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EvacuSafe: A Real-time Model for Building Evacuation Based on Dijkstra's Algorithm

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Abstract

Building evacuation strategies directly affect the success of an emergency response plan in reaction to a disastrous event in a building. Evacuation alternatives result from applying time delays or altering path planning in the evacuation strategy. The best strategy for evacuation depends on the characteristics of the building, circumstances of the particular emergency, and reactions of the evacuees during the emergency. A real-time evacuation management model that identifies the fire hazard, contemplates possibilities, foresees consequences, and eventually proposes the best strategy of evacuation during the emergency can reduce the risk of a failed evacuation. In this paper, a real-time model is proposed, whose main goal is to discover the safest strategy of path-planning at every instant of time during an evacuation. The model focuses on fire emergencies, as they are the dominant cause of fatalities in buildings compared to other types of natural and manmade disasters. The proposed model first defines a risk factor for each compartment based on the location of the fire and any potential blockages caused by structural collapse or door malfunction. The lowest risk path is then calculated based on a modified Dijkstra's algorithm. The model is developed and implemented such that it conforms to the Active Dynamic Signage System (ADSS). Herein, a model is designed to monitor the building in real-time and in case of any unexpected event, changes to the evacuation strategy are communicated to occupants using ADSS. The case study shows that the proposed model for real-time evacuation management can significantly enhance the safety level of evacuation compared to the conventional shortest path evacuation plan.

Keywords: Evacuation; Dijkstra; Route risk index; Geometric network graph; BIM; IFC; Fire safety; active dynamic signage system; real-time path-planning

1. Introduction

Successful evacuation management needs decision making and action within a very short time frame of seconds. To make fast decisions, the person in charge must comprehend the status of the building, estimate the distribution of the occupants, recognize the type and the location of the hazard, decide the best strategy of evacuation, and communicate the strategy to occupants. These tasks are more complex than they seem. First, variations in the initial conditions of an emergency can generate tremendous numbers of distinct emergency scenarios. Second, each emergency scenario probably has multiple potential strategies of evacuation, which have to be evaluated carefully to find the best solution. Third, the human commander has to stay alert throughout the emergency and improvise solutions for unexpected situations that deviate from the forecasted plan. One or several human emergency commanders are often challenged to handle such complexities of decision making, data interpretation and coordination accompanied with strict time constraints. Inevitably, human errors, their limited computation capacity and unsubstantiated heuristic reasoning highlight the need for automated support systems to enhance decision-making and coordination processes.

The catastrophic nature of emergencies makes them especially challenging to recreate. While helpful to practice, emergency evacuation drills often do not reveal all aspects of the event. Computer simulation can stochastically imitate the course of events an emergency, and computer-based crowd simulation approaches make it possible to model occupant movements, behaviors and interactions during the evacuation. Moreover, software applications and simulators make it possible to model the characteristics and forecast the behavior of the hazard itself. Such tools enable us to examine a specific building design and evaluate the safety of evacuation processes in that facility. Computer-based decision support systems can be designed by simulating discrete emergency scenarios and evaluating them to determine a safe strategy of evacuation.

The main goal of evacuation management is to facilitate the complex process of decision making during the emergency event. It is no surprise that the real evacuation process will likely be different from the simulated event, triggered by, for example, people selecting different escape routes, variation in the number and distribution of evacuees, the development of congestion or bottlenecks, changes in the original threat's behavior, or the creation of a new threat during the emergency. During an evacuation, there is rarely sufficient time to run multiple fire or crowd simulations to evaluate the effects of evacuation strategies.

A real-time evacuation management model should respond to situational changes in an emergency and generate new plans that secure the safety of the occupants. It would ideally also have an evacuee guidance module to direct occupants and leverage its dynamic path-planning capabilities. Evacuation processes are typically evaluated based on the shortest exit routes or shortest evacuation time. We believe a successful path-planning model needs also to assess and rank its strategies based on the level of safety and risks to the evacuees' lives.

Therefore, the main objectives of this paper are to:

1. Develop EvacuSafe as a real-time evacuation management tool for occupant egress planning during fire emergency events.
2. Demonstrate how EvacuSafe can improve the overall safety of occupants using agent-based crowd simulation and an active dynamic signage system (ADSS)

2. Literature Review

The main goal of an evacuation management system (EMS) is to secure the safe egress of occupants from a facility during an emergency. Its design requires accurate, up-to-date information about the physical and functional characteristics of the building. This information can be collected, organized, and digitally represented in a building information modeling (BIM) file. Geometric and semantic structured data in BIM enables researchers to transform a building into custom network graphs representing the connectivity between navigable spaces. The transformation of BIM into a network graph allows the use of graph exploration algorithms for path-planning. The automatic generation of networks from 3D building models is currently one of the major challenges in this area of research (Mortari et al. 2019).

