EVAQ: PERSON-SPECIFIC EVACUATION SIMULATION FOR LARGE CROWD EGRESS ANALYSIS

A Thesis

by

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ABSTRACT

Timely crowd evacuation in life-threatening situations such as fire emergency or terrorist attack is a significant concern for authorities and first responders. An individual's fate in this kind of situation is highly dependent on a host of factors, especially (i) *agent dynamics:* how the individual selects and executes an egress strategy, (ii) *hazard dynamics:* how hazards propagate (e.g., fire and smoke spread, lone wolf attacker moves) and impair the surrounding environment with time, (iii) *intervention dynamics:* how first responders intervene (e.g., firefighters spread repellents) to recover environment. This thesis presents EVAQ, a simulation modeling framework for evaluating the impact of these factors on the likelihood of survival in an emergency evacuation. The framework captures the effect of personal traits and physical habitat parameters on occupants' decision-making. In particular, personal (i.e., age, gender, disability) and interpersonal (i.e., agent-agent interactions) attributes, as well as an individual's situational awareness are parameterized in a deteriorating environment considering different exit layouts and physical constraints. Further, the framework supports a variety of hazard propagation schemes (e.g., fire spreading in a given direction, lone wolf attacker targeting individuals), and intervene schemes (e.g., firefighters spreading repellents, police catch the attacker) to support a wide range of emergency evacuation scenarios. The application of EVAQ to crowd egress planning in an airport terminal and a shopping mall in the fire emergency is presented in this thesis, and results are discussed. Result shows that the likelihood of survival decreases with a decrease in availability of the nearest exits and a resulting increase in congestions in the environment. Also, it is observed that the incorporation of group behavior increases the likelihood of survival for children, as well as elderly and disabled people. In addition, several verifications and validation tests are performed to assess the reliability and integrity of EVAQ in comparison with existing evacuation modeling tools. As personalized sensing and information delivery platforms are becoming more ubiquitous, findings of this work are ultimately sought to assist in developing and executing more robust and adaptive emergency mapping and evacuation plans, ultimately aimed at promoting people’s lives and wellbeing.

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For the better understanding of the simulation result, 3-D visualization of emergency evacuation was developed by Mr. Nipun Nath using Autodesk Maya, a doctoral student in the Department of Construction Science, and a researcher in the Construction Informatics and Built Environment Research (CIBER) Lab. All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

ABMs	Agent-Based Models
BIM	Building Information Modeling
BFS	Breadth First Search
CAD	Computer Aided Design
DFS	Depth First Search
EMS	Emergency Medical Service
FEMA	Federal Emergency Management Agency
FBI	Federal Bureau of Investigation
FDS	Fire Dynamic Simulator
ISO	International Standards Organization
IMO	International Maritime Organization
NIST	National Institutes of Standards and Technology
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
SS	Simulation Time Steps
V&V	Verification and Validation

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1 INTRODUCTION

1.1 Motivation

Improper crowd management, more specifically, erroneous evacuation strategies may increase casualties during an emergency. An emergency situation may arise due to 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 beforehand, rather than waiting for the time of crisis. In this regard, thorough investigation of emergency mapping and egress route assignment (i.e., workplace layout, the position of exits, floor plans, and safe or refuge areas) during all stages of design, construction, and operation of a building or facility are deemed critical (Kobes, Helsloot, De Vries, & Post, 2010; Wright, 2007).

Among all causes of accidents in the built environment, fire-related accidents cause a large number of lives and property loss both in residential and commercial buildings. In 2015, the FEMA (2017) had 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. Records show that 32% of fatalities are caused by ineffective egress and escape-related planning (FEMA, 2017) which is often caused by large population 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. NFIRS identified leading contributing factors to fire fatalities in residential buildings during 2013-2015 (FEMA, 2017). As Figure 1 shows, in 61.7% of reported cases, fire pattern is one of the major causes of civilian fire fatalities. Besides, human factor (e.g., gender, age, physical disability, interaction with involved individuals) has also been cited as a significant factor contributing to 32.1% of reported fire fatalities.

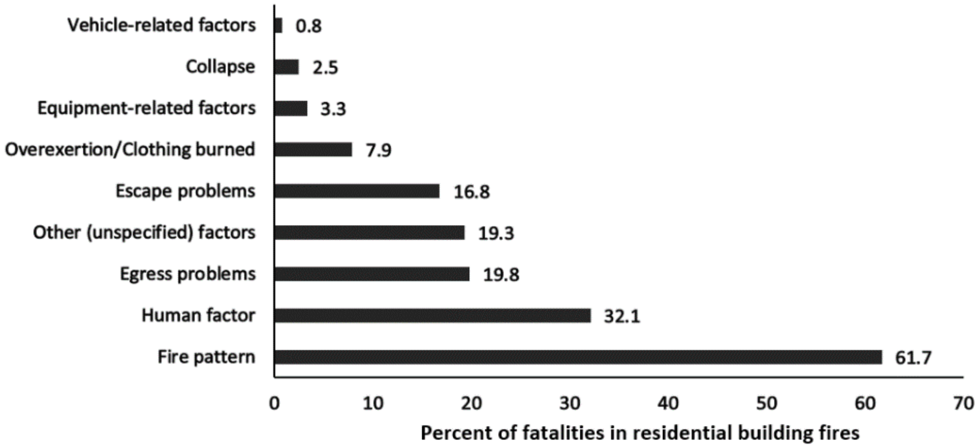


Figure 1: Contributing factors to fire fatalities in residential buildings.

In addition to fire, other causes of the loss of life include attacks by a knife stabber, lone wolf attacker, or shooter who randomly walks around in a crowded area. According to the 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 EMS units in the U.S. from 1999-2008 (Smith, 2013). Therefore, it is imperative that much attention be drawn to studying and characterizing emergency action planning for crowd evacuation under different scenarios including building fire or random attacker.

Previous research has developed evacuation models mostly to understand the human and social behavior of a crowd during the evacuation process (Zheng, Zhong, & Liu, 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 models only model crowd movements in hazard-free environments, overlooking the influence of hazard in steering crowd behavior. Moreover, the value of intervention systems (i.e., fire extinguishers, sprinklers) to evacuation from 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.

1.2 Research Goal

The main objective of this research is to design an end-to-end simulation framework, EVAQ, for modeling emergency evacuations while capturing the key events occurring during the evacuation, and information about the safety of the involved individuals. In developing EVAQ, two research questions were identified and successfully addressed,

1. How an individual's characteristics affect his/her survival probability (micro-level)?

2. How the system dynamics (e.g., environment, hazard, or intervention) affect the likelihood of survival rate (macro-level)?

To address these questions, EVAQ considers four principal factors of an emergency evacuation, all of which influence the fate of evacuees, namely:

(a) Layout of the affected environment (e.g., building plan, exit layout) and building materials (e.g., fire resistance rates).
(b) Dynamics of the hazard (e.g., hazard type, propagation speed, and pattern).
(c) Dynamics of potential intervention (e.g., repellent type, effectiveness).
(d) Evacuees' personal (e.g., age, gender, disability) and interpersonal a.k.a., behavioral (e.g., interaction among involved individuals) characteristics.

Accordingly, the architecture of EVAQ consists of four main modules, namely:

1. Environment module (for modeling building plan, exit layout, and construction materials).
2. Hazard module (for modeling hazard propagation and ramification).
3. Intervention module (for modeling repellents and their interaction with the hazard).
4. Agent module (for modeling personal and interpersonal characteristics of evacuees', and their exit strategies).

Multiple fire-affected scenarios are modeled as proof-of-concept examples to develop and demonstrate the skeleton and implementation of EVAQ. In addition to the fire hazard, this research also investigates the evacuation process in the presence of hazards with random movement patterns to imitate social disturbance (e.g., knife stabber, lone wolf attacker, random shooter).

1.3 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 fire safety design assessment and safe egress analysis (Ronchi, & Nilsson, 2013). Previously, researchers categorized existing evacuation models based on modeling principles (Gwynne, Galea, Owen, Lawrence, & Filippidis, 1999), methodological approaches (Zheng et al., 2009), occupant movement, their behavior, route choice, user availability, validation procedure and so on (Kuligowski, Peacock, & Hoskins, 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, Ren, & Zhou, 2003; Yuan, Fang, Wang, Lo, & Wang, 2009). On the other hand, *simulation models* try to realistically represent the occupant's exit strategy considering their unique characteristics with acceptable quantitative results (Fahy, 1999; Owen, Galea, & Lawrence, 1996; Thompson, Lindstrom, Ohlsson, & Thompson, 2003). Additionally, *risk assessment models* quantify risks associated with safe egress of occupants from a hazard-affected environment (Fraser-Mitchell, 1994; Shestopal & Grubits, 1994).

According to the methodological approaches, evacuation models can be classified into macroscopic and microscopic 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 & Schadschneider, 2002; Wei, Song, Lv, Liu, & Fu, 2014), *multi-lattice models* (Guo & Huang, 2008; Guo, Chen, You, & Wei, 2013), *social force models* (Yang, Dong, Wang, Chen, & Hu, 2014), *agent-based models* (Bonabeau, 2002; Goldstone, & Janssen, 2005), and *game theory models* (Lo, Huang, Wang, & Yuen, 2006). *Macroscopic models*, on the other hand, model pedestrian dynamics similar to a body of fluid, thus ignoring individuals' distinctive behaviors during evacuation (Guo, Huang, & Wong, 2011; Lee, 2012). Given the complex nature of crowd behavior, researchers have 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, Kokubo, & Nishinari, 2007) or social force approach (Yang, Zhao, Li, & Fang, 2005; Wei-Guo, Yan-Fei, Bing-Hong, & Wei-Cheng, 2006), lattice gas model based on social force (Song, Xu, Wang, & Ni, 2006), ABMs in combination with cellular automata (Bandini, Federici, Manzoni, & Vizzari, 2005; Toyama, Bazzan, & Da Silva, 2006) or social force (Braun, Bodmann, & Musse, 2005; Pelechano, Allbeck, & Badler, 2007).

Kuligowski et al. (2010) reviewed 25 computational tools and classified them based on different features such as occupant movements and their behaviors, public availability, modeling method, and validation scheme. Table 1 and Table 2 summarize such classifications and corresponding features.

Table 1: Categorization of simulation tools based on availability, structure, perspective and validation scheme.

Simulation Tools	Public Availability	Grid/Structure	Model Perspective	Validation Scheme
ASERI (Schneider, 2001)	Free or with a fee	Continuous network	Microscopic	Past literature
ALLSAFE (Heskestad & Meland, 1998)	Consultancy basis	Coarse network	Macroscopic	Other models
BldEXO (Gwynne et al., 1999)	Free or with a fee	Fine network	Microscopic	Fire drills
CRISP (Fraser-Mitchell, 1994)	Consultancy basis	Fine network	Microscopic	Fire drills
EVACNET4 (Francis & Saunders, 1979)	Free or with a fee	Coarse network	Macroscopic	Fire drills
EGRESS 2002 (Ketchell et al., 2002)	Consultancy basis	Fine network	Microscopic	Fire drills
EXIT89 (Fahy, 1999)	Not released yet	Coarse network	Microscopic	Fire drills
EvacuatioNZ (Ko, Spearpoint, & Teo, 2007)	Not released yet	Coarse network	Microscopic	Past literature
EPT (Harmon & Joseph, 2011)	Consultancy basis	Fine network	Microscopic	Fire drills
FDS+Evac (Heliövaara, 2007)	Free or with a fee	Continuous network	Microscopic	Other models
GridFlow (Bensilum & Purser, 2003)	Free or with a fee	Continuous network	Microscopic	Past literature
Legion (Kagarlis, 2008)	Consultancy basis	Continuous network	Microscopic	Code
Myriad II (Still, 2007)	Consultancy basis	Continuous network	Microscopic	Past literature
MassMotion (Morrow, 2010)	Consultancy basis	Continuous network	Microscopic	Code
MASSEgress (Pan, 2006)	Not released yet	Continuous network	Microscopic	Past literature
PathFinder (Thornton et al., 2011)	Consultancy basis	Fine network	Microscopic	Code
PEDROUTE (Daly, McGrath, & Annesley, 1991)	Free or with a fee	Coarse network	Macroscopic	No validation
PEDFLOW (Helbing & Molnar, 1995)	Free or with a fee	Continuous network	Microscopic	Past literature
PedGo (Klüpfel, 2007)	Consultancy basis	Fine network	Microscopic	Fire drills
STEPS (MacDonald, 2003)	Free or with a fee	Fine network	Microscopic	Code
Simulex (Thompson & Marchant, 1995)	Free or with a fee	Continuous network	Microscopic	Fire drills
SimWalk (Steiner, 2007)	Free or with a fee	Continuous network	Microscopic	Fire drills
SpaceSensor (Sun & de Vries, 2009)	Free or with a fee	Continuous network	Microscopic	Other models
SGEM (Lo & Fang, 2000)	Consultancy basis	Continuous network	Microscopic	Other models
WAYOUT (Shestopal & Grubits, 1994)	Free or with a fee	Coarse network	Macroscopic	Fire drills

Table 2: Categorization of simulation tools based on fire model, occupant movement and behavior, and modeling method.

