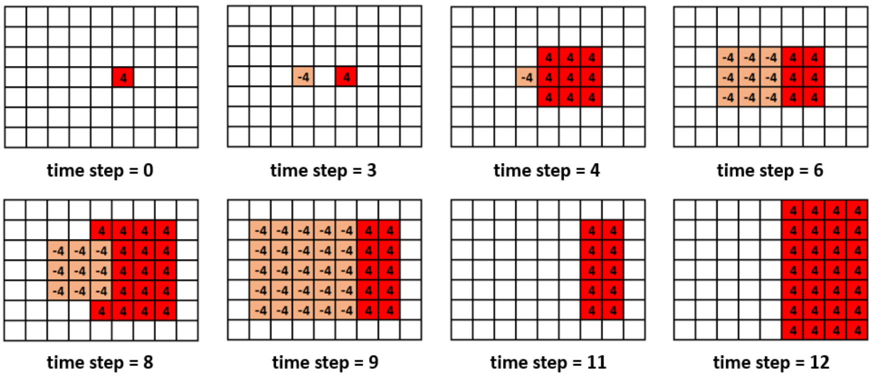



Fig. 8 Implementation of repellent propagation in a hazard-affected environment

will remain active in the environment following its initiation. For a better understanding of the interaction between repellent (cells coded as -4) and hazard (cells coded as 4 and $t_H$ = 4; considering a constant fire propagation time), the scenario illustrated in Fig. 8 is used.

In this figure, repellent properties are described as repellent_position_descriptors = {(3, 3): [0, 3, 3, 0, 3, 7]} which implies that the repellent initiates in position (3, 3) of the grid at 3SS and propagates symmetrically (coded as 0). As repellent propagation time is $t_R$= 3SS, at 6SS, the repellent will propagate from (3, 3) to all eight adjacent cells symmetrically. Accordingly, new cell descriptors are created, and they inherit the same properties of the source cell (i.e., repellent's propagation direction, propagation time, maximum propagation time, repellent deceleration rate, initiation time, and duration). Similar to the fire hazard, repellent propagation time may increase after a number of steps of propagation. However, in this example, the repellent is considered to propagate at a constant speed (this is coded by assigning the value of 3 to maximum propagation time, and 0 to repellent deceleration rate). Since repellent duration is 7, it will become inactive after 10SS (initiation time + duration).

### *3.3.2 Repellents to human threats*

A targeted repellent dynamically adjusts its direction toward hazard to mitigate the hazard as early and efficiently as possible. For example, firefighters gradually move from periphery to the center of a burning fire to extinguish it. Similarly, law enforcement officials may run toward or chase an attacker to prevent him/her from causing further damage. In the current implementation of EVAQ, targeted repellent movement is presented by modeling the bi-directional flow of evacuees. Specifically, two evacuees with different goals can create an adversarial pair enabling them to move toward each other. Fig. 9 shows an attacker (marked as 4) moving to the right direction while a repellent (i.e., police officer marked as -4) moves to the left direction toward the attacker.

In the repellent movement model used in this test case, the targeted repellent and the randomly moving attacker are considered to be present in the system at $t$ = 0 (i.e., simulation initiation time) and $t$ = 3, respectively. Consequently, the repellant starts moving toward the attacker at $t$ = 4. For each movement, the repellent computes the shortest path between its current cell and the hazard cell and then moves to the next cell along this path. Eventually, the repellent meets the hazard and mitigates it. In the example illustrated in Fig. 9 targeted repellent is considered to take 1SS to move from one cell to another in the direction of the hazard.

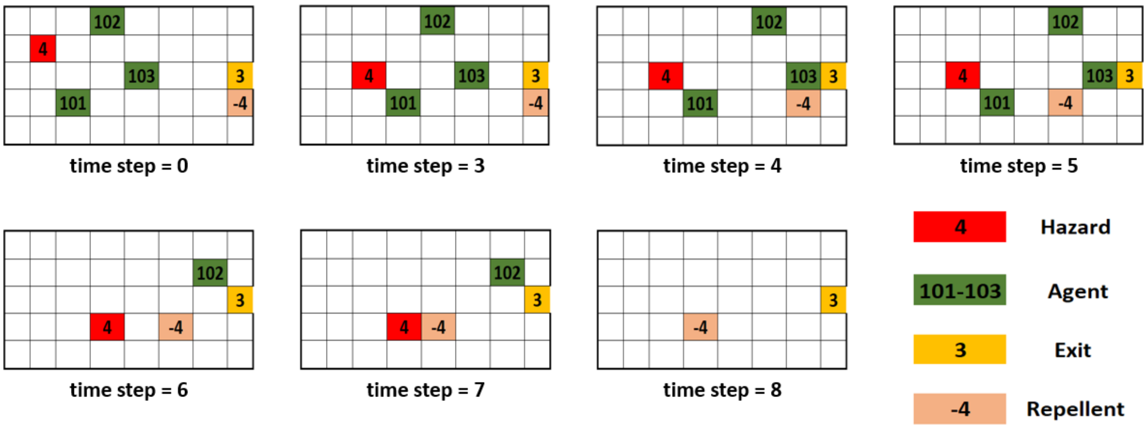



Fig. 9 Targeted repellent movement in a hazard-affected environment

### *3.4 Human characteristics modeling*

Evidently, an evacuee's personal and interpersonal characteristics have a major impact on his/her movement during an emergency. Therefore, EVAQ considers human characteristics to model egress strategies selection and execution in a hazard-affected environment. Once the parameters and constraints of the evacuation model are fully defined, the first step of the simulation process is to model personal (a.k.a. physical) characteristics of people that can influence their fates (i.e., survival or death). Attributes such as age, gender, and disability are generated using results from previous studies (Shi *et al*. 2009). The aggregation of these attributes determines two limiting factors that can potentially impact an evacuee's fate, namely velocity and egress plan. The current implementation of EVAQ supports modeling of people with different velocities for 12 different combinations of attributes (gender: male or female; age: child, adult, or elderly; disability: yes or no). For age distribution, children are considered as less than 12 years old, and elderly people are considered as more than 65 years old (Shi *et al*. 2009). Table 1 shows the parameters (mean, standard deviation) of normally distributed velocity for different personality types.