Indoor modeling approaches can be categorized as geometric or symbolic spatial models. Geometric models represent the entire space as continuous or discrete elements that can be further broken down into cells or boundary-based sub-spaces. Square and hexagonal grids are two well-known examples of geometric spatial models (Bandi and Thalmann 2000, Yuan and Schneider 2010). Symbolic models represent the space using topological relations or graphs based on the connectivity and reachability between the sub-spaces (Mortari et al. 2019). Graph-based models are the most widely used examples of symbolic spatial models (Winter et al. 2018). In symbolic models, indoor spaces are represented by place identifiers and defined by architectural properties of the space. Graph-based models have applications ranging from emergency management to path-planning and indoor navigation services.

Methods to extract the network graph of indoor spaces include medial axis transform (MAT), visibility graph (VG), door-to-door algorithm, and their variations (Cheng et al. 2018, Rüppel et al 2010, Yu 2006). The medial axis of a polygon is the collection of all points inside the polygon having more than one closest point on the polygon's boundary (Lee 2004). The MAT algorithm is applied to the 2D footprint of a space and produces a geometric topology network (GTN) of the building (Taneja et al. 2011). Straight medial axis transform (S-MAT) is a modified version of MAT in which the edges are straight lines rather than parabolic curves (Lee 2004). BIM files of oil and gas platforms were used to generate path-planning graphs based on the VG methodology (Cheng et al. 2018). In VG, the nodes of the graph are vertices of the obstacles in the environment. The edges are the line connections between pairs of obstacle vertices, each of which does not intersect the obstacles.

MAT and VG are applied where the exact path is required, for instance, in autonomous robot navigation. However, herein, only the sequence of the spaces and their approximate distances are needed and the application of MAT or VG in this subject will complicate the solution and create unnecessary redundancy. Compared to MAT and VG, therefore, room-to-door-to-room network graphs can better serve the purpose of the current research.

BIM can be used to construct a room-to-door-to-room network graph that facilitates path-planning in a building (Yan et al. 2011). It can also be combined with Bluetooth-based sensor networks, shortest route evacuation planning, and a real-time evacuation guidance mobile APP to assist evacuees, firefighters, and commanders during evacuations (Cheng et al. 2017). Finally, a combination of BIM and agent-based crowd simulation can assist planning of labor evacuation in construction sites (Marzouk and Al Daour 2018).

The interoperability of industry foundation classes (IFC) facilitates the data exchange of building information between software applications (Ismail et al. 2018). This interoperability privilege, plus the available geometric-, crowd- and environment-related attributes in IFC, make it possible to extract the topological connectivity graph of the building directly from the IFC data structure (Zhu et al. 2018). Automated codes can extract geometric and semantic knowledge from IFC for analysis in graph databases such as Neo4j (Ismail et al. 2018). It is also possible to import IFC into a GIS application and use GIS functions to find the shortest path between two locations (Xu et al. 2016). The combination of IFC transformations to build network graphs and GIS provides the opportunity to make a unified graph of indoor and outdoor spaces for navigation (Teo and Cho 2016). Retrieved information from IFC can be used to determine the connected spaces in a building by finding the common doors between them (Eastman et al. 2009). Here, the connection between the center of each space to the next center is considered an edge of the network graph.

Traditionally, the main purpose of egress design and path-planning has been to find the shortest path of evacuation. The original problem of finding the shortest path between two points has been solved using graph exploration methods. Dijkstra’s algorithm searches to find the globally shortest path between two nodes of a graph (Dijkstra 1959). The cost function of the algorithm in its simplest form is based on the distance between the nodes. A* is another widely used algorithm, but instead of performing a global search, it contains a heuristic function. Similar to Dijkstra’s, it calculates the cost of traversed paths, while the heuristic leads the search directly towards the goal (Hart et al. 1968). The computational load of A* is much less than Dijkstra’s, making the algorithm faster. However, the solution is not necessarily the global optimum. A scale coefficient in the heuristic of A* lets the search speed adjust to fit the time constraints of the emergency at the cost of a suboptimal solution (Wang et al. 2014).

In emergency management, Dijkstra’s has been used to find the shortest rescue path to victims (Wu and Chen 2012), in combination with BIM for evacuation (Cheng et al. 2017), and with help from the MAT algorithm (Chen and Chu 2016, Shi et al. 2008). Moreover, efforts have been made to detect blockage in building emergency routes using closed cable circuit (CCC) sensors and video cameras (Ergen et al. 2015). The blockage could be the result of structural collapse, furniture displacement, or door malfunctions. Prior knowledge about the blockage locations allows a more accurate, safe, and effective path-planning.

Crowd simulation methods model individual behaviors and crowd interactions during evacuation processes. This capability allows crowd simulation to complement mathematical path planning methods that focuses on individuals rather than the population. Phenomena such as congestion, queueing, or herding, which emerge from interactions of individuals with each other or environment, can be studied with crowd simulation. Cellular automata, flow-based models, social force models (SFM) and agent-based models are the most frequently used approaches of crowd simulation.