Simulation Tools	Fire Model	Occupant Movement	Occupant Behavior	Modeling Method
ASERI	Yes	Inter-person distance	Conditional	Behavioral model with risk assessment capabilities
ALLSAFE	Yes	Unimpeded flow	Implicit	Partial behavioral model
BldEXO	Yes	Conditional	Conditional	Behavioral model
CRISP	Yes	Conditional	Conditional	Behavioral model with risk assessment capabilities
EVACNET4	No	User's choice	No	Movement/optimization model
EGRESS 2002	Yes	Based on space density	Conditional	Behavioral model
EXIT89	Yes	Based on space density	Conditional	Partial behavioral model
EvacuatioNZ	Yes	User's choice	Conditional	Behavioral model
EPT	Yes	User's choice	Conditional	Behavioral model
FDS+Evac	Yes	Inter-person distance	Conditional	Partial behavioral model
GridFlow	No	Based on space density	Implicit	Partial behavioral model
Legion	Yes	Inter-person distance	Conditional	Behavioral model
Myriad II	Yes	Based on space density	Conditional	Behavioral model
MassMotion	No	Conditional	Conditional	Behavioral model
MASSEgress	No	Conditional	Conditional	Behavioral model
PathFinder	No	Inter-person distance	No	Movement model
PEDROUTE	No	Based on space density	Implicit	Partial behavioral model
PEDFLOW	Yes	Inter-person distance	Conditional	Behavioral model
PedGo	Yes	Conditional	Conditional	Behavioral model
STEPS	Yes	Conditional	Conditional	Behavioral model
Simulex	No	Inter-person distance	Implicit	Partial behavioral model
SimWalk	No	Follow a potential map	Conditional	Partial behavioral model
SpaceSensor	No	Conditional	Conditional	Behavioral model
SGEM	No	Based on space density	Implicit	Partial behavioral model
WAYOUT	No	Based on space density	No	Movement model

Considering the parameters listed in Tables 1 and 2 EVAQ can be positioned in the context of computational tools for egress analysis as a fine-grid microscopic network capable of modeling hazards (e.g., fire) and occupant movements and behaviors. In particular, the floor plan in EVAQ is divided into an array of small grid cells (0.5m×0.5m), creating a fine-grid network model. EVAQ is a microscopic simulation environment as it simulates evacuees' movement throughout the evacuation process and can give information about each person at any point in time. Moreover, EVAQ incorporates fire model, and occupants' movements depend on the availability (i.e., emptiness) of the surrounding cells and the conditions (e.g., hazard type, propagation speed, and pattern) of the hazard-affected environment. Therefore, EVAQ models allow the incorporation of evacuees' conditional behaviors. EVAQ is a partial behavioral model as it primarily simulates evacuees' movement strategies considering the different combinations (e.g., age, gender, disability, group interaction) of agent behaviors. Last but not least, EVAQ is verified and validated using previous literature and results are compared to those of other simulation models. It must be noted that as described in this Thesis, EVAQ offers unique features such as modeling of hazard intervention systems and random-walking hazards which makes it an ideal platform for simulating large crowd evacuations in a variety of scenarios.

It must be noted that most of the simulation tools listed in Table 1 and 2 are only available commercially or through consultation services. Besides, ambiguities in model development and limited availability of open source 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. Specifically, no literature was found on simulating the effect of an intervention system in evacuation from a hazard-affected environment. Lastly, some evacuation simulation models (e.g., EVACNET4, MASSEgress, Simulex) are unable to the propagation of hazards in a deteriorating environment and its impact on egress route selection and movement drifts.

1.4 Organization of the Thesis

The thesis is organized as follows:

- Section 2 documents the EVAQ framework development in Python programming language. Detailed information and explanation of the structure of the framework are presented including concepts or algorithms used for modeling hazard propagation, repellent propagation, and evacuees' exit strategy selection and execution in a dynamic (i.e., hazard-affected) environment.
- Section 3 demonstrates the steps followed to verify and validate EVAQ using a series of standardized test methods and datasets suggested by NIST. V&V experiments are performed to benchmark the performance of EVAQ and evaluate its applicability to performance-based building design and analysis.
- Section 4 presents the implementation of EVAQ to model the impact of key factors (e.g., human characteristics, environmental constraints, hazard and intervention systems) on the likelihood of survival in an emergency evacuation. Two specific

scenarios for crowd egress planning in a fire emergency, namely an airport terminal and a shopping mall are presented, and results are discussed.

- Section 5 summarizes the research contributions and presents the future direction of the research.
- Appendix A presents the flowchart of the key steps of the simulation process in EVAQ with pseudo-code for each of the model components (i.e., hazard, intervention, agent) to facilitate the discussion of the flowchart.

2 EGRESS FRAMEWORK: EVAQ

2.1 Introduction

In this Section, the skeleton of EVAQ is described. EVAQ has been developed using the Python programming language. The following Subsections contain detailed information and explanation of the structure of the framework, as well as concepts or algorithms used for modeling hazard propagation, repellent propagation, and evacuees' exit strategy and execution in a dynamic (i.e., hazard-affected) environment.

2.2 Framework Architecture

Figure 2 depicts the architecture of EVAQ, which consists of four key modules, namely the *Environment* module, *Hazard* module, *Intervention* module, and *Agent* module. All modules interact with each other via the *Simulation Engine*. The generated results are animated or visualized through the *Visualizer*.

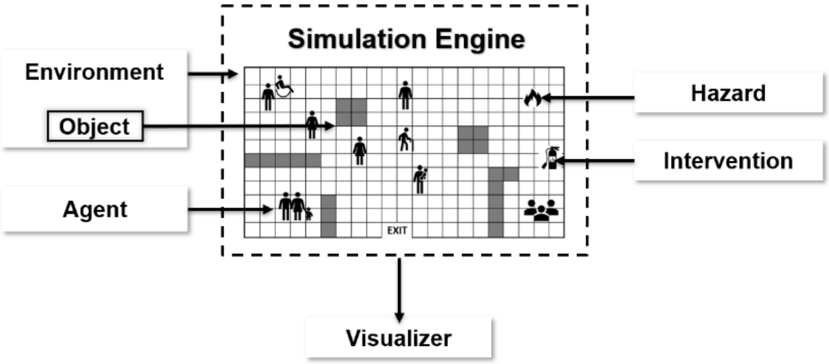


Figure 2: Architecture of EVAQ framework.

(a) 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, where each cell can accommodate one person. 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 *Environment* module also contains a sub-module named *Object* to model the material types of different objects (e.g., wall or ceiling finishes) in the environment, particularly their fire resistance properties (Milke, Kodur, & Marrion, 2002).

(b) 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 direction, initiation time, speed, and deceleration over time. The current implementation of EVAQ allows for multiple hazards, each with its distinct characteristics.

(c) The *Intervention* module initiates fire repellents (i.e., sprinkler system, fire extinguisher) by specifying their position in the environment. It models different repellent characteristics such as initiation time, lifetime, as well as propagation pattern, direction, speed, and deceleration over time. The current implementation of EVAQ allows multiple repellents, each with its distinct characteristics.

(d) The *Agent* module generates individual persons and distributes them in the grid to represent a crowd. Each person is defined using a set of attributes such as age (child, adult, elderly), gender (female, male), and physical trait (disabled, able). The current implementation of EVAQ also supports group formation (e.g., friends or family members who stick together during evacuation). Group members select the same egress route and exit for evacuation. This module models the exit strategy of evacuees using a variant of the BFS Algorithm (Leiserson & Schardl, 2010).

(e) The *Simulation Engine* is a key module of EVAQ architecture that controls the interaction of all four modules described above. The simulation starts with the user input describing the initial state of the hazard-affected environment, occupant distribution and their attributes, as well as repellent positions. The user input is stored in the environment_state matrix. Next, agents, hazards, and repellents interact with each other following basic interaction procedures, and their positions are updated in an iterative loop. The simulation loop is terminated once the fate (death or survival) of all agents is determined. The flowchart of the overall simulation process and pseudo-code for each component of EVAQ is presented in Appendix A.

(f) The *Visualizer* module is programmed in MATLAB. This main function of this module is to generate animations of the simulated evacuation process to facilitate the communication of simulation results. It receives the position of agents, hazards, and repellent in each simulation time step and creates a color-coded animation.

2.3 Module 1: Environment

The *Environment* module discretizes a building floor plan into cells. To quantify cell size, the average human shoulder-to-shoulder width (0.5m) is considered. This assumption also supports the fact that human shoulder width is a major factor in the design of doorways or stairways (Still, 2000). The submodule *Object* represents different building material types according to their flame spread ratings (Hurley et al., 2015). The flame spread rating of the objects (e.g., walls, furniture) captured through this submodule determines how long it takes for a fire to consume those objects and propagate to the next cell. In the current implementation of EVAQ, the *Environment* module stores the user input of the physical environment in the environment_state matrix. Although user input is the preferred method for configuring the physical environment, it is also possible to generate environment_state matrix using a random generator in Python.

Figure 3 shows an example of a shopping mall where the floor layout is discretized into square cells to create the environment for EVAQ simulation. The dimensions of the floor in this Figure are 15m wide by 35m long, which is divided into a 30×70 grid containing 2,100 cells each being 0.5m×0.5m. There are 7 exits, including 3 regular and 4 accessible exits. An accessible exit is primarily intended for disabled agents. As a general rule, while disabled people cannot use regular exits, able people can use accessible exits. Cells marked as exits (either regular or accessible) are considered as the final destinations for people trapped in a hazard-affected environment, and as such, the egress strategy of each evacuee 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 also referred to as exit capacity. For this specific test case, some exits are 3-cells wide (1.5m), that means each can accept at most three people at the same time. Initially, the mall is populated with 200 people with ID numbers from 101 to 200. Each cell within the grid is marked 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).

2 = Cell is a regular exit.

3 = Cell is an accessible exit.

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 this cell.

52 = Class B material for object in this cell.

53 = Class C material for object in this cell.

>101 = Cell is occupied by a person whose ID is the same as the marked integer.

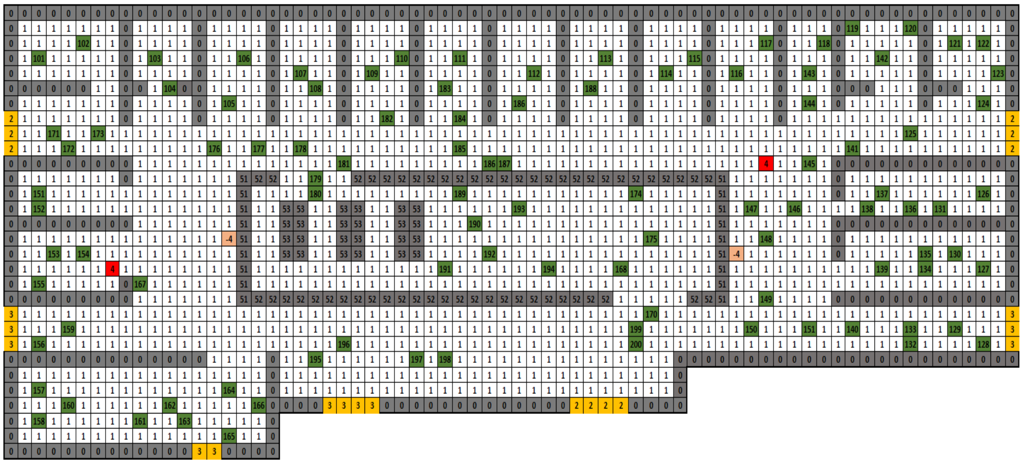


Figure 3: Initial grid layout of a shopping mall floor plan for evacuation simulation.

2.3.1 Time and space granularity

Time and space granularity plays a pivotal role in designing a simulation framework (Guo, Hu, & Wang, 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. For example, if an agent's real velocity is 1.5 m/s in normal condition, and the space granularity is represented as the cell dimension (e.g., 0.5m), then the agent takes 0.33s to move from her current cell to an adjacent cell. Under this condition, if simulation time granularity is chosen as 0.11s, then the same agent will take three SS to complete this move. In EVAQ, time granularity is specified such that all event times including agent 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., agent, hazard) does not move more than one cell in any given simulation time step; however, an entity can move one cell in several time steps This is consistent with the previous notion of time granularity. To avoid precision loss (and capture all movements of hazards and people), in the current implementation of the simulation framework, time granularity is chosen as, 1SS = 0.25s and space granularity as, 1 cell = 0.5mx0.5m. If the speed of three agents, for example, is given as 2 m/s, 1 m/s, and 0.67 m/s, then according to the conversation rule,

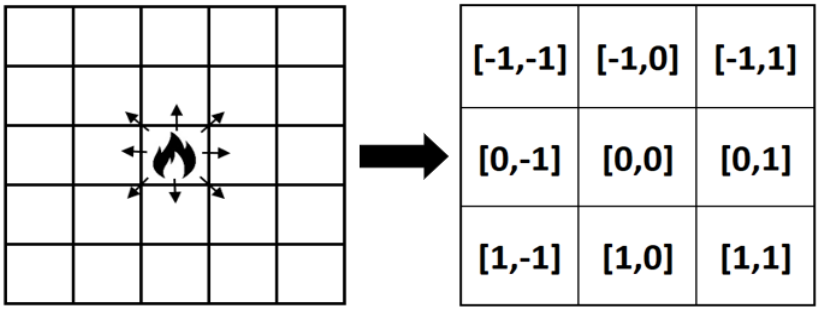
2 m/s = 2 meter per 1 sec = 0.5 meter per 0.25 sec = 1 cell per 1 SS.

1 m/s = 1 meter per 1sec = 0.5 meter per 0.5 sec = 1 cell per 2 SS.

0.67 m/s = 0.67 meter per 1 sec = 0.5 meter per 0.75 sec = 1 cell per 3 SS.

2.4 Module 2: Hazard

The current implementation of EVAQ supports hazard propagation with time, and thus fulfills the requirement of dynamic constraint modeling. 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 Figure 4. At present, EVAQ allows two types of hazard modeling, namely fire and random attacker as discussed in the following Subsections.