At the beginning of the simulation, for each evacuee, the velocity value is randomly selected from the corresponding distribution, thus introducing stochasticity in the evacuation model. Next, absolute velocity values are converted to simulation time and space units using the previously described time and space granularity to calculate the simulation time steps taken by each evacuee to move from one cell to the next. In EVAQ, these physical characteristics are user-defined and stored in a designated text file named `agent_characteristics`. The content of this file is parsed to the simulation to generate the time steps corresponding to the movements of each person in the environment during evacuation.

In addition to personal characteristics, understanding human interactions and interpersonal characteristics are very crucial in crowd evacuation planning and emergency mapping (Lo *et al*. 2006, Li and Qin 2012, Tan *et al*. 2015). For example, friends or family members mostly stick together and take the same path during evacuation, some tend to follow a leader (a.k.a., leader-follower behavior) (Ji and Gao 2006), some people help others in need first, for example, a child, or a disabled person (a.k.a., altruistic behavior) (Pan *et al*. 2007). Sometimes, lack of situational awareness creates a tendency in an individual to follow a group of people who are at a closer

Table 1 Velocity distribution of different evacuee class (Shi *et al*. 2009)

| Evacuee Class (attributes) | Mean (m/s) | Std. Deviation (m/s) |
|---|---|---|
| male, child, able | 1.08 | 0.26 |
| male, child, disabled | 0.92 | 0.34 |
| male, adult, able | 1.24 | 0.45 |
| male, adult, disabled | 1.06 | 0.26 |
| male, elderly, able | 1.05 | 0.15 |
| male, elderly, disabled | 0.91 | 0.13 |
| female, child, able | 1.08 | 0.26 |
| female, child, disabled | 0.92 | 0.34 |
| female, adult, able | 1.30 | 0.38 |
| female, adult, disabled | 1.06 | 0.26 |
| female, elderly, able | 1.04 | 0.16 |
| female, elderly, disabled | 0.89 | 0.14 |

distance to him/her, rather than following those who are farther away (a.k.a., herding behavior) (Pan *et al*. 2007). The current implementation of EVAQ supports three distinct types of such group behavioral patterns and formations, as listed below:

Group I for *leader-follower behavior*: when a group of people (three or more) is uncertain about their exit plan, a leader emerges from this group, and everyone else in the group follows the leader's strategy. A natural choice for a leader is the person nearest to the closest exit, as it is easier for him/her to commit to a particular exit. The rest of the group members will then follow the same egress path.

Group II for *altruistic behavior*: when a group of people (two or more) consists of a child or a disabled person, all group members move at the velocity of its weakest member (i.e., minimum velocity of all members) to ensure that no one in that group is left behind.

Group III for *herding behavior*: when an evacuee is not fully affiliated with the environment, or uninformed about possible exit positions, s/he moves toward the nearest group of people. The target group is identified by first calculating (in the real world, eyeballing) the unaffiliated individual's distance to all surrounding groups, followed by moving in the direction of the least total distance.

Sometimes, people may compete for the same exit (a.k.a., *competing behavior*) (Kirchner *et al*. 2003), whereas sometimes, they take the exit in an orderly fashion (a.k.a., *queuing behavior*) (Bo *et al*. 2007). In EVAQ, an exit that is *n*-cells wide can accept at most *n* people at the same time. Therefore, the person closest to the exit takes the exit first, followed by the next closest person, and so on until all evacuees' positions are updated. This exhibits an orderly queuing behavior based on the physical distance to the exit. In certain cases, competition may arise when two or more people are at the same distance from a 1-cell wide exit. In this situation, the person with a higher velocity will take the exit first followed by the next fastest person, and so on. If two or more people have the same velocity and are both one cell away from an exit, one of them is randomly selected to take the exit first. This exhibits a competitive behavior. In EVAQ, congestion at the exit depends on the evacuee's position in front of the exit and is solved pursuing either queuing or competitive behavior.

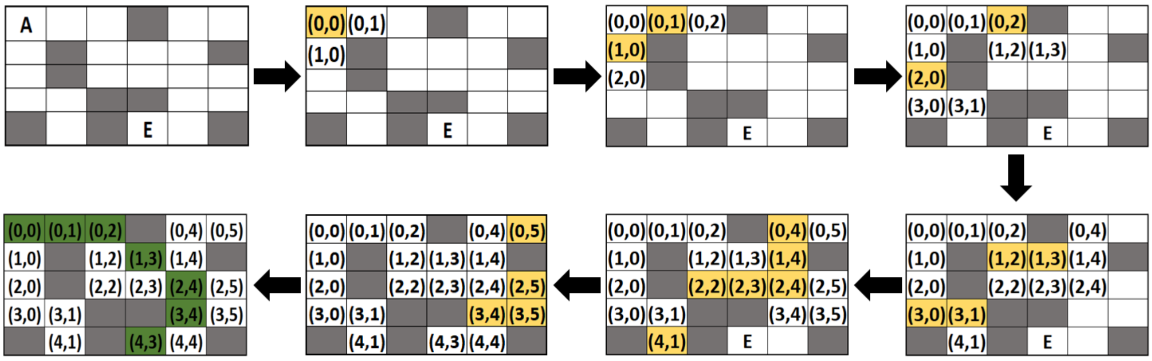



Fig. 10 Systematic heterogenous movement process using the BFS algorithm

### *3.5 Human movement modeling*

The current implementation of EVAQ supports human movements based on dynamic decision-making. This means that evacuees do not choose their egress routes only at the beginning of the simulation, as in previously developed models (Gwynne *et al*. 199, Zheng *et al*. 2009). Rather, they have the ability to change their mind afterward and reconsider their decisions dynamically by taking into account the latest state of the environment (i.e., which cells are no longer available). This egress planning, selection, and execution scheme is devised using the breadth-first search (BFS) algorithm (Leiserson and Schardl 2010), which is widely used in connected graph problems such as a traveler exploring paths within a neighborhood to reach a destination (Stout 1996, Li *et al*. 2017). The BFS algorithm systematically considers all available adjacent cells to a person's current location, and then adjacent cells of those adjacent cells, and so on, until the traverse reaches the desired destination (as shown in Fig. 10). In evacuation modeling, preferred destinations are exit locations within the floor layout. The algorithm identifies the nearest available exit based on the current state of the environment. BFS traversals work based on available (unoccupied) cells or evacuee IDs, as these cells can be occupied by evacuees (cells with white background in Fig. 10). Once a person moves from one cell to another, the first cell becomes unoccupied and the next one becomes occupied. In Fig. 10, person A moves from one cell to another avoiding occupied cells (marked as grey representing obstacles) and reaches to exit E. Besides, if a cell becomes affected by a hazard, it is marked as unavailable (occupied) for evacuees forcing them to update their egress strategy accordingly or change their egress route. Note that a cell occupied by a repellent remains available for evacuees.