[-1,-1]	[-1,0]	[-1,1]
[0,-1]	[0,0]	[0,1]
[1,-1]	[1,0]	[1,1]

Figure 4: Adjacency of a fire hazard cell.

2.4.1 Fire propagation model

Fire spreads to other objects either by radiation or through the smoke layer consumed in the upper portion of the environment (Milke et al., 2002). As new objects ignite, the temperature of the smoke layer increases causing more heat to be radiated to surrounding objects. In a small space, unburned objects ignite almost simultaneously; the phenomenon commonly referred to as *flashover* (Milke et al., 2002). However, for large environments, it is more likely that objects will ignite sequentially. The sequence of the ignition depends on the fuel arrangement, and composition and ventilation available to support combustion of available fuels (Hurley et al., 2015). Currently, a forest-fire inspired model (Bak, Chen, & Tang, 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. The parameter t_H represents the pace of fire spread, which follows the conversion of time and space granularity described in Subsection 2.3.1. In EVAQ, 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. Generally speaking, a smaller t_H means a faster spread of fire and vice versa. For example, for $t_H = 10$, the fire propagates to its adjacent cells at every 10SS (i.e., 10SS, 20SS, 30SS, 40SS, …) which indicates a slower pace than the fire with $t_H = 5$.

Using this criterion, fire is modeled to propagate from its initial position in either symmetrical or directional pattern. As shown in Figure 5, in symmetrical propagation (case 0), fire propagates to all of its adjacent cells. In directional propagation (cases 1 through 8), fire consumes a certain portion of its adjacent cells depending on the direction of spread (i.e., upward, downward, left, right, up-left, up-right, down-left, and down-right). In particular, each fire-affected cell propagates only to its three adjacent cells in upward, downward, left, and right patterns of fire propagation, and to its two adjacent cells for the remaining directional propagation patterns at t_H multiples. In Figure 5, for each fire propagation pattern (cases 0 through 9), three-time steps are demonstrated which include the initiation point at time 0 (left grid in each scenario), first step in propagation at time t_H

(middle grid in each scenario), and second step of propagation at time $2t_H$ (right grid in each scenario). The area affected by fire after each step of the propagation is termed *blockage area.* The designed simulation framework supports the inclusion of several hazards in different directions within the same environment, a feature that is largely missing in many existing frameworks (Tang & Ren, 2008; Guo et al., 2013; Nguyen, Ho, & Zucker, 2013). The pseudo-code for hazard propagation process in EVAQ is presented in Appendix A.

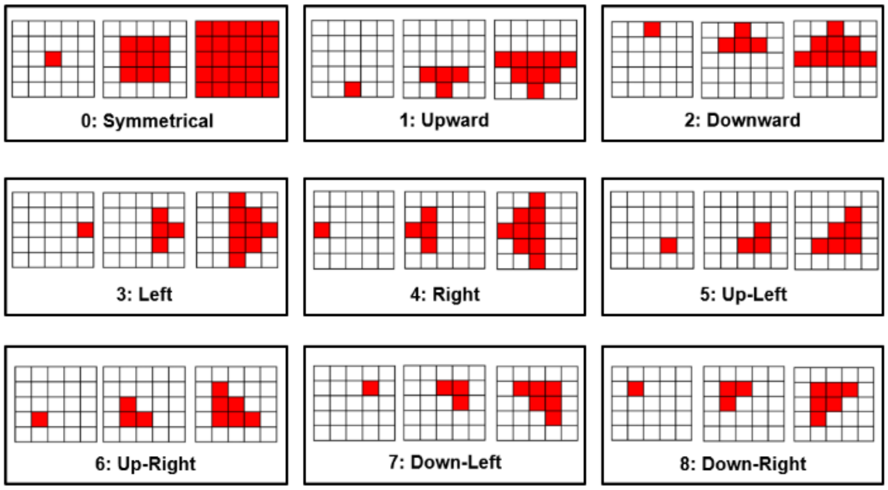


Figure 5: Symmetrical and directional fire propagation at times 0, t_H, and $2t_H$.

2.4.2 Fire propagation in reality

In reality, fire does not propagate at a constant speed. Fuel properties, fuel quantity, ventilation (natural or mechanical), compartment geometry (volume and ceiling height), the location of the fire, and ambient conditions (e.g., temperature, air flow) are some major contributing factors to fire development and spread in any environment (Hurley, 2015).

The classic fire development curve (NIST, 2010) in Figure 6 shows that fire growth is not limited by a lack of oxygen; rather, energy level (or temperature) continues to increase until all available fuel is consumed (fully developed). At this stage, as the fuel is burned away, the energy level begins to decay, and fire decreases in size and continues to propagate at a lower speed until full decay. The key to this fire development model is that oxygen is available at all times to generate the energy (or temperature) and the speed of fire propagation gradually decreases with time after the ignition.

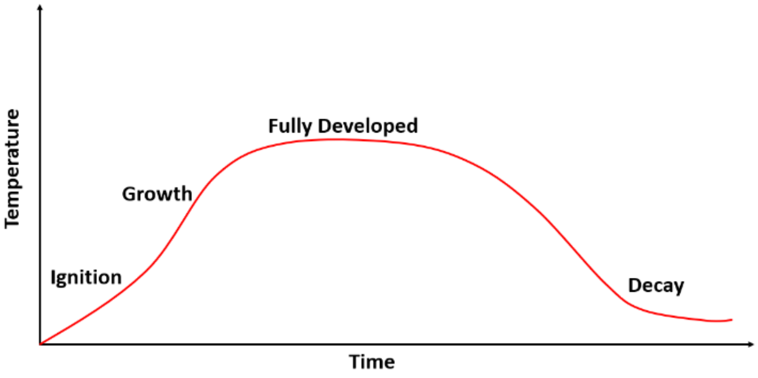


Figure 6: Classic fire development curve.

In EVAQ, in order to incorporate variation in propagation time, two more attributes are to the fire model, namely maximum fire propagation time and fire deceleration rate. These two variables capture the full spectrum of time-dependent propagation of fire, similar to what is shown in Figure 6. In this research, maximum fire propagation time is considered 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. The described attributes of fire propagation thus provide maximum flexibility to users when simulating different fire-affected environments. In EVAQ, all fire attributes are linked to the hazard position and stored in the 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, `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, as shown in the Figure 7. Accordingly, new cell descriptors are created for the position (3, 1) and (2, 2). These new cell descriptors inherit the properties of the source cell (i.e., they have the same propagation time, direction, deceleration rate, maximum fire propagation time). Fire propagation time increases by one at every two steps of propagation (as deceleration rate coded as 2) until it reaches to maximum fire propagation time (coded as 7). As shown in Figure 7, a 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), and it increases to $t_H = 6$ in the next two steps (16SS, 22SS), and finally, $t_H = 7$ (29SS, 36SS, 43SS, …) as the fire reaches its maximum propagation time or decay phase.

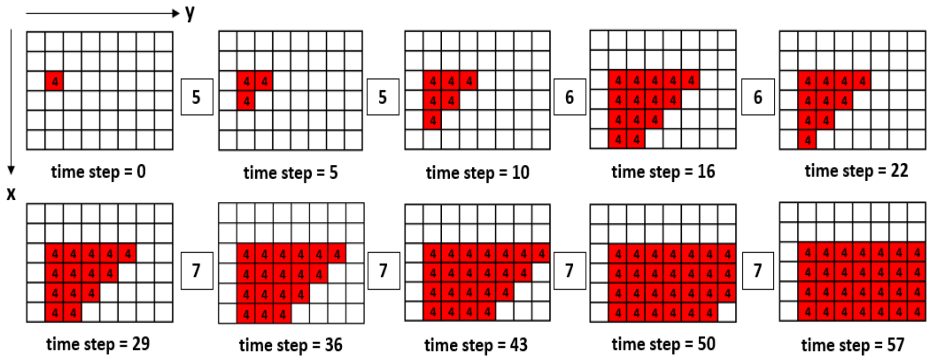


Figure 7: Schematic representation of a sample directional propagation of fire hazard.

2.4.3 Hazard-environment interaction

The International Building Code (IBC) categorizes interior walls and ceiling finishes into three classes according to the flame spread index from 0 to 200 (Hurley et al., 2015). These classes are:

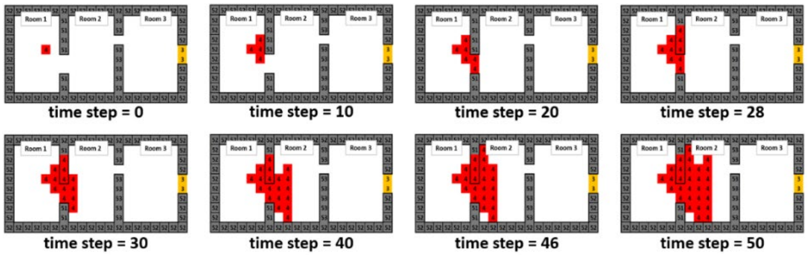
Class A (0-25): inorganic materials (e.g., brick, gypsum wallboard).

Class B (26-75): whole-wood materials (e.g., cedar, hemlock).

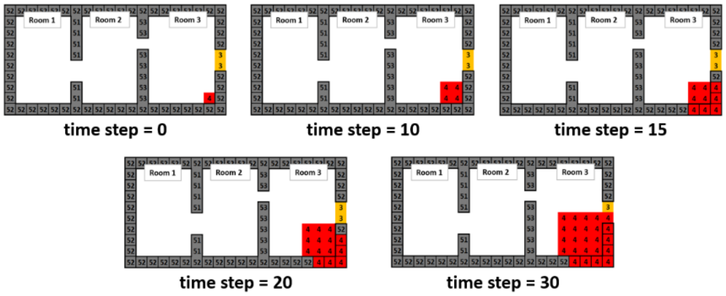
Class C (76-200): reconstituted wood materials (e.g., plywood, fiberboard).

The flame spread index determines the extent of the fire-retardant property of building materials. The lower the index value, the higher the control against the spread of fire in the environment. Almost all new buildings must follow safety regulations to restrict the rate of fire spread. For example, finishes in vertical exit ways or corridors leading to exits should have a lower index value than the finishes in the living room (Hurley et al., 2015).

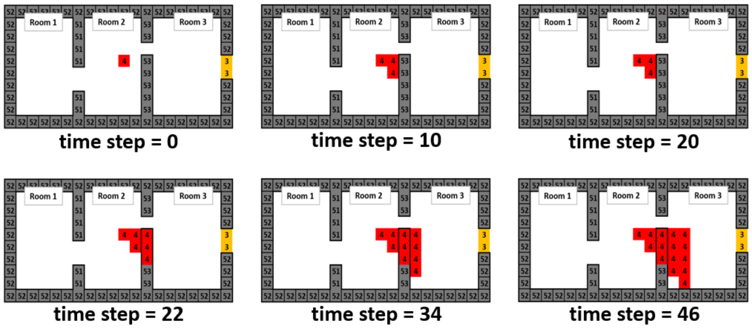
In EVAQ, the *Object* submodule in the *Environment* module encapsulates these three types of materials (cells marked as 51, 52, 53 in the environment). In particular, fire propagation time increases by 8, 5, and 2 for cells marked as 51, 52, and 53 respectively. This means that when the fire reaches cells marked as 51, 52, or 53, these cells act similar to a repellent to fire propagation. A schematic representation of a hazard-environment interaction is illustrated in Figure 8, where a 20×10 environment with two divider wall in the center is modeled, separating the space into three rooms. For this space, Class A (marked as 51) and Class C (marked as 53) materials are used for the interior wall finish, whereas Class B (marked as 52) material is used for the exterior wall finish. If fire propagation time is taken as $t_H = 10$, fire initiates at its ignition position (marked as 4) in room 1, 2 and 3 at 10SS, and generally continues to propagate at 20SS, 30SS, 40SS, 50SS, and so on. In Figure 8(a) the fire spread is temporarily blocked (delayed by 8SS) in part due to the presence of cells marked as 51 (divider wall). After 10SS fire propagates to Class A cells at 28SS (10+8) and adjacent to Class A cells at 46SS in the right direction. Similarly, in Figure 8(b) fire spread is temporarily blocked (delayed by 2SS) in part due to the presence of cells marked as 53 (divider wall). After 10SS fire propagates to Class C cells at 22SS (10+2), instead of propagating at 20SS. For this case, the fire continues to be propagating down-right direction at 34SS, 46SS, and so on. Finally, in Figure 8(c) fire spread is temporarily blocked (delayed by 5SS) in part due to the presence of cells marked as 52 (exterior wall). After 10SS fire propagates to Class B cells at 15SS (10+5), instead of propagating at 20SS. For this case, the fire continues to be propagating symmetrically at 30SS to the adjacent cells of Class B cells.



(a) Fire propagation delayed by 8SS due to Class A material.



(b) Fire propagation delayed by 5SS due to Class B material.



(c) Fire propagation delayed by 2SS due to Class C material.

Figure 8: Schematic representation of hazard-environment interaction.

2.4.4 Human threat movement model

In the current implementation of EVAQ, two types of human threat movement patterns are modeled. This allows for maximum flexibility in describing life-threatening situations involving lone wolf attackers (e.g., suspect carrying a knife, shooter wandering in a crowded area).

In the first model, the attacker is assumed to not follow any predictable movement pattern, rather randomly moving in the environment. In EVAQ, such pattern is referred to as "random walk" model. To model random walk, an attacker is initiated using a starting position (cell) and a movement time t_H. At every multiple of t_H, the attacker moves from its current cell to any one of the eight adjacent cells randomly without following any pattern. Here, cell adjacency is defined similar to Figure 4. This random movement continues until the fate (i.e., death or survival) of all people in the environment is determined. A schematic representation of a random-walking hazard (attacker) is illustrated in Figure 9.