## 4. Application and Analysis

In the following Subsections, results of person-specific egress simulation by EVAQ are discussed. Findings confirm that EVAQ can successfully simulate large crowd evacuations by modeling evacuees' personal (i.e., age, gender, disability) and interpersonal (i.e., group interactions) attributes, and situational awareness in a deteriorating environment. Results also show the effectiveness of EVAQ in simulating the impact of the space design (e.g., shape and size of rooms and obstacles, number and width of exits) in crowd evacuation.

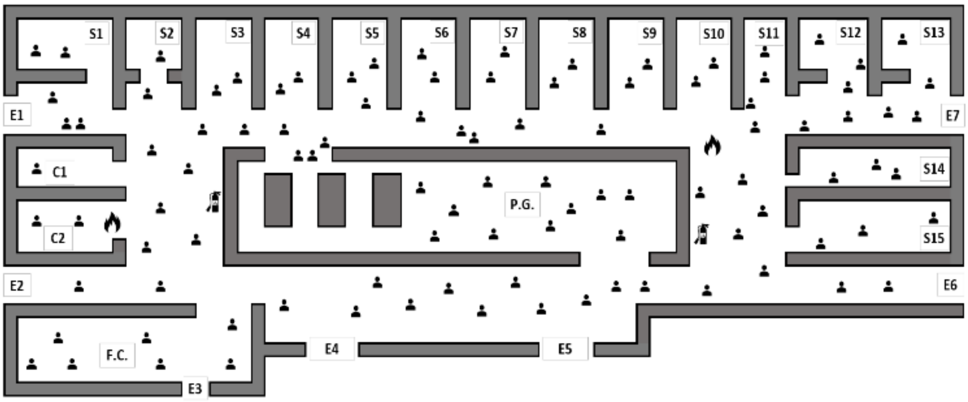



Fig. 11 Shopping mall layout and distribution of shoppers and fire hazards

### 4.1 Shopping mall egress analysis under fire emergency

In this hypothetical scenario, a shopping mall is modeled to assess the performance of EVAQ for emergency evacuation mapping. As shown in Fig. 11, the 1,012.5 m$^2$ mall floor consists of 15 stores, restrooms, two cafés and a food court, and children playground area. A total of 200 people (shown by human icon), 2 fire initiation points (shown by flame icon), and 7 main exits (E1 through E7) are modeled. To study the evacuation pattern during emergency, two test cases are considered and modeled in EVAQ. These include,

**Test case 1:** Evacuation is possible only through the main exits of the shopping mall.

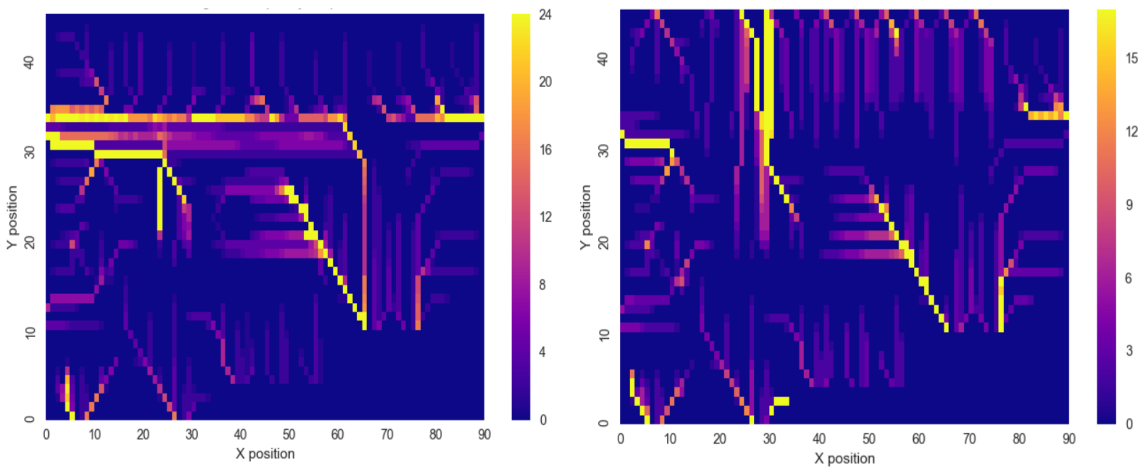
**Test case 2:** 15 additional emergency exits (located in the back of the 15 stores) can be accessed and used for evacuation.

To perform egress analysis for both cases, the following assumptions are considered,

a) A total of 200 people of 12 different types (see Table 1) are randomly distributed in the environment.
b) Half of the population (i.e., 100 people) exhibit one of the three different group behaviors, namely altruistic (20 people), leader-follower (50 people), and herding (30 people) behavior.
c) Each evacuee chooses his/her nearest exit and pursues it using either queuing or competitive behavior based on his/her distance from that exit.
d) No pre-evacuation time is considered.

#### 4.1.1 Effect of exits

Two specific test cases (test case 1 and 2) are considered for this scenario, and a total of 30 simulations are run for each case. It is confirmed that allowing people to use more exits results in a reduced evacuation time. In particular, the average evacuation time over 30 simulations is reduced from 660.4 seconds in test case 1 to 456.3 seconds in test case 2. Results also indicate that 34 more people survive in test case 2 (122 survivals in test case 1 compared to 156 survivals in test case 2) due to the availability of more exits. Fig. 12 illustrates evacuees' density maps for both test cases. In this figures, light-colored lines represent the salient evacuation paths that are highly utilized (occupied for 20+SS for test case 1 and 15+SS for test case 2) during the evacuation process, while




(a) (b)

Fig. 12 Evacuees' density map for (a) test case 1, and (b) test case 2

dark-colored lines indicate less utilization of evacuation paths by evacuees. It is evident from these figures that when fewer exits are accessible for emergency evacuation, more congestion is expected at each exit, whereas people are more evenly routed (less density) when 12 additional exits are deployed for evacuation.