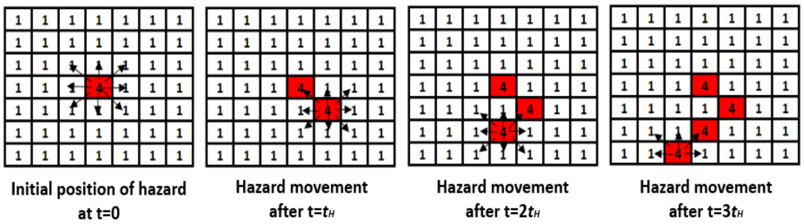


Figure 9: Schematic representation of random hazard movement.

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 initiated by a starting position (cell) and a movement time

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

2.5 Module 3: Intervention

An added modeling feature that distinguishes EVAQ from its predecessors and creates a more realistic output is the ability to incorporate intervention systems (e.g., fire extinguisher, sprinklers). The following Subsections describe the propagation models of repellent materials in more details.

2.5.1 Repellents to fire hazard

Air, heat, and fuel are the three major components of fire generation in any environment (Hurley et al., 2015). Therefore, any fire-fighting technique should involve removing any or a combination of these elements from the environment. Fire extinguisher and sprinkler systems are two widely used repellent mechanisms for fire hazards. There are primarily three types of fire extinguisher systems, namely *water extinguisher* that cools down the environment by removing heat from the fire, and *dry chemical extinguisher* and *carbon dioxide extinguisher* prevent fire (Schmidt, 1974). In buildings, fire extinguishers are often installed in hallways or passageways or by the side of stairs. Home fire sprinklers, on the other hand, include a network of piping filled with water under pressure installed behind the walls and ceilings (Alpert & Ward, 1984). If a fire breaks out, the air temperature above the fire rises (Cao, Song, Liu, & Mu, 2014), and higher air temperature activates the sprinkler (Hoffmann & Galea, 1993). Consequently, the sprinkler sprays water forcefully over the flames, extinguishing them entirely in most cases, or at least controlling the heat and advancement of harmful smoke material. It must be noted that only the sprinkler nearest to the fire activates with an increase in the air temperature. Home fire sprinklers discharge roughly 10-25 gallons of water per minute and it continues until the time firefighters arrive and shut down the system manually (Hurley, 2015).

2.5.2 Repellents propagation modeling

In the current implementation of EVAQ, fire extinguisher chemical is modeled such that it propagates toward the direction of approaching the fire, while the water sprayed from a sprinkler system can propagate in both symmetrical and directional patterns. As shown in Figure 10, possible patterns of repellent propagation (symmetrical or directional) resemble the fire propagation patterns introduced in Subsection 2.4.1 and depicted in Figure 5.

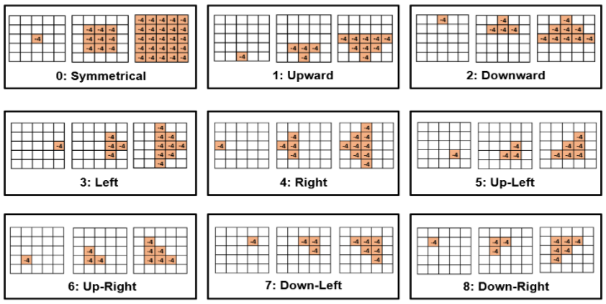

0: Symmetrical
1: Upward
2: Downward
3: Left
4: Right
5: Up-Left
6: Up-Right
7: Down-Left
8: Down-Right

Figure 10: Symmetrical and directional repellent propagation at times 0, t_H, and $2t_H$.

All key attributes of a given repellent such as its effectiveness and the variation of its propagation time are stored and updated in repellent_position_descriptors 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 will remain active in the environment following its initiation. The pseudo-code for repellent propagation process in EVAQ is presented in Appendix A.

2.5.3 Repellent-hazard interaction

For a better understanding of the interaction between repellent and hazard, the scenario illustrated in Figure 11 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). 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). A schematic representation of this symmetrical repellent propagation is illustrated in Figure 11, where cells coded as 4 represent fire (t_H = 4; considering a constant fire propagation time), and cells coded as -4 represent repellent. The pseudo-code for repellent-hazard interaction process in EVAQ is presented in Appendix A.

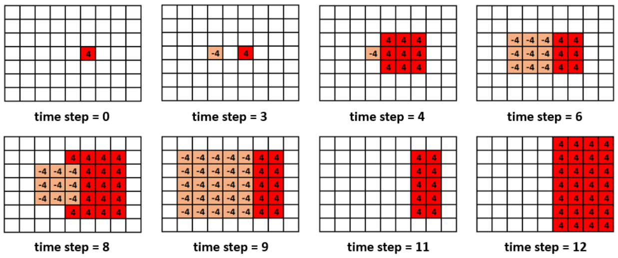


Figure 11: Implementation of repellent propagation in a hazard-affected environment.

2.5.4 Targeted repellent movement model

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 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 EVAQ, the targeted repellent movement is presented by modeling the bi-directional flow of agents. Specifically, two agents with different goals can create an adversarial pair enabling them to move toward each other. Figure 12 shows an attacker (marked as 4) moving in the right direction while a repellent (i.e., law enforcement officials 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 Figure 12 targeted repellent is considered to take 1SS to move from one cell to another in the direction of the hazard.

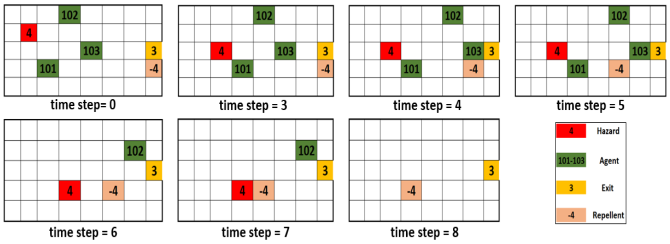


Figure 12: Targeted repellent movement in a hazard-affected environment.

2.6 Module 4: Agent

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. The following Subsections demonstrate the contributing factors and algorithmic approach to evacuee’s movements, as well as explain potential interactions between hazard, repellent, and agent modules.

2.6.1 Evacuee’s personal characteristics

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 the age distribution, children are considered as less than 12 years old, and elderly people are considered as more than 65 years (Shi et al., 2009). In a static environment (no hazards present), the goal of each person is to pick the nearest exit considering his/her attributes that collectively define his/her velocity.

Table **3** shows the parameters (mean, standard deviation) of normally distributed velocity for different agent types.

Table 3: Velocity distribution of different agent class.

Agent 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

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 (Subsection 2.3.1) to calculate the simulation time steps taken by each evacuee to move from one cell to the next. In the current implementation of EVAQ, these physical characteristics are defined by the user and stored in a designated text file named agent_characteristics. The simulation engine reads this file and generates the time steps corresponding to the movements of each person in the environment, in order to simulate the evacuation process.

2.6.2 Evacuee's interpersonal characteristics

Agent-agent interaction is one of the most crucial in crowd evacuation planning and emergency mapping (Lo et al., 2006; Li & Qin, 2012; Tan, Hu, & Lin, 2015). For example, friends or family members mostly stick together and take the same path during evacuation, or follow a leader (a.k.a., leader-follower behavior) (Ji, & Gao, 2006), some people help others who need help, for example, a child, or a disable person (a.k.a., altruistic behavior) (Pan, Han, Dauber, & Law, 2007). Sometimes, lack of situational awareness creates a tendency in an individual to follow a group of people who are at a closer 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 follows,

(a) Group I for *leader-follower behavior*: when a group of people (three or more) is uncertain about their exit plan, a leader emerges out of 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.

(b) 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.

(c) Group III for *herding behavior*: when an evacuee is not fully affiliated with the environment, or uninformed about possible exit positions, then s/he moves toward the nearest group of people. Such a person identifies the target group by first calculating (in the real world, eyeballing) his/her distance 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, Klüpfel, Nishinari, Schadschneider, & Schreckenberg, 2003), whereas sometimes, they take the exit in an orderly fashion (a.k.a., queuing behavior) (Bo, Cheng, Hua, & Lijun, 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 agent position in front of the exit and is solved pursuing either queuing or competitive behavior. The pseudo-code for agent movement process (both individual and group) in EVAQ is presented in Appendix A.

2.6.3 Agent movement modeling: Breadth First Search algorithm

The current implementation of EVAQ supports agent 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., 1999; 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 BFS algorithm (Leiserson & 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). There are other search algorithms used for graph traversal problem as well, namely the DFS, Dijkstra, and A*. However, DFS is not suitable for identifying the shortest path in graph traversal problems as it may output a loop (Tarjan, 1972). Furthermore, A* is useful for weighted graphs (Dijkman, Dumas, & García-Bañuelos, 2009), whereas in EVAQ, the generated graph (i.e., grid system) is unweighted as all cells are equidistant. As a result, to solve the shortest path problem in an unweighted graph, BFS and Dijkstra are the two preferred choices (Yusoff, Ariffin, & Mohamed, 2008). However, in terms of time complexity BFS works best for unweighted graphs. This is because the time complexity of BFS is $O(V+E)$, where V is the number of nodes and E the number of edges. In comparison, the complexity for Dijkstra is $O(V+E \log V)$.

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 Figure 13). 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 marked with 1 (as shown in Figure 3) or agent IDs, as these cells can be occupied by evacuees (marked as white in Figure 13). Once a person moves from one cell to another, the first cell becomes unoccupied and the next one becomes occupied. In Figure 13, agent A moves from one cell to another avoiding occupied cells (marked as grey represents obstacle) 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 agents.

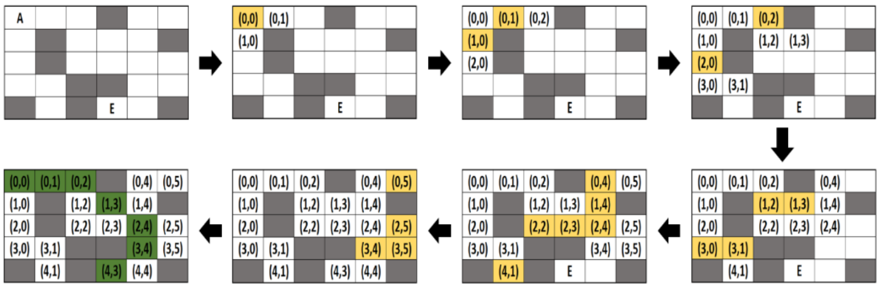


Figure 13: Systematic heterogenous agent movement process using the BFS algorithm.

2.6.4 Agent-fire-repellent interaction

For a better understanding of agent-fire-repellent interaction, a schematic representation of evacuees' movements based on dynamic decision-making is illustrated in Figure 14. In this Figure, a 10m×10m grid is shown in which the properties of the hazard cell (marked with 4) is defined by,

`hazard_position_descriptors` = {(4, 6): [0, 3, 3, 0]}.

This description implies that hazard propagation follows a symmetrical pattern, and the hazard propagates every 3SS (i.e., 3SS, 6SS, 9SS, 12SS, …). Similarly, repellent cell descriptors is defined as follows,

`repellent_position_descriptors` = {(6, 6): [1, 2, 2, 0, 2, 4]}.

This description implies that the repellent initiates at 2SS, and constantly propagates at 4SS, and 6SS (because repellent propagation time = 2). The repellent activates in the environment and restricts fire propagation for (2+4) or 6SS. Also, based on its description, this repellent propagates toward the top of the grid (upward direction). Finally, the repellent is terminated at 7SS.

Now, suppose that an evacuee, marked as 101 in Figure 14, who is a male, an able adult takes 2SS to move from one cell to the next. The evacuee's and the hazard's initial positions, as well the evacuee's initial optimal egress route (dashed line) to exit 2 is shown in 0SS. At 2SS, the evacuee moves one cell diagonally, and at 3SS, hazard propagates into the eight adjacent cells, which also affects the evacuee's initial optimal egress route. However, as repellent propagates upward at 4SS and retards the fire, the evacuee finds an opportunity to stick to his/her original egress plan. At 6SS, evacuee, repellent, and hazard positions are updated according to their properties. In particular, the evacuee moves one cell to the left, and the repellent propagates upward to the adjacent five cells. As the repellent keeps the fire hazard from propagating downwards until 6SS, fire can only propagate upwards. Thus, the evacuee can still stick to his/her initial egress route. At 9SS, fire propagates again, but prior to this propagation, at 8SS, the evacuee has already moved one more cell to the left. Finally, at 12SS, fire propagates one more time, which causes the evacuee to be trapped inside the hazard-affected area (a.k.a., blockage area).

In the current implementation of EVAQ, this evacuee is considered compromised, and his/her fate is determined (i.e., death). It must be noted that in reality, if a person is trapped inside the blockage area and there are no safe egress routes, s/he will wait for as long as possible for help to arrive. However, in this implementation, this behavior is not modeled, and rather, a trapped person is considered compromised and subsequently removed from the system. The pseudo-code for agent plan execution in presence of hazard and repellent is presented in Appendix A.

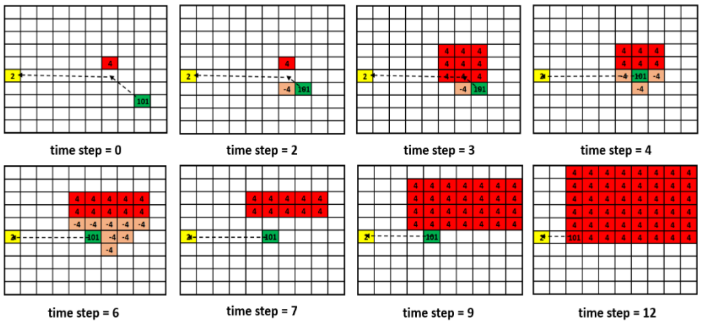


Figure 14: Evacuee egress route toward an exit in a hazard-affected environment in the presence of repellent.

2.6.5 Situational awareness of agent

Evidently, an evacuee's level of knowledge of the environment can influence his/her exit strategy selection and execution. In a fully observable environment, people have situational awareness as they are moving. In EVAQ, this is described by assigning the value of 1 to the crowd knowledge level, implying that evacuees do not inadvertently drift from their optimal egress routes (zero random movements) and they are fully affiliated with the environment (i.e., exit locations are known to them). In contrast, in a partially observable environment (e.g., limited visibility, smoke inhalation, excess heat, or being new to the environment), people may randomly move while trying to find the nearest exit. In EVAQ, this is described by assigning randomness (ranging from 0.1 to 1) to agent movements and lowering the crowd knowledge level until it approaches 0. At zero level of knowledge, evacuees do not possess any affiliation with the environment, thus making 100% random movements between unoccupied cells in their immediate vicinity.

In the current implementation of EVAQ, this is achieved by allowing agents to probabilistically choose their next move from one of the two options: (i) the next cell as identified by the optimal exit plan (this is the best possible move), (ii) the next cell will be randomly selected from all unoccupied adjacent cells based on a uniform distribution. In particular, a variable fate_control determines the extent of randomness in agent movement. Besides, another variable named drift_flag is also introduced and used to identify if an agent will (drift_flag = 1) or will not (drift_flag = 0) drift from their optimal exit plan. A fate_control= 0 implies a fully-observable environment (i.e., no randomness in the movement; drift_flag = 0). In contrast, a fate_control value ranging from 0.1 to 1.0 indicates partially observable environment (drift_flag = 1). For example, fate_control = 0.5 means that the environment is partially observable to agents and they have a 50% chance to take the best possible next move or take any random cell amongst the unoccupied cells in their surrounding neighborhood. If situation degrades, there could be 100% random movement that implies fate_control = 1. In this case, people take more time to evacuate the environment compared to when there is 0% random movement. It is also observed that more people would be compromised due to the increase in random movements.

2.7 Summary & Conclusions

In this Section, the architecture of EVAQ, an open-source person-specific large crowd evacuation simulation framework, was explained. EVAQ has been developed in Python and is capable of modeling key events of an evacuation process in a hazard-affected environment while incorporating information on attributes of involved individuals (i.e., evacuees). 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) agent module (for modeling personal and interpersonal characteristics of evacuees', and subsequent exit strategy). 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.

3 VERIFICATION AND VALIDATION

3.1 Introduction

ISO (2008) defines V&V as follows:

- Verification: "*the process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method*."
- Validation: "*the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method*."

The NIST presents a review of the current procedures, tests, and methods available in the existing literature to assess the V&V of building evacuation models (Ronchi, Kuligowski, Reneke, Peacock, & Nilsson, 2013). Although these guidelines were originally developed by IMO for maritime evacuation simulation tools, they are often employed for other application areas (e.g., buildings, transportation systems).

It must be noted that unlike other classes of simulation models, V&V of evacuation simulation models is not trivial since in the majority of cases, there is a lack of standardized testing procedures and real-world emergency evacuation datasets, causing modelers to adopt inconsistent procedures, or simply overlook this important step in simulation modeling (Ronchi et al., 2013). However, V&V is always required for accreditation of results, and for assessing the reliability of generated simulation output. Therefore, in this Section, the steps followed to verify and validate EVAQ using a number of NIST suggested test methods and datasets are discussed, in order to benchmark its performance and better evaluate its applicability to performance-based building design and analysis.

3.2 Verification Tests

The performance of EVAQ is assessed using a series of hypothetical tests suggested for the verification of evacuation models by NIST. These tests are organized according to five main core components of evacuation models (Ronchi et al., 2013), namely 1) pre-evacuation time, 2) movement and navigation, 3) exit usage, 4) route availability, and 5) flow conditions/constraints. These elements are required for the most basic representation of an evacuation scenario. The tests conducted for this purpose address different functionalities in EVAQ models, and a qualitative evaluation is performed by comparing EVAQ results (via observation of the model's visualization output) with the expected evacuees' behaviors in the real world. Besides, some quantitative evaluation is performed by considering the difference between the expected results and the simulation results. Table 4 presents the list of verification tests successfully conducted for EVAQ along with a comparison with Simulex (Kuligowski et al., 2010). It must be noted that while Simulex can simulate movements between floors (i.e., elevation change), the current implementation of EVAQ uses a 2D grid to model the environment, and as such, verification for 'speed on stairs' is out of the current scope of the framework. However, as previously stated, EVAQ can model dynamic environments (imitating real-world evacuation scenarios in the presence of hazards), while Simulex only considers static environments. This makes EVAQ an ideal candidate for the ‘dynamic availability of exit’ test. In the following Sub-sections, quantitative analyses of three verification tests (e.g., pre-evacuation time distribution, speed in the corridor, affiliation, and maximum flow rates) are presented.

Table 4: Verification tests for evacuation model.

Core Component	Sub-element Test	EVAQ	Simulex
1	Pre-evacuation time distribution	Y	Y
2	Speed in a corridor	Y	Y
	Speed on stairs	N	Y
	Movement around a corner	Y	Y
	Assigned demographics	Y	Y
	Reduced visibility vs. walking speed	Y	Y
	Occupant incapacitation	N	N
	Elevator usage	N	N
	Horizontal counter-flows (rooms)	Y	Y
	Group behaviors	Y	Y
	People with movement disabilities	Y	Y
3	Exit route allocation	Y	Y
	Social influence	Y	Y
	Affiliation	Y	Y
4	Dynamic availability of exit	Y	N
5	Congestion	Y	Y
	Maximum flow rates	Y	Y

3.2.1 Pre-evacuation time distribution

IMO test 5 is used to verify the ability of evacuation models to reproduce imposed pre-evacuation times. This test can also be used to verify distribution assignment in the simulation framework. The *pre-evacuation time* refers to the time window between the moment an alarm or cue is evident and when individuals start traveling to exit(s) to evacuate the place (Shi et al., 2009) and consists of recognition time and response time. The *recognition time* begins with an alarm or cue and ends with the first response. The *response time*, on the other hand, begins with first response until all individuals start traveling to the exit(s). The time required to reach an exit from the moment a person starts moving in the system is often referred to as the *movement time*.

Scenario: A room of size 8m by 5m with a 1m-wide exit located centrally on a 5m wall is modeled in EVAQ. A total of 10 occupants are randomly distributed in the room marked as 101-110, as shown in Figure 15. Occupants are assigned uniformly distributed pre-evacuation times ranging between 5s and 10s.

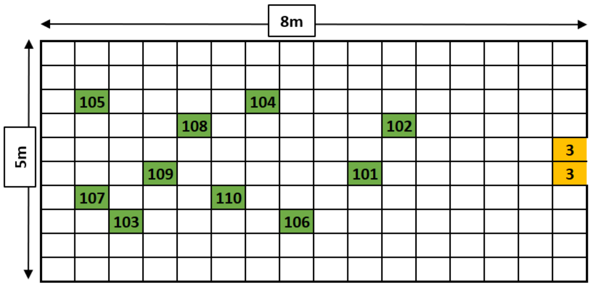


Figure 15: Geometric layout of pre-evacuation time distribution test.

Expected Result: Pre-evacuation time of each occupant should fall within the specified range. Total evacuation time can be represented as normally distributed over multiple simulation runs.

Simulation Result: The stacked bar chart in Figure 16 shows that the pre-evacuation time of each occupant falls within the range of 5s to 10s, thus affirming the expected results. In addition, after 100 simulation runs, the total evacuation time appears to be more or less normally distributed, as shown in Figure 17 with a mean value of 30.27s and a standard deviation of 10.9s, affirming the expected results.

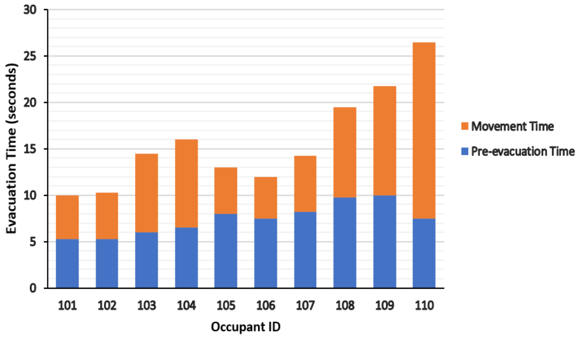


Figure 16: Evacuation time for each occupant.

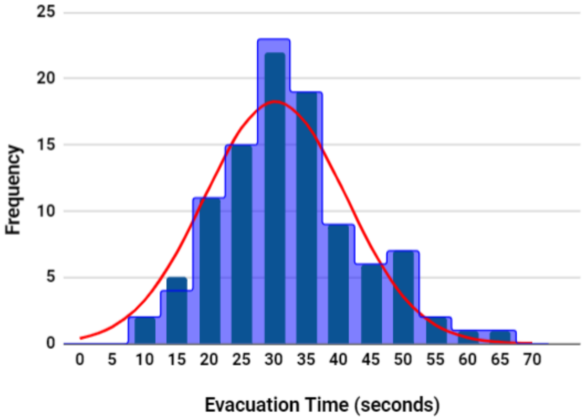


Figure 17: Distribution of evacuation time.

3.2.2 Speed in a corridor

IMO test 1 proposed is used to verify if an occupant can maintain his/her assigned velocity over the simulation time.

Scenario: A corridor of size 4m wide and 20m long is modeled in EVAQ with 4×40 grid cells. An occupant is assigned a speed of 1 m/s and walks along the corridor from one end to the other to reach an exit, as shown in Figure 18.

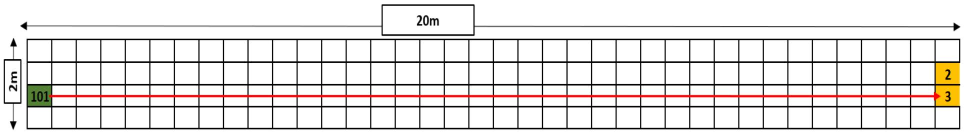


Figure 18: Geometric layout of speed in a corridor test.

Expected Result: Given the velocity and distance values, the occupant should be able to cover the 20m long distance in 20s.

Simulation Result: Considering the space and time granularity (i.e., 1 cell = 0.5m; 1SS = 0.25s), the occupant velocity is converted as follows:

1 m/s = 1 meter per 1s = 0.5 meter per 0.5s = 1 cell per 2SS.

This implies that the occupant takes 2SS to move from one cell to the next. Simulation result shows that the occupant takes exactly 160SS or (80×0.25 = 20s) to complete the evacuation.

3.2.3 Maximum flow rate

IMO test 4 is suggested to set a conservative requirement of maximum admitted flow rates.

Scenario: A Room of size 8 m by 5 m with a 1m-wide exit located centrally on the 5 m walls is modeled in EVAQ, as shown in Figure 19. A total of 100 occupants (of different characteristics) are placed in the room and assigned to the exit. This combination results in a density of 2.5 people/m^2 (100 people divided by 40 m^2). This high density is chosen to investigate flow rates in a congested area.

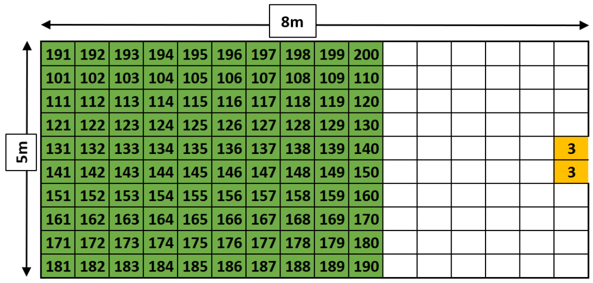


Figure 19: Geometric layout of maximum flow rate test.

Expected Result: According to the NFPA, the maximum design flow rate at an exit location should not exceed 1.33person/m/sec (Ronchi et al., 2013).

Simulation Result: Considering 1SS = 0.25sec and 1 cell = 0.5m, the average evacuation time (over 20 simulation runs) is found to be 337SS = 337×0.25 = 84.25sec, and the average flow rate is calculated as 100/84.25 = 1.18 person/m/sec, which is less than the prescribed limit of 1.33person/m/sec by 11.2%. This can be attributed to the fact that occupants are of mixed types (different genders, ages, disability status), adding some variability to the results.

3.3 Steps of Validation of Simulation Models

Validation of simulation models is a challenging problem, especially in evacuation simulation studies. Previously, researchers have proposed validation strategy to solve this problem. According to (Thomsen, Levitt, Kunz, Nass, & Fridsma, 1999), validation of any simulation models consists of several steps as shown in Table 5. Toy problems and intellective experiments are used to validate the reasoning assumptions of the simulation framework. Validation of the representation and usefulness depends on the experiments done in previous steps. Authenticity, Generalizability, and Reproducibility experiments are used to validates if the simulation system can capture the key features being studied. Finally, the usefulness of the simulation system is validated using Retrospective, Gedanken, Natural History, Intervention experiments.

Table 5: Steps of validation trajectory.

Validation Steps	Description
Toy problems	Develop test cases to assess whether micro-behavior has been correctly encoded.
Intellective Experiments	Examine hypothetical problems in an idealized setting.
Authenticity	Represent a real-world scenario with the simulation model.
Generalizability	Assess if the model is over-fitted to a particular test setting.
Reproducibility	Validate if two modelers will get the same result for the same scenario.
Retrospective	Duplicate past performance calibrate model (if required).
Gedanken	Perform ”what-if” analysis based on the retrospective evaluation.
Natural History	Predict future result and evaluate by performing the real-world experiment.
Intervention	Deploy model in the real world to monitor performance.