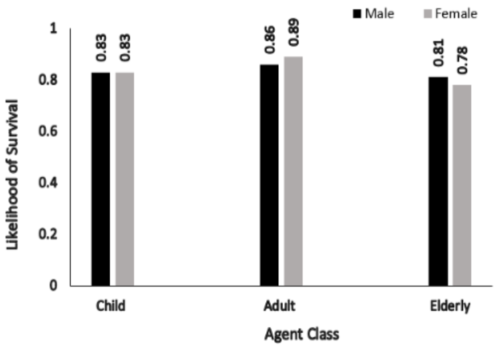
It must be noted that while such findings (i.e., fewer exits lead to more congestion at the exit locations, adding to evacuation time) are not surprising, some more nuanced conclusions of such analyses with real implication to emergency planning are identifying the best possible positioning of the exits, and the degree to which each added exit could help save lives. Since implementing such layout modifications in the real world are costly, EVAQ can provide an opportunity to better understand the tradeoff between cost and safety.

#### *4.1.1 Effect of intervention system*

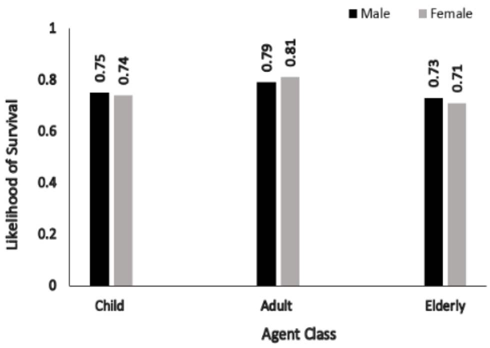
The developed EVAQ model for this scenario is also used to determine the effect of an individual's characteristics and environmental constraints on their likelihood of survival (*LS*), which is defined using Eq. (1),

$$LS_X = \frac{No. survived\ agents\ in\ class\ X}{No. agents\ in\ class\ X} \tag{1}$$

To understand the effect of the intervention system on the likelihood of survival, the simulation model of the shopping mall scenario is revisited. As shown in Fig. 11, there are 2 fire extinguishers in the mall to control fire propagation. This model is run for test case 1 over 30 times (using different seed numbers) for both with and without fire extinguishers in the system. Results illustrated in Fig. 13 and Fig. 14 show that the likelihood of survival increases in the presence of a hazard intervention system regardless of evacuees' gender and disability status. In terms of age, the likelihood of survival of children and elderly people increases by 11% due to the use of intervention system whereas for adults it increases by 9%. This can be also attributed to the fact that the survival of vulnerable evacuees (e.g., children and elderly people) largely depends on group interactions (i.e., it may be difficult for a child or elderly person to find the exit and safely

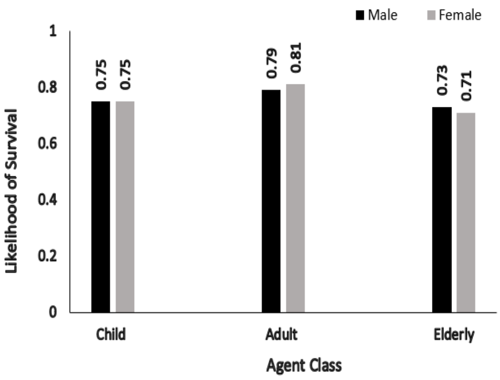



(a) Test case 1

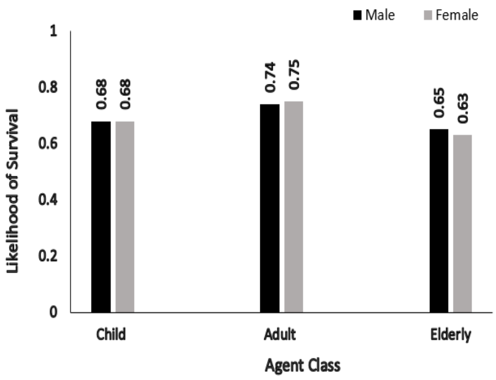



(b) Test case 2

Fig. 13 Likelihood of survival of able evacuees (a) with, (b) without hazard intervention system




(a) Test case 1




(b) Test case 2

Fig. 14 Likelihood of survival of disabled evacuees (a) with, (b) without hazard intervention system

evacuate without any help), which is present in this scenario. Finally, for this simulation, the output of the EVAQ model shows that on average, 163 out of a total of 200 people could safely evacuate (i.e., 82%), in the presence of hazard intervention system or fire extinguisher in the environment. However, only 128 people (i.e., 64%) could be saved without a hazard intervention system in the environment.

### *4.2 Airport egress analysis under human attacker*

In this hypothetical scenario, a regional airport terminal is modeled to assess the performance of EVAQ for emergency evacuation mapping. The model imitates the evacuation process in a dynamic (threatened by human attacker) environment and identifies critical egress issues during the egress. As shown in Fig. 15, the 800 m$^2$ terminal floor consists of check-in counters, offices, restrooms, café and bars, and retail shops. A total of 275 people (shown by human icon), 3 random knife stabbers (shown by human attacker icon), and 8 police officers (shown by police icon) are

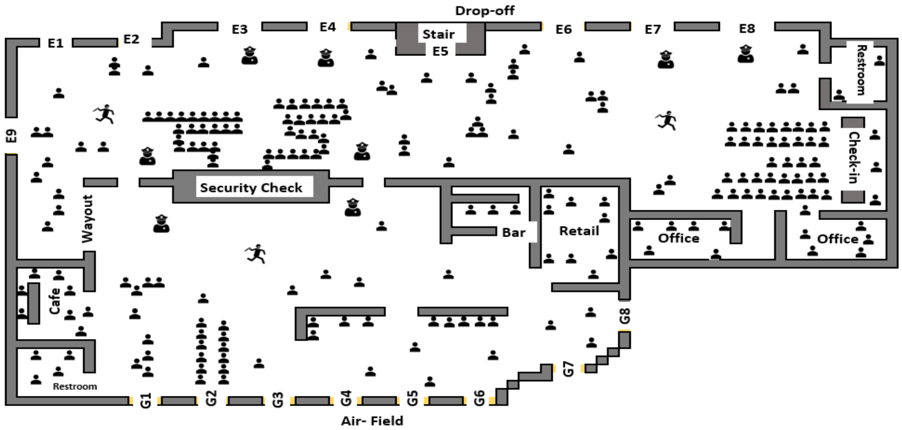



Fig. 15 Airport terminal layout and distribution of travelers, human attackers, and police officers

modeled. Also, there are 9 exits (E1 through E9) and 8 boarding gates (G1 through G8) in the airport terminal. Each traveler must go through a security checkpoint before entering the secured area and boarding the plane. To study the evacuation pattern during human attack, two test cases are considered and modeled in EVAQ. These include,

**Test case 1:** The security checkpoint remains open and accessible to the crowd during evacuation, allowing people to move in and out of the secured area to egress.