Seven of these steps were most applicable to EVAQ and thus were selected and carried out (or will be carried out as part of future work) to assess the performance of EVAQ, as shown in Table 6.

Table 6: Steps of validation performed by EVAQ.

Validation Steps	Description
Toy problems	Investigated several small-scale problems for individual component testing (verification tests).
Intellective Experiments	Performed experiments on idealized settings such as an open floor with multiple people.
Authenticity	Modeled real-world environments such as the Rhode Island nightclub fire.
Generalizability	Modeled a variety of environments such as an airport terminal and a shopping mall.
Reproducibility	Confirmed model stability by running models several times and recording output for statistical analysis.
Retrospective	Replicated the results of past work (e.g., Rhode Island nightclub fire event)
Gedanken	Performed for the Rhode Island test case (e.g., distribution of agent, fire position, exit assignment)
Natural History	Fire drill (future work).
Intervention	Face validation (future work).

3.4 Validation Tests

As stated earlier, it is very difficult to find experimental datasets to test the validity of emergency evacuation models in a manner that all key model components (e.g., pre-evacuation time, movement and navigation, exit usage, route availability, and flow conditions/constraints) are assessed. In this research, the performance of EVAQ is validated against Simulex with respect to the maximum flow rate. In addition, a historical fire incident (as one of the very few publicly available datasets) is modeled and simulated in EVAQ to validate its performance in comparison with previous evacuation literature (Grosshandler, Bryner, Madrzykowski, & Kuntz, 2005).

3.4.1 Maximum flow rate test

The maximum flow rate test is used in a scenario involving the evacuation of 100 individuals from space with exits of varying widths. The simulation results of the crowd flow rate test are compared with the previously reported results from Simulex to check for consistency (Thompson & Marchant, 1995). For comparison, similar settings such as the configuration and number of occupants are used for both EVAQ and Simulex. However, there are a number of basic differences between the two platforms that should be noted. First, EVAQ uses a fine network model where a floorplan is divided into small grid cells, and occupants move from one cell to the next in discrete times. The minimum cell size considered for EVAQ is 0.5m by 0.5m (i.e., the space occupied by one person standing) (Still, 2000). In contrast, Simulex allows the modeling of a continuous plane representing the floorplan. Second, given a particular setting, simulation results from Simulex will not fluctuate, since it is a deterministic model, whereas in EVAQ, due to the stochasticity in movement speeds and the dynamic nature of egress route selection and execution, results differ from one simulation run to the next.

In the maximum flow rate test with Simulex, the exit width ranges from 0.7m to 3.0m with increments of 0.1m. In contrast, since in EVAQ, exit width is a function of cell size (minimum cell size is 0.5m×0.5m), only six exit widths (0.7m, 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m) are considered for the comparison, as listed in

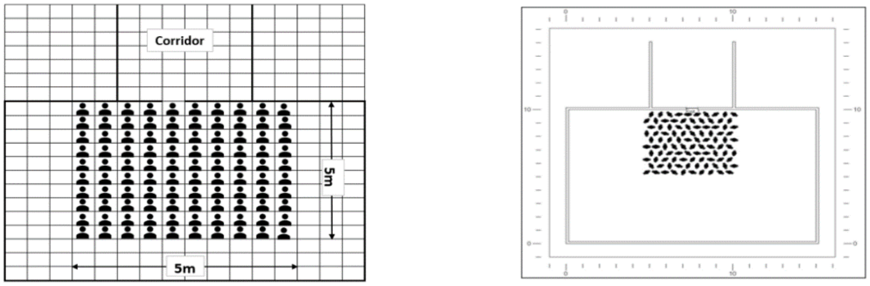
Table 7. For the 0.7m-wide exit, the entire layout is discretized into 0.7m cells, and for all other exit widths (i.e., 1.0m, 1.5m, 2.0m, 2.5m, 3.0m), the layout is divided into

0.5m cells. A total of 100 individuals are distributed within a 5m by 5m space around a single exit, as shown in Figure 20. A corridor is placed on the other side of the exit.

The crowd is expected to go through the exit and then continue walking along the corridor. For comparing simulation results between Simulex and EVAQ, the position and movement velocity (unimpeded movement velocity, 1.19m/s) of each are kept identical (Thompson & Marchant, 1995). Also, for the EVAQ model, validation test is conducted in a fully observable environment (i.e., no randomness in evacuees' movements). Constant velocity and no movement randomness makes the EVAQ model deterministic, creating a better baseline for comparison with the deterministic Simulex model. The flow rate Q (person/m/s) is calculated by Equation 1 (Thompson & Marchant, 1995),

$$Q = \begin{cases} \frac{80}{w(T_{90}-T_{10})} (w \geq 1.1m) \\ \frac{65}{w(T_{70}-T_{5})} (w < 1.1m) \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In Equation (1), w is the exit width in meters, and T_5, T_{10}, T_{70}, and T_{90} represent the times it takes for 5, 10, 70, and 90 people to pass through the exit, respectively.



(a) Environment in EVAQ

(b) Environment in Simulex

Figure 20: Initial crowd distribution for crowd flow rate validation test.

One simulation run by Simulex and EVAQ is conducted for each exit width (0.7m, 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m). The output of Simulex is collected from the previous literature (Thompson & Marchant, 1995). The comparison with the output of EVAQ is tabulated in

Table 7. The relative difference in evacuation time flow rates between the two models is calculated using Equation 2 and listed in

Table 7. In addition, Figure 21 illustrates the variation in flow rate and total evacuation time with different exit widths for EVAQ and Simulex.

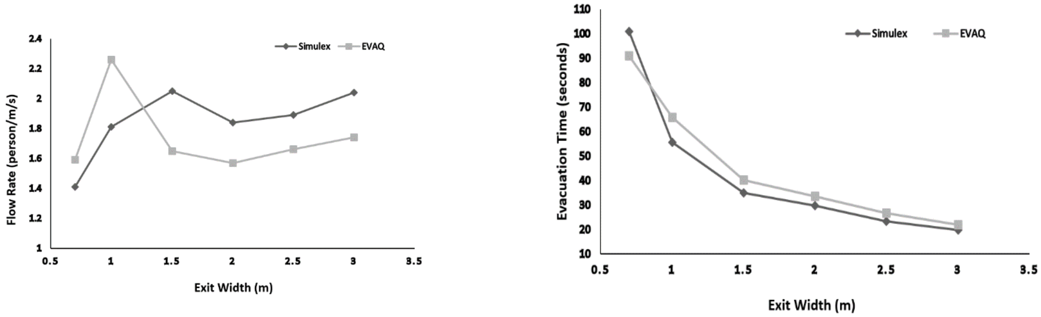
$$Relative\ Difference\ (RD)(\%) = \frac{Absolute\ Difference}{Absolute\ Arithmetic\ Mean} \times 100\% \text{..........................(2)}$$

Table 7: Comparison of simulation results in Simulex (S) and EVAQ (E).

Exit Width (m)	**T_5 (s)**		**T_{10} (s)**		**T_{70} (s)**		**T_{90} (s)**		**Total Time (s)**			**Flow Rate (person/m/s)**		
	S	**E**	**S**	**E**	**S**	**E**	**S**	**E**	**S**	**E**	**RD**	**S**	**E**	**RD**
0.70	6	5.4	12	9.9	72	63.9	92	81.9	100	90.9	10	1.41	1.59	12
1.00	3	3.6	7	5.4	39	32.4	50	41.4	55.5	65.9	17	1.81	2.26	22
1.50	3	2.7	5	4.5	24	27.9	31	36.9	34.9	40.2	14	2.05	1.65	21
2.00	2.5	2.3	4.8	4	21	23.4	26.5	29.4	29.8	33.5	11	1.84	1.57	16
2.50	1.5	1.4	3.2	3.6	17	18.9	20.1	22.9	23.4	26.7	13	1.89	1.66	12
3.00	1.3	1.2	3.4	3.2	14	14.4	16.5	17.3	19.8	21.9	10	2.04	1.86	9

According to Table 7, the evacuation time and flow rate do not differ much for Simulex and EVAQ. The difference in total evacuation time between the two platforms range between 10% and 17%, which implies that the time to evacuate all people is relatively close for the two frameworks. The same observation applies to flow rate results, where the output of the two platforms differs in the range of 9% to 22%. Given the difference in modeling principles described earlier, such discrepancy is expected, and results are within striking distance from each other.

Considering Figure 21(a) and (b) the trends of simulation results for the particular test case described here are similar between the two platforms. For example, in both Simulex and EVAQ models, it can be observed that increasing the exit width causes the total evacuation time to decrease. Note that, if each exit cell could accommodate more than one person at a time, an increase in flow rate and a resulting decrease in evacuation time could be expected. Finally, this example also demonstrates that crowd behavior at the exit location can significantly influence the egress process.



(a) Flow Rate

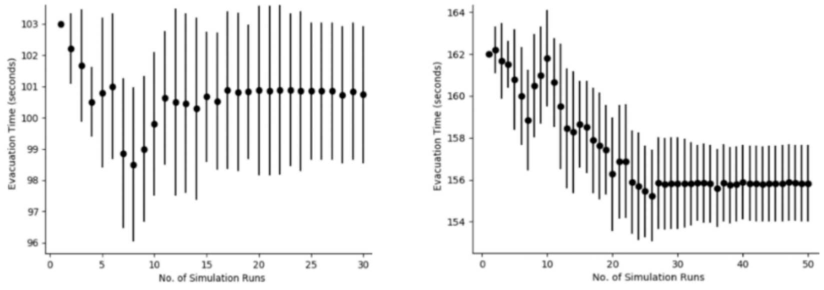
(b) Evacuation Time

Figure 21: Variation in flow rate and evacuation time for different exit widths in Simulex and EVAQ.

3.4.2 Required number of the simulation run

While deterministic simulation requires only one run to generate valid predictions, in stochastic simulation modeling, it may not always be trivial to determine the required number of simulation runs to yield statistically significant results. To achieve best results, modelers often run simulations for multiple (e.g., 10, 20, 50, or more) times. However, it is imperative to run a complex stochastic model enough times to understand its predictions while not spending time and computational resources by running it more than necessary iterations. Moreover, large number of simulation runs may not be feasible when models are run in a network or have a large number of parameters (Ritter, Schoelles, Quigley, & Klein, 2011). For example, for a model with 100 parameters, making 100 runs per parameter setting requires 100,000 runs. To avoid this situation, research suggests that a model is run until it has stable performance in key predictions (Ritter et al., 2011; Currie & Cheng, 2016). Here, for evacuation analysis each test case is run for several iterations until it arrives at a stable and valid output (e.g., evacuation time). To this end, mean-variance plot for different numbers of simulation runs is developed for each test case of different parameter settings. This plot facilitates to determine the required number of runs that yields a stable prediction of each parameter. For example, Figure 22(a) shows the mean-variance plot of evacuation time for the example illustrated in the previous Section (i.e., maximum flow rate validation test). To introduce the stochasticity in the previous example 40% randomness in agent movement is considered (i.e., partially observable environment) to evacuate the environment. For an exit width of 0.7m, the EVAQ model provides a mean evacuation time of 100.80 seconds over 20 simulation runs. To arrive at this number, the simulation was run for 30 times, and mean-variance values were plotted.

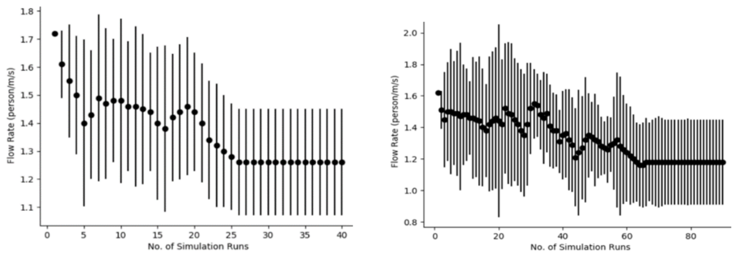
As Figure 22 suggests, with increasing the number of simulation runs beyond 20, the mean and variance of evacuation time values (in seconds) does not change significantly. Therefore, the resultant distribution (mean, variance) is considered to have converged, and no significant variation can be seen after 20 simulation runs. In other words, the mean evacuation time is stable after 20 simulation runs. However, an increase in randomness requires more simulation runs for stable prediction. As shown in Figure 22 (b) for 80% random movement required simulation runs increases to 40 (mean evacuation time of 155.84 seconds). The same test case has been used for the parameter 'flow rate' to determine the required number of simulations in the presence of 40% and 80% random movements. Results show that with an increase in randomness the required number of simulation runs to achieve stable output increases to 30 (mean flow rate of 1.26 persons/m/s), 80 (mean flow rate of 1.18 persons/m/s) respectively (Figure 23). It must be noted that Figure 22 and Figure 23 show the cumulative plots of mean-variance of the vertical axis variable (i.e., evacuation time, flow rate). In addition to cumulative plots, evacuation time or flow rate can be plotted for each individual run to visualize the actual variability of these parameters from one simulation run to the next.



(a) 40% randomness in agent movement

(b) 80% randomness in agent movement

Figure 22: Mean-variance plot for different numbers of simulation runs for stable evacuation time prediction.



(a) 40% randomness in agent movement (b) 80% randomness in agent movement

Figure 23: Mean-variance plot for different numbers of simulation runs for stable flow rate prediction.

3.4.3 Replication of historical event-the Rhode Island nightclub fire case

EVAQ is used to replicate a historical event of fatal fire occurred at a nightclub in Rhode Island. The dataset used for this validation experiment is obtained from the literature, and the simulation results are further compared with those reported by NIST (Grosshandler et al., 2005).

Environment: The nightclub floorplan is illustrated in Figure 24(Grosshandler et al., 2005). The building is a single-story wood frame with approximately 415 m^2 in floor area. As shown in Figure 24, there are four exit locations (the front entrance, backside exit door, kitchen exit door, and a platform exit door). Since most of the evacuees were aware of the main entrance, some congestion started to occur in front of the main entrance after some time of fire initiation. 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 windows. However, due to the lack of information about window positions, the corresponding EVAQ model considers that people were only using the exits to evacuate.

Assumptions: To simulate the emergency evacuation for the environment illustrated in Figure 24, EVAQ considers the following assumptions,

a) From NIST data, a total of 350 people (all adults, 50%-50% between males and females) are randomly distributed 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 only aware of the front entrance and some people tried to take platform exit door which was compromised after 30seconds of fire initiation.

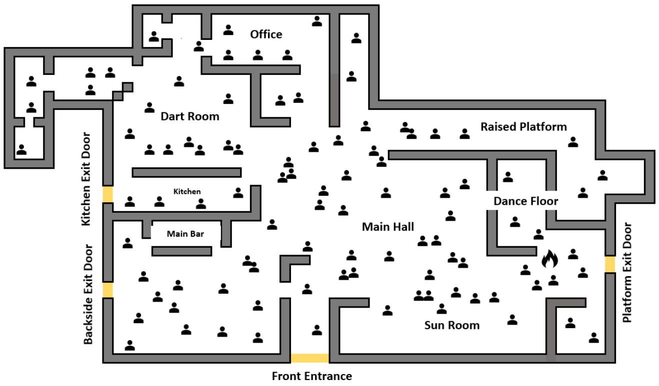


Figure 24: Layout of the Rhode Island nightclub floor.

<u>Simulation Result:</u> Using different random spatial distributions of people and hazard in the environment, the EVAQ simulation determines the average results over 20 simulation runs, as listed in Table 8, where a comparison is also made with NIST reported data. Results indicate that the EVAQ model closely replicates the NIST report.

Table 8: Comparison of simulation result between EVAQ model and NIST data for the Rohde 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

3.5 Summary & Conclusions

This Section presents the V&V methodology for EVAQ framework to evaluate the reliability of its application. Several NIST suggested verification tests for the emergency evacuation model have been performed and the results are further compared with another evacuation simulation tool Simulex. The result shows EVAQ can simulate dynamic availability of exits which is not possible in the Simulex environment. However, EVAQ cannot model congestion at the stair use which is included in the future direction of the research.

On the other hand, to validate the evacuation model steps of validation trajectory have been followed demonstrated by Thomsen et al., (1999). Two validation tests have been performed suggested by NIST—maximum flow rate test and the replication of Rhode Island nightclub fire incident. The results from the maximum flow rate test are further compared with the results from Simulex for the environment. The result shows that difference variation ranges between 9% and 22% due to the different modeling method of Simulex and EVAQ. On the other hand, Rhode Island simulation result shows that EVAQ can simulate a large environment with higher occupant load.

4 APPLICATION STUDIES AND ANALYSIS OF RESULTS

4.1 Introduction

This Section presents the implementation of EVAQ to answer the research questions previously listed in Subsection 1.2 by evaluating the impact of factors such as human traits (personal and interpersonal characteristics), environmental constraints, as well as hazard and intervention systems and their interactions on the likelihood of survival in an emergency evacuation. Two specific scenarios for crowd egress planning in a fire emergency, namely an airport terminal and a shopping mall are presented, and results are discussed.

4.2 Airport Terminal Evacuation Plan

In this Section, an airport departure terminal is modeled to assess the performance of EVAQ for egress strategy planning and analysis. The model imitates the evacuation process in a dynamic (deteriorating in the presence of fire hazards) environment and identifies critical egress issues for further investigation and consultation with building codes. As shown in Figure 25, the 800 m^2 terminal floor consists of check-in counters, offices, restrooms, café and bars, and retail shops. In this scenario, 275 people (shown by human icon) and 3 fire initiation points (shown by flame icon) are 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 a fire emergency, 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 the 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 Figure 25 for egress.

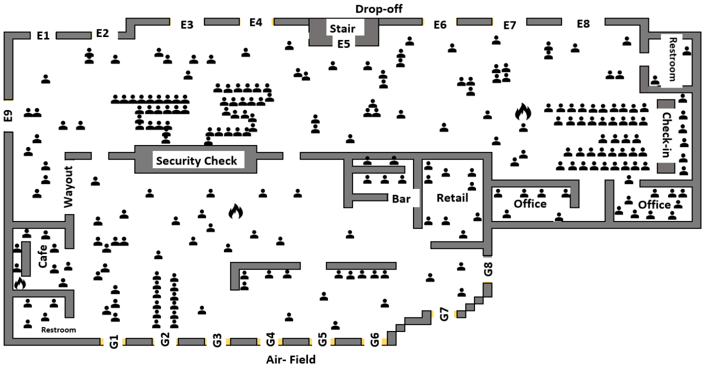


Figure 25: Airport terminal layout and distribution of travelers.

To perform egress analysis for both of the cases, three assumptions are considered as follows,

a) A total of 275 people of 12 different types (see Table 3) 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 randomness in agent movement and no pre-evacuation time is considered.

4.2.1 Minimum evacuation time

To establish a baseline for evacuation analysis, EVAQ is first used to determine the minimum time required to evacuate the terminal building under full occupancy and no fire propagation with time (i.e., static environment state). The movement speed of each person is predefined according to their physical characteristics, as described in

Table **3**. The goal of each person is to find and arrive at the nearest exit and use that exit (either in a queue or with the competition with others) to evacuate to safety. A total of 30 simulation runs are conducted with different seeds and the average evacuation time of people for safely exiting is illustrated in Figure 26.

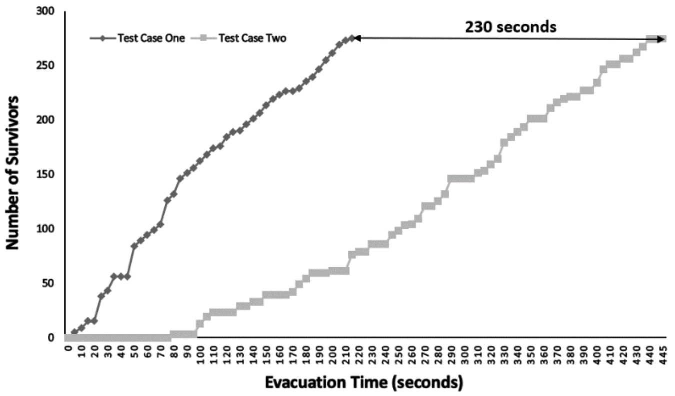


Figure 26: Cumulative plot of the average number of people evacuating the terminal building with time.

According to results, in test case 1 (i.e., security checkpoint is open) it takes 860 SS or 215 seconds to evacuate the terminal, while in test case 2 (i.e., security checkpoint is closed), it takes 1780 SS or 445 seconds to evacuate the terminal. The difference in evacuation time (230 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 egress, thus creating more congestion and longer queues at exit locations.

4.2.2 Situational awareness

As previously described in Subsection 2.6.5, an evacuee's level of knowledge of the environment can influence his or her exit strategy selection and execution. Table 9 shows the average evacuation time at two extreme levels of knowledge (i.e., full and none) for the abovementioned test cases. For each test case, a total of 30 simulation runs are conducted. As expected, in both cases the evacuation time is longer for people with no knowledge about their surroundings than those with full knowledge.

Table 9: Average evacuation time at distinct levels of knowledge for the airport terminal evacuation scenario.

Test Case	**Level of Knowledge**	**Evacuation Time (sec.)**
1	1	215
	0	480
2	1	445
	0	1,020

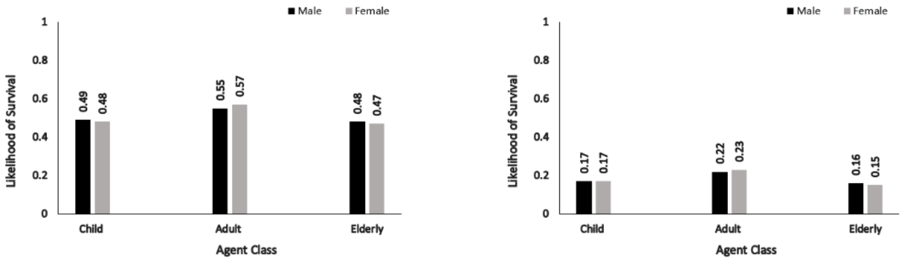
Of note, when it comes to situational awareness, more is not always necessarily better. A well-designed evacuation simulation model developed in EVAQ provides more insight into this by helping users understand what degree of situational awareness is required in what type of environment for survival. For example, in a layout with abundant exits, it is easy to locate an exit, even if evacuees have limited situational awareness.

4.2.3 Likelihood of survival

The developed EVAQ model for this scenario is used to determine the effect of an individual's characteristics and environmental constraints on their likelihood of survival rate, which is defined using Equation (3) below,

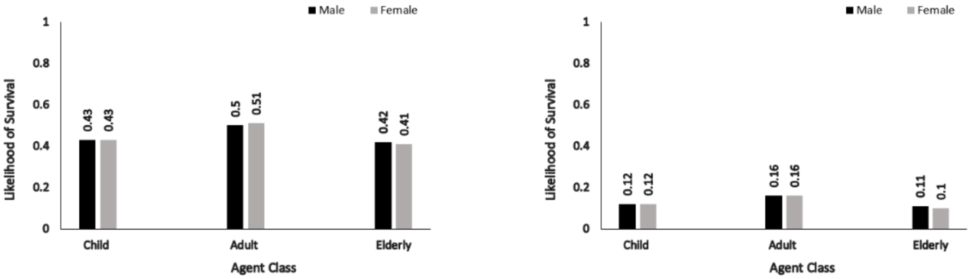
$$Likelihood\ of\ survival\ of\ class\ X\ agents = \frac{No.of\ survived\ agents\ in\ class\ X}{Total\ no.of\ agents\ in\ class\ X}\dots\dots\dots(3)$$

Similar to the static environment state, the velocity values of evacuees are predefined according to their physical characteristics, and the goal of each person is to find and arrive at the nearest exit to evacuate to safety. Two test cases are considered and a total of 30 iterations are run for each case using different seed numbers. It is found that in test case 1, the likelihood of survival is generally higher than in test case 2, regardless of agent type. This is due to the fact that in test case 2, the security checkpoint remains inaccessible during evacuation, thus creating more chaos and congestion in the secured area of the terminal, adding to the likelihood of people being compromised as fire spreads. Figure 27and Figure 28 illustrate the likelihood of survival for 12 different agent classes in the environment for both cases.



(a) Test case 1 (b) Test case 2

Figure 27: Likelihood of survival of able agents for (a) test case 1, and (b) test case 2.



(a) Test case 1 (b) Test case 2

Figure 28: Likelihood of survival of disabled agents for (a) test case 1, and (b) test case 2.

According to these Figures, the likelihood of survival decreases with a decrease in availability of the nearest exits and a resulting increase in congestions in the environment. These Figures also show the effect of evacuees' personal characteristics on their survival. In terms of age, the likelihood of survival of children and elderly people is almost equal but less than that of adults. This can be 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 evacuate without any help), which is not present in this scenario. Finally, while there is no significant difference in the likelihood of survival for different genders, disability status can play a role in an evacuee’s chance of survival. In particular, the fate of a disabled person largely depends on the availability of special exits, as well as the presence of group behavior and interactions. For the airport terminal simulation, the output of the EVAQ model shows that on average, 174 out of a total of 230 able people could safely evacuate (i.e., 73%), while only 29 out of a total of 45 disabled people could safely evacuate (i.e.,64%) for test case 1. However, these two value decreases for test case 2—55% and 39% respectively.

4.3 Shopping Mall Evacuation Plan

In this Section, a shopping mall is modeled to assess the performance of EVAQ for egress strategy planning and analysis. As shown in Figure 29, the 1,012.5 m^2 mall floor consists of 15 stores, restrooms, two cafés and a food court, and children playground. In this scenario, 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 of the cases four assumptions are considered as follows,

a) A total of 200 people of 12 different types (see Table 3) 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.

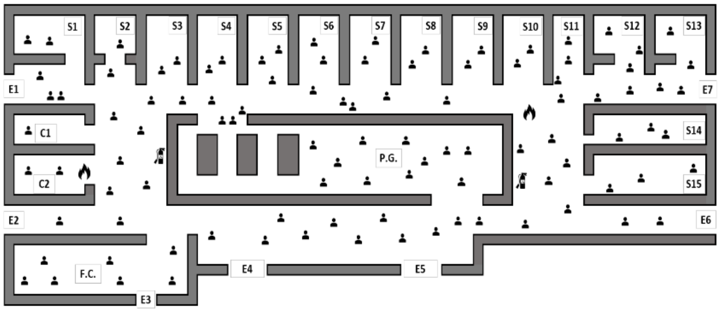
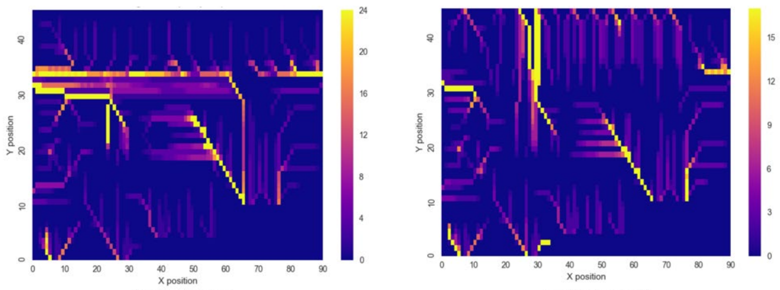


Figure 29: Shopping mall layout and distribution of shoppers.