**Test case 2:** The security checkpoint and boarding gates remain inaccessible to maintain the integrity of the secured area, thus separating the secured and unsecured areas of the terminal during the evacuation. In this case, travelers who have already entered the secured area can only use the exit marked as *wayout* in Fig. 15 for egress.

To perform egress analysis for both cases, the following assumptions are considered,

a) A total of 275 people of 12 different types (see Table 1) are randomly distributed in the environment, and no group behavior is considered.
b) Each evacuee chooses his/her nearest exit and pursues it using either queuing or competitive behavior based on his/her distance from that exit.
c) No pre-evacuation time is considered.
d) Attacker's goal is to maximize damage, so his/her movement pattern is in accordance with the density of people in the environment.
e) Attackers are initiated by a starting position (cell) and a movement time $t_H = 4$, implying that each attacker moves at multiples of $t_H$ from its current cell to an adjacent cell in the direction of the highest density of people in the environment.
f) Police officers are initiated at time $t = 5$ and their movement time is $t_R = 3$. This means that each officer moves at multiples of $t_R$ starting at (5+3) or 8SS from his/her current cell to an adjacent cell in the direction of human attacker in the environment.

A total of 30 simulation runs are conducted (using different seed numbers) and the average evacuation time of survived people is illustrated in Fig. 16. According to results, in test case 1 (i.e., security checkpoint is open) it takes 1,080 SS or 250 seconds to evacuate the terminal, while in test case 2 (i.e., security checkpoint is closed), it takes 1,920 SS or 420 seconds to evacuate the terminal. The difference in evacuation time (170 seconds) can be attributed to the fact that in test case 2 people inside the secured area are only allowed to use *wayout* and the boarding gates to

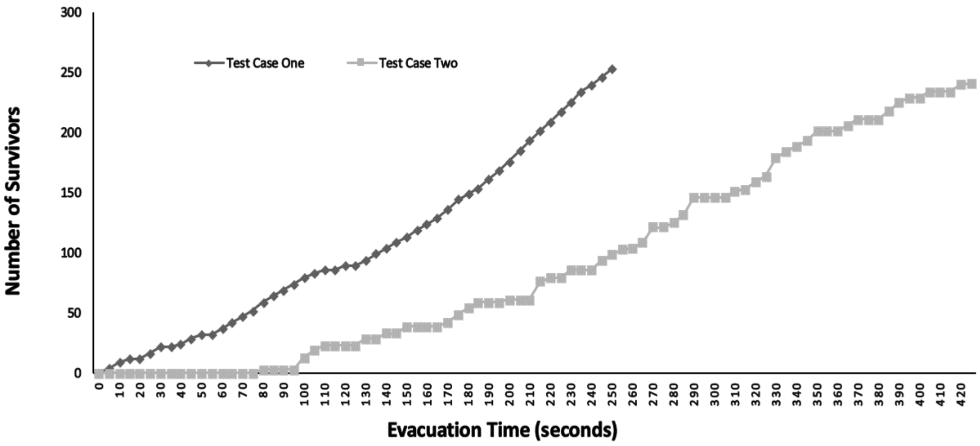



Fig. 16 Cumulative plot of the average number of people evacuating the terminal building with time

egress, thus creating more congestion and longer queues at exit locations. For test case 1, a total of 253 people can be saved whereas for test case 2, only 241 people are saved. This is due to the fact that for test case 1, people can escape using more exit points (specifically, security check point and boarding gates) while police officers are eliminating the human attackers from the environment. On the other hand, for test case 2, more people were trapped in the secured area leading to more compromised lives (taken by attackers) during the evacuation process.

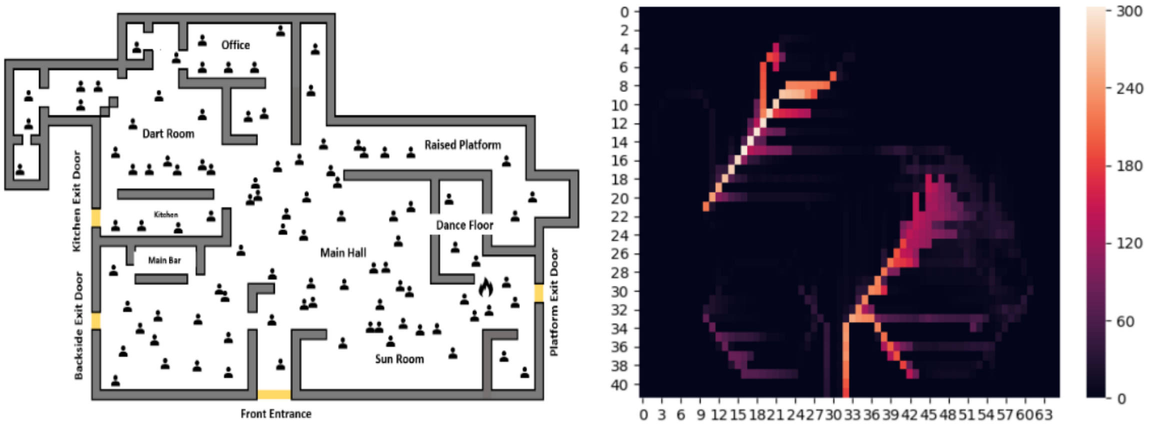
## 5. Validation

In order to validate the performance of EVAQ, data from a historical fire incident (The Station nightclub in West Warwick, Rhode Island) is used. This dataset is one of the few publicly available datasets maintained by the National Institute of Standards and Technology (NIST) and used in previous simulation validation studies (Grosshandler *et al*. 2005, Chaturvedi *et al*. 2006).

### *5.1 Replication of fire evacuation in Rhode Island Station nightclub*

The nightclub floorplan is illustrated in Fig. 17(a) and the evacuation pattern is shown in Fig. 17(b). The building is a single-story wood frame with approximately 415 $m^2$ in floor area. As shown in Fig. 17(a), there are four exit locations (front entrance, backside exit door, kitchen exit door, and a platform exit door). Since most of the evacuees were familiar with the main entrance, some congestion started to occur in front of the main entrance after fire started. According to NIST data, the platform door became impassable due to the spread of fire approximately 30 seconds later. Therefore, to simulate this event, fire initiation point (shown by flame icon) is placed near the platform door. It was also reported that 79 people were able to escape by breaking window glasses. However, due to the lack of information about window positions, the corresponding EVAQ model considers that people were only using the exits to evacuate.

To simulate the emergency evacuation for the environment illustrated in Fig. 17, EVAQ considers the following assumptions,




(a) Layout of the Station Nightclub floor (b) Evacuees' density map (sim. run = 1)

Fig. 17 Layout and evacuation pattern of the Rhode Island Station Nightclub fire incident

Table 2 Comparison of simulation results between EVAQ model and NIST data for the Rhode Island nightclub fire

| Data | Total Number of People | Survivors | | | Total Fatalities |
|---|---|---|---|---|---|
| | | Using Exits | Using Windows | Total | |
| NIST | 350 | 171 | 79 | 250 | 100 |
| EVAQ | 350 | 273 | - | 273 | 77 |

a) From NIST data, a total of 350 people (all adults, 50%-50% distribution of males and females) are randomly positioned on the floor (shown by human icon).
b) A total of 230 people are randomly selected and assigned to main entrance for egress.
c) A total of 20 people are randomly selected and assigned to platform door for egress.
d) All evacuees evacuate the building using either queuing or competitive behavior based on their distance to the exit.

It must be noted that assumptions (b) and (c) are consistent with NIST data which suggest that most of the people were only aware of the front entrance and some people tried to take platform exit door which was compromised after 30 seconds of fire initiation. The evacuees' density map shown in Fig. 17(b) is generated from the first simulation run where the total evacuation time was 300SS. In this figures, light-colored lines represent the salient evacuation paths that are highly utilized (occupied for 240+SS) during the evacuation process, while dark-colored lines indicate less utilization of evacuation paths by evacuees. It is evident from this density map that most of the people used front entrance and the kitchen exit door for safe exit, and there was congestion for a long time. Using different random spatial distributions of people and hazard in the environment, EVAQ simulation output is averaged out over 20 simulation runs, as listed in Table 2, where a comparison is also made with NIST reported data. Results indicate that the EVAQ model closely replicates the NIST model.

The NIST report also contained simulation results of the Rhode Island nightclub fire evacuation obtained from Simulex (Thompson *et al*. 2003) and buildingEXODUS (Gwynne *et al*. 1999). Both tools were utilized to determine the minimum evacuation time from the nightclub in the absence of

Table 3 Comparison of simulation results between EVAQ, Simulex, and buildingEXODUS

| Simulation platform | Total Number of People | Total Evacuation Time (s) | Relative difference (%) with EVAQ |
|---|---|---|---|
| EVAQ | | 222 | - |
| Simulex | 420 | 188 | 16.5 |
| buidilgnEXODUS | | 202 | 9.4 |

fire. In this paper, EVAQ is used to determine the minimum evacuation time using similar assumptions on the input, and results are compared to Simulex and buildingEXODUS. The assumptions are as follows,

(a) A total of 420 people exist in the environment, of which 384 are located in the main hall, sunroom and main bar, and the remaining 36 are located in the kitchen, restroom, offices, and corridor.
(b) All evacuees evacuate the building using competitive behavior based on their distance to the nearest exit.

In total, 20 simulation runs are conducted, and results are listed in Table 3. Moreover, the relative difference (*RD*) in evacuation times obtained from EVAQ compared to Simulex, and buildingEXODUS is calculated by dividing the absolute difference (*AD*) by the absolute arithmetic mean (*AAM*) and expressed in percentage point, as shown in Eq. (2),

$$RD(\%) = \frac{AD}{AAM} \times 100 \tag{2}$$

According to Table 3, total evacuation time does not differ much between EVAQ, Simulex, and buidilgnEXODUS. In particular, the relative difference in total evacuation time (in the absence of fire) between EVAQ and Simulex, and EVAQ and buildingEXODUS ranges between ~9% and 16%, respectively. Given the difference in modeling principles of these three simulation platforms, such discrepancy is expected and results are within striking distance from each other.

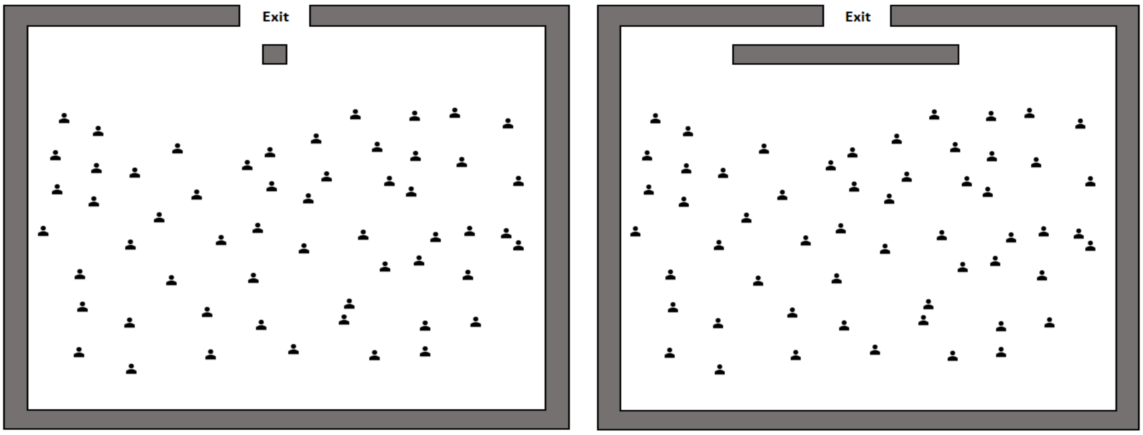
### *5.2 Investigating the role of architecture in occupants' safety*