4.3.1 Effect of additional emergency exits

Two specific test cases (test case 1 and 2) are considered for this scenario, and a total of 20 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 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.

Figure 30 (a) and (b) illustrate evacuees' heat maps in 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 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.



(a) Test case 1

(b) Test case 2

Figure 30: Heat map of evacuees' movement patterns for (a) test case 1, and (b) test case 2.

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.

4.3.2 Effect of randomness in evacuees' movements

As previously explained, in a dynamic environment people may take random steps to find and arrive at nearest exits due to the limited visibility, smoke inhalation, and excess heat. To analyze the impact of hazard severity on evacuees' fates, the EVAQ simulation of the shopping mall scenario is revisited. Figure 31 shows that the chance of survival decreases with an increase in movement randomness (due to limited visibility, smoke inhalation, and excess heat) from 0 (no random moves) to 1 (all random moves), in both test cases 1 and 2.

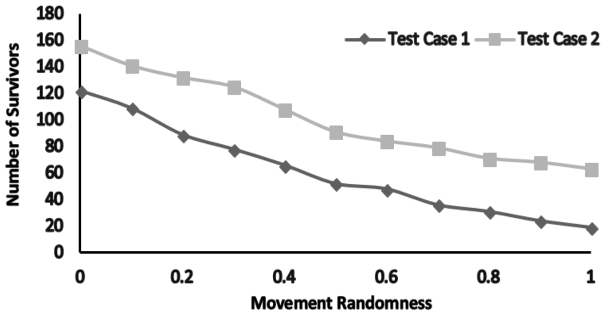
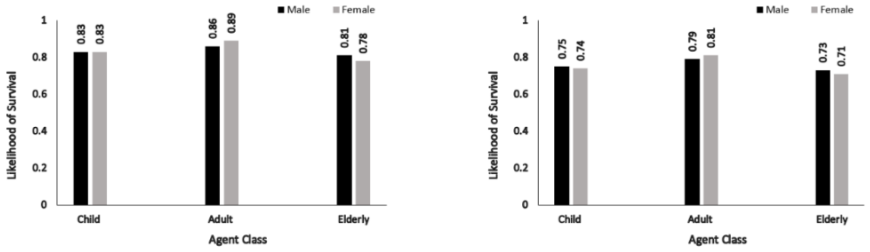


Figure 31: Survival rate at different levels of randomness in shopping mall evacuation.

4.3.3 Effect of a hazard intervention system

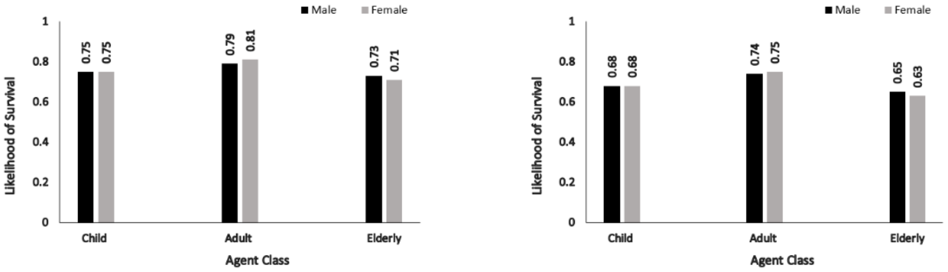
To understand the effect of the intervention system on the likelihood of survival, the EVAQ simulation of the shopping mall scenario is revisited. As shown in Figure 29, there are 2 fire extinguishers in the mall to control fire propagation. This model is run for test case 1 over 30 times (using different seed numbers) for both with and without fire extinguishers in the system. Results illustrated in Figure 32 and Figure 33 show that the likelihood of survival increases in the presence of a hazard intervention system regardless of evacuees' gender and disability status. Also, it is observed that the incorporation of group behavior increases the likelihood of survival for children, as well as elderly and disabled people.



(a) Test case 1

(b) Test case 2

Figure 32: Likelihood of survival of able agents (a) with, and (b) without a hazard intervention system.



(a) Test case 1

(b) Test case 2

Figure 33: Likelihood of survival of disabled agents (a) with, and (b) without a hazard intervention system.

4.3.4 Effect of firewall

To understand the effect of the firewall on the survival rate, the EVAQ simulation of the shopping mall scenario is revisited. As shown in Figure 29, the wall surrounding the playground is modeled for three types of materials mentioned in Subsection 2.4.3. Three test cases are developed with three different materials (e.g., Class A, Class B, and Class C). For these three test cases two main assumptions are considered as follows,

a) All agents take only main exits (E1-E7) for evacuation.

b) No use of fire extinguisher.

Each test case is run over 20 times with different seed numbers. Results show that on average more people can be saved if the wall is modeled with Class A materials rather than Class C materials. The reason is that Class A materials more effectively prevent the fire from propagating to adjacent cells than Class C materials. Table 10 shows the average number of evacuees survived for each class of materials.

Table 10: Average number of survivors due to firewall of different materials for the shopping mall evacuation scenario.

Test Case	Material of Playground Wall	Number of Survivors
1	Class A	169
2	Class B	147
3	Class C	129

4.4 Summary & Conclusions

In this Section, EVAQ was used to model two person-specific egress simulation in fire emergency (an airport terminal and a shopping mall), and results were 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.

In the airport terminal evacuation simulation, it was found that less availability of alternative exit routes and lack of situational awareness of existing exits in the environment create more congestion and longer queues at the main entrance and eventually increase average evacuation time. Besides, on average, the likelihood of survival for different agent classes decreases by 60% due to congestion at the main entrance for both able and disable evacuees.

In the shopping mall evacuation model, it was found that the positioning of the exits should be considered carefully, as it decreases the evacuation time and increases the survival rate as well. The effect of the intervention system in the hazard affected area is also studied with the shopping mall evacuation model. It shows the use of an intervention system increases the survival probability by 10% on average for different agent classes. Also, the incorporation of group behavior increases the likelihood of survival for children, elderly and disabled people, which is not observed for the airport terminal evacuation model.

As personalized sensing and information delivery platforms are becoming more ubiquitous, findings of this work are ultimately sought to assist in developing and executing more robust and adaptive emergency mapping and evacuation plans, ultimately promoting people's lives and wellbeing.

5 CONTRIBUTIONS & CONCLUSIONS

5.1 Introduction

The overarching goal of this research was to design and test a person-specific 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-affected environment. To achieve this goal, an end-to-end simulation framework was developed which takes as input the layout of the environment, as well as the characteristics of and interactions between evacuees, hazards, and intervention systems, to facilitate evacuees' decision-making, and increase the likelihood of survival by suggesting the best possible egress strategy in a deteriorating environment. In this Section, a concise statement on research contributions and a discussion of the limitations and directions for future work are presented.

5.2 Contributions to the Body of Knowledge

The contributions of the research are 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. As described throughout this Thesis, 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, Klein, Hostikka, & Floyd, 2010), EVAQ has the ability to model dynamic 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. Qualitative and quantitative results of verification tests indicate that EVAQ can successfully model occupants' pre-evacuation time distribution, movement, navigation, exit choice/usage, exit route availability, and flow constraints. Besides, EVAQ was validated using NIST dataset from a historical incident of fatal fire at a nightclub in Rhode Island. Collectively, the outcome of the V&V stage indicates the potential of EVAQ for improved crowd management and emergency mapping.

The scientific contributions of the research presented in this Thesis 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).

5.3 Future Work & Conclusions

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 **3**, 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 agent 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, Song, Lv, & Fang, 2015; Cao, Song, & Lv, 2016).

Moreover, the research presented in this Thesis was mainly 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, Petty, Knight, & Schueler, 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 and datasets replicating historical events (Thomsen et al., 1999). While using retrospective evaluation allows a wide range of "what-if" analysis 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).

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APPENDIX

In this Appendix, the flowchart of the key steps of the simulation process in EVAQ is presented (Figure 34). Several pieces of pseudo-code for each of the model components (i.e., hazard, intervention, agent) are also included to facilitate the discussion of the flowchart. This Section demonstrates the functionality of EVAQ written in Python language, specifically the process of simulation result generation which is finally converted into a 2D visualization with the help of MATLAB visualizer.

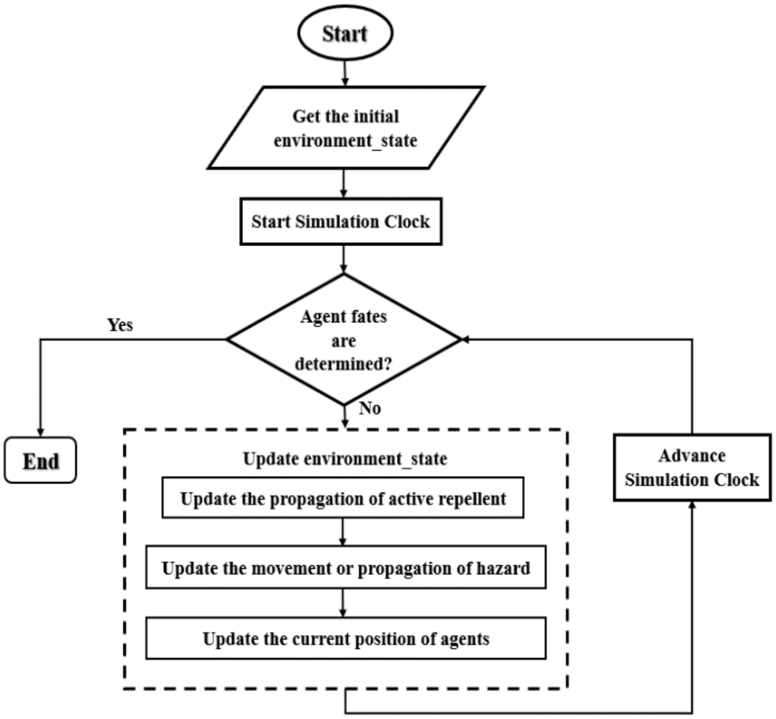

Figure 34: Flowchart of the overall simulation process.

Repellent Propagation:

```
[1] FOR each repellent cell descriptor in the list of repellent cell descriptors
     [2] GET all required information from the descriptor
     [3] IF current simulation time is the activation time of the repellent AND current simulation time lies within the boundary of initiation time and repellent duration
          [4] COMPUTE new cells where repellent propagates
          [5] FOR each new repellent cell
               [6] CREATE new repellent cell descriptor
          [7] END FOR
     [8] END IF
[9] END FOR
[10] APPEND the new repellent cell descriptors to the list of repellent cell descriptors
```

Hazard Propagation:

```
[1] FOR each hazard cell descriptor in the list of hazard cell descriptors
     [2] GET all required information from the descriptor
```

```
          [3] IF current simulation time is the activation time
          of the hazard
          [4] UPDATE the hazard cell descriptor for future
          propagation
               [5] COMPUTE new cells where hazard propagates
               [6] FOR each new hazard cell
                    [7] FOR each cell in the list of object
                    position descriptors
                         [8] IF the new hazard cell contains an
                         object
                              [9] COMPUTE delayed activation
                              time for the hazard cell
                         [10] END IF
                    [11] END FOR
                    [12] CREATE new hazard cell descriptors
               [13] END FOR
          [14] END IF
     [15] END FOR
     [16] APPEND the new hazard cell descriptors to the list of
     hazard cell descriptors
```

Repellent-Hazard Interaction:

```
[1] FOR each repellent cell descriptor in the list of repellent cell descriptors
    [2] GET all required information from the descriptor
    [3] IF current simulation time lies within the boundary of initiation time and repellent duration
        [4] FOR each cell in the list of hazard cell descriptors
            [5] IF the repellent cell contains any hazard
                [6] APPEND cell position to the list of mitigated hazard positions
            [7] END IF
        [8] END FOR
    [9] END IF
[10] END FOR
[11] FOR each cell position in the list of mitigated hazard positions
    [12] REMOVE the corresponding descriptor from the list of hazard cell descriptors
[13] END FOR
```

Agent Decision Making:

Independent Agent:

```
[1] FOR each agent position in the list of current agent positions
    [2] COMPUTE exit path as the shortest safe path current position to the nearest exit
    [3] IF there is no safe path to exit
        [4] UPDATE the agent's exit path to stay in current position
    [5] END IF
    [6] UPDATE the agent's plan with the exit path
[7] END FOR
```

Group Agent:

```
[1] FOR each agent group in the list of the agent group
    [2] IDENTIFY the common destination for the group
    [3] FOR each member agent of the group
        [4] COMPUTE exit path as the shortest safe path from current position to the common destination
        [5] IF there is no safe path to common destination
            [6] UPDATE the agent's exit path to stay in current position
```

```
        [7] END IF
        [8] UPDATE the agent's plan with the exit path
    [9] END FOR
[10] END FOR
```

Agent Plan Execution:

```
[1] SORT agent list based on the distance of agents from exit
[2] FOR each agent in the sorted agent list
    [3] IF agent is not at the exit already
        [4] IF agent is executing the exit plan (fully observable environment)
            [5] COMPUTE agent's next position as per exit plan
        [6] ELSE
            [7] COMPUTE agent's next position as a random adjacent position
        [8] END IF
        [9] IF agent's next position is empty (no other agent)
            [10] UPDATE agent's position to the next position
```

```
        [11] END IF
    [12] END IF
[13] END FOR
```