Recent studies have indicated that architectural adjustments could reduce bottlenecks at the exit and hence reduce the evacuation time (Shi *et al*. 2019). To further explore this claim, an experiment was designed involving a single-room scenario inspired by previous studies (Shiwakoti and Sarvi 2013, Shi *et al*. 2019). In this scenario, 100 people (shown by human icon) are randomly distributed in a 10m×15m room, as shown in Fig. 18. There is a 1.5m-wide exit, and two types of obstacles in close distance to the exit are considered, namely a 0.5m×0.5m square column (Fig. 18a), and a 5m-long wall (Fig. 18b). Evacuation time is observed for the benchmark case with no obstacles (a.k.a., standard design) and each of the two cases (square column and long wall) for various distances to the exit.

To study the impact of architectural adjustments on emergency evacuation two test cases are considered and modeled in EVAQ. These include,

**Test case 1:** Each evacuee is assigned a normal walking speed randomly drawn from a normal distribution (*M* = 1.31 m/s, *S.D.* = 0.13 m/s)

**Test case 2:** People are panicked and running to safety. Therefore, each evacuee is assigned a running speed drawn from a normal distribution (*M* = 2.62 m/s, *S.D.* = 0.26 m/s).




(a) Exit blocked by square column (b) Exit blocked by long wall

Fig. 18 Single room layout and distribution of people

In total, 9 scenarios are established, as listed in Table 4, and the following assumptions are considered to perform egress analysis,

(a) A total of 100 people are randomly distributed in the environment, and no group behavior is considered.
(b) Each evacuee chooses his/her exit and pursues it using either queuing or competitive behavior based on his/her distance from that exit.
(c) No pre-evacuation time is considered.

For the analysis, a number of parameters including the total evacuation time (*TET*), average evacuation time (*AET*), flow rate of evacuees (*F*), and specific flow rate (*SFR*) are considered and calculated using the following formulae (Shi *et al.* 2019),

$$TET = t_N - t_1 \tag{3}$$

$$AET = \frac{TET}{N} \tag{4}$$

$$FR = \frac{N}{TET} \tag{5}$$

$$SFR = \frac{FR}{b} \tag{6}$$

In Eq. (3), $t_1$ and $t_N$, represent the time of first and last person taking the exit to evacuate, respectively. Also, in Eqs. (4) and (5), *N* denotes the total number of people in the environment, and in Eq. (6), *b* represents the exit width. To select the best design with obstacles, relative efficiency (*RE*) for specific flow rate in all eight experiments (2 through 9) is calculated using Eq. (7), considering experiment 1 as standard design. Table 4 illustrates the result of all experiments.

$$RE = \frac{SFR - SFR_{standard}}{SFR_{standard}} \times 100 \tag{7}$$

Table 4 List of experiments for single room evacuation simulation scenario

| Experiment Number | Type of Obstacle | | | Distance from Exit to Obstacle | | | |
|---|---|---|---|---|---|---|---|
| | No Obstacle | 0.5m×0.5m Column | 5m-Long Wall | 0.5m | 1.0m | 1.5m | 2.0m |
| 1 | √ | - | - | - | - | - | - |
| 2 | - | √ | - | √ | - | - | - |
| 3 | - | √ | - | - | √ | - | - |
| 4 | - | √ | - | - | - | √ | - |
| 5 | - | √ | - | - | - | - | √ |
| 6 | - | - | √ | √ | - | - | - |
| 7 | - | - | √ | - | √ | - | - |
| 8 | - | - | √ | - | - | √ | - |
| 9 | - | - | √ | - | - | - | √ |

Table 5 Simulation results from different experimental setup

| Experiment Number | Total Evacuation Time (sec) | | Average Evacuation Time (sec/person) | | Flow of Evacuees Passing the Exit (person/sec) | | Specific Flow Rate (person/sec/m) | | Relative Efficiency (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Test Case 1 | Test Case 2 | Test Case 1 | Test Case 2 | Test Case 1 | Test Case 2 | Test Case 1 | Test Case 2 | Test Case 1 | Test Case 2 |
| 1 | 25.5 | 12.75 | 0.255 | 0.128 | 3.921 | 7.843 | 2.614 | 5.223 | - | - |
| 2 | 25.5 | 12.75 | 0.255 | 0.128 | 3.921 | 7.843 | 2.614 | 5.223 | 0 | 0 |
| 3 | 25.5 | 12.75 | 0.255 | 0.128 | 3.921 | 7.843 | 2.614 | 5.223 | 0 | 0 |
| 4 | 25.5 | 12.75 | 0.255 | 0.128 | 3.921 | 7.843 | 2.614 | 5.223 | 0 | 0 |
| 5 | 25.5 | 12.75 | 0.255 | 0.128 | 3.921 | 7.843 | 2.614 | 5.223 | 0 | 0 |
| 6 | 25 | 12.25 | 0.25 | 0.122 | 4.00 | 8.163 | 2.667 | 5.44 | 2 | 4 |
| 7 | 24.25 | 11.5 | 0.242 | 0.115 | 4.12 | 8.70 | 2.75 | 5.79 | 5 | 10 |
| 8 | 26.75 | 13.25 | 0.267 | 0.132 | 3.74 | 7.547 | 2.49 | 5.03 | -5 | -3 |
| 9 | 28 | 14.5 | 0.28 | 0.145 | 3.57 | 6.90 | 2.381 | 4.60 | -9 | -12 |

Results shown in Table 5 imply that for both test cases, the presence of a square column does not have any significant influence ($RE$ = 0% for both test cases) with increasing distance from exit (experiments 2 through 5). However, when people are in panic, evacuation time reduces by 50% (from 25.5sec in test case 1 to 12.75sec in test case 2) and hence, flow rate increases (from 2.61person/sec/m to 5.23person/sec/m). This can be attributed to the fact that obstacles blocking the exit divide the congestion at the exit and thus reduce the pressure among evacuees. Moreover, for both test cases, flow rate is larger than the standard design (experiment 1) when wall is located at 0.5m and 1.0m from the exit. Therefore, for architectural adjustment of the exit design, these two experiments can be considered (experiments 6 and 7). However, in both test cases, experiment 7 proves to be the best design with higher relative efficiency. Therefore, it can be concluded from the result of all 9 experiments that sometimes, placing obstacles close to an exit can decrease the evacuation time and increase the crowd outflow.

## 6. Research contributions

The contributions of this research can be categorized as methodological contributions and scientific contributions. The development of a comprehensive evacuation simulation tool is considered as the key methodological contribution of this research. EVAQ is a holistic system that models all key components of an emergency evacuation (e.g., environment, people, hazards, and intervention systems) and controls their interactions in real time through the simulation engine. This enables modelers to revise individual components without affecting the integrity of the model. EVAQ adopts a combination of cellular automata-agent based simulation modeling where each evacuee individually assesses his/her status and the status of the surrounding environment for making a rule-based decision (Bonabeau 2002). In addition, the ability to model intervention systems is an entirely new direction of research in evacuation simulation modeling. Moreover, beyond modeling typical mechanical intervention systems such as home water sprinkler recently presented by NIST in FDS (McGrattan *et al*. 2010), EVAQ has the ability to model dynamic (targeted) intervention systems (e.g., police officers chasing an attacker, firefighters moving against the crowd flow to put out fire).

Several verification tests prescribed by NIST were conducted to evaluate the performance of EVAQ. While the description of such tests are beyond the scope of this paper, details can be found in another publication by Datta (2018). Qualitative and quantitative assessment of verification results indicate that EVAQ can successfully model occupants' pre-evacuation time distribution, movement, navigation, exit choice/usage, exit route availability, and flow constraints. Besides, EVAQ is validated using a NIST dataset from a historical incident of fatal fire at the Station Nightclub in Rhode Island. Collectively, successful verification and validation indicates the potential of EVAQ for improved crowd management and emergency mapping.

The scientific contributions of this research include creating person-specific egress strategies by capturing key events occurring during the evacuation process, as well as factoring in information on attributes of involved individuals. EVAQ provides insights into crucial evacuation planning parameters such as evacuees' likelihood of survival given their personal and interpersonal characteristics. This can help designers and architects evaluate building/facility layouts to minimize the number and severity of potential casualties in case of an emergency, and subsequently modify their designs prior to construction. Moreover, this information helps to make important decisions at all levels of emergency management. Specifically, EVAQ can help in benchmarking a design against historical data such as school shootings or workplace disturbances to investigate whether a given building design meets the minimum requirement of an emergency evacuation. Results demonstrate that the likelihood of survival is directly proportional to the number and location of exits, the presence of intervention systems, signage, and evacuees' situational awareness (drift).

## 7. Conclusions and future work

The overarching goal of this research was to design and test a large crowd simulation modeling tool for investigating the role and impact of human characteristics (e.g., personal and interpersonal), environmental constraints, and intervention systems on the safe egress of evacuees from a hazard-impacted environment. To achieve this goal, an end-to-end simulation framework, called EVAQ, was developed and tested in multiple scenarios including emergency evacuations in a shopping mall, airport terminal, and nightclub fire. EVAQ takes as input the layout of the environment, as well as the characteristics of and interactions between evacuees, hazards, and intervention systems, and calculates the best possible egress strategy in a deteriorating environment.

The current implementation of EVAQ does not consider the variation in evacuees' velocities during an emergency. In essence, each person in the system is initially assigned a velocity value sampled from the distribution in Table 1 and maintains the same velocity during the evacuation until the completion of his/her egress plan. In reality, however, velocity is subject to change during the evacuation. For instance, an evacuee may decide to slow down for a while to catch a breath or speed up as s/he sees hazard approaching. In general, the instantaneous velocity of evacuees is a function of their status, as well as the severity of hazards, and the availability of free space in the environment. Incorporating variations in velocity values can result in a more realistic output, which can, in turn, lead to more informed simulation-based decision-making.

To better capture the actual velocity distribution of evacuees in the environment, EVAQ uses a grid division of space (i.e., 1 cell = 0.5m×0.5m). However, by reducing this cell size, the evacuation environment can be represented at a finer level, which helps to approximate the human velocities with higher precision. For example, if the cell size is reduced to 0.25m×0.25m, then an evacuee can only cover multiples of 0.25m per simulation time. By further reducing the cell size to 0.1m×0.1m, an evacuee can cover multiples of 0.1m per simulation time. The latter retains the individual's velocity with higher precision and thus better captures the overall distribution of evacuees' movements (including mean and standard deviation). To avoid precision loss in a finer grid system, the environment can be modeled in such a way that each person occupies more than one cell (multi-grid model) as previously done in different evacuation studies (Song *et al*. 2006, Cao *et al*. 2015, Cao *et al*. 2016).

Moreover, this research is primarily focused on designing and testing the main skeleton of EVAQ considering the four key components of any evacuation scenario, namely environment, people, hazards, and intervention systems. In the environment module, user input is used for configuring the physical environment. However, creating functionality that allows the integration of CAD/BIM files in EVAQ for the automated generation and population of the building/facility layout will be of great value since it can lead to more intuitive interface design while allowing the integration of EVAQ functionalities with those of CAD/BIM software. The current implementation of EVAQ does not consider elevation changes in a floor plan. In other words, evacuees are modeled in a 2D grid system. Therefore, staircase, elevators, and escalators are not part of the modeled environment. Also, incorporation of physics-based evacuation modeling (Cantrell *et al*. 2018) allows modelers to analyze a more extensive range of human behavior (e.g., pushing, falling, trampling), all likely events during a real-world emergency evacuation.

In the current implementation, EVAQ is validated through retrospective experiments suggested by NIST and datasets replicating historical events (Thomsen *et al*. 1999). While using retrospective evaluation allows a wide range of "what-if" analyses to be performed, for full confidence in the results, it is ideal the outcome be assessed against established theories, real-world cases (difficult to accomplish given the scarcity of datasets in this domain), or verified by experts (i.e., face validation).

With rapid proliferation of personalized sensing and information delivery systems, findings of this work are ultimately sought to assist facility/building planners, designers, and occupants in developing and executing more robust emergency mapping and evacuation.

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