In cellular automata, the modeling space is divided into a two-dimensional grid. Entities can move from a node to any of the 8 adjacent nodes if it is not occupied by another entity. Two limitations of this method are its inability to represent real-life movements of the individuals and modelling individuals that move at different speeds (Santos and Aguirre 2004). Cellular automata models are discrete in time and space and typically use square meshes that cause errors in the case of incorrect choice of map projection or directional biases (Clarke 2014). Researchers have used cellular automata to study occupant behavior during emergencies (Yang et al. 2005), such as herding (Kirchner and Schadschneider 2002) and competitive egress behaviors (Kirchner et al. 2003).

Flow-based modeling simulates crowds based on the principles of fluid and particle motions. In this approach, nodes and arcs are used for graphical representation. Nodes represent a calculated useable area containing people; and arcs represent the flow in passageways between the nodes. Flow-based software such as EVACNET4, EESCAPE, and EGRESSPRO, do not modeling the individuals' social behavior or interactions during the evacuation process (Kisko et al. 1998, Kendik 1986, Simenko 2001).

SFM is currently one of the most widely used approaches in pedestrian simulation modeling. In this approach, an individual's actions are subject to external forces, which define their speed and direction. These forces result from their interactions with other pedestrians, their physical environment, or their motivation to act. In the initial version of SFM (Helbing and Monar 1995), several factors affecting the motion of pedestrians were considered, including their intention to reach their destinations, to avoid or approach objects and other pedestrians, and to detour from obstacles and borders. The resultant force determines the state of the pedestrians over time in terms of location, speed, and acceleration. Improved versions of the model included the effect of panic (Helbing et al. 2000). SFM have been applied to study evacuation from a one-exit room (Parisi and Dorso 2005, Parisi and Dorso 2007), the effect of leadership within multi-exit evacuations (Hou et al. 2014), and the effectiveness of wall versus ground exit signs (Yuan et al. 2018).

ABM's main strength is the ability to model actions and interactions of autonomous agents in a simulation environment (Morvan 2012). Crowd simulation requires a tool to model populations, individual behaviors, and agent interactions; and ABM covers all of these aspects. ABM's bottom-up approach models unique behaviors of heterogeneous humans, including emergent behaviors of panic, competitiveness, queuing, herding, and the kin effect (Bo et al. 2007, Pan et al. 2007, Yang et al. 2005, Pan et al. 2006). The main challenge in ABM is to understand such emergent human behaviors and formulate them into mathematical rules. The fusion of ABM and SFM has been used to simulate crowd evacuation in a terrorist attack and an earthquake (Lin et al. 2006, Zhang et al. 2018, Liu 2018).

Mathematical fire modelling was a significant step in the design of fire protection systems, estimation of fire risks, and study of the effects of fire on people and properties (Nelson 2002a). Mathematical fire modelling dates to the 1940's and is categorized as 1) hand calculations, 2) zone models, and 3) computational fluid dynamics (CFD), also known as field models (Gorbett 2008). In hand calculation models, algebraic equations inferred from empirical experiments are used to simulate the characteristics and expansion pattern of a specific fire. Zone models divide each compartment to an upper and a lower zone. The upper zone encompasses the fire plume and gas products; the lower zone comprises the safe ambient air. In this approach, the transfer of mass and energy between the zones is the main subject of study. The well-known computer program for zone modelling, Consolidated Model of Fire Growth and Smoke Transport (CFAST), was developed by the U.S. National Institute of Standards and Technology (NIST) (Peacock 2005). CUrisk, developed at Carleton University, attempts to combine sub-models of smoke and fire growth, occupant evacuation, and property economic loss to perform a risk assessment on fire safety designs (Zhang et al. 2016). In CUrisk a 2-zone model is used as the fire simulator. In field models, to study the transfer of energy and mass, the space is divided into many cubic cells. Compared to zone models, field models are considerably heavier in terms of computational load. Fire Dynamics Simulator (FDS) developed by NIST is the most frequently used computer program for field models (McGrattan et al. 2010). FDS has provided invaluable knowledge about fire behavior. For instance, researchers showed that the expansion of smoke depends on the exact location of the fire in the floor plan (Abdel-Gawad and Ghulman 2013). A fire simulation in a 50-story building using FDS showed that elevator lobbies can significantly increase the time until the shaft fills up with smoke and decrease the temperature and pressure difference inside the shaft (He et al. 2015). It was also used to conclude that emergency fans, which operate during a fire event, have a significant role in reducing the smoke density inside a multi-story building.

Evacuation models were complemented by FDS to reflect the effect of fire growth in the course of evacuation by influencing the reactions of the evacuees (Choi and Chi 2019, Shi et al. 2008). FDS+EVAC, which is an agent-based model capable of simulating evacuation during a fire, incorporates the effect of temperature, smoke, and noxious gas on the movement of agents (Korhonen 2010, Nguyen et al. 2019). However, in FDS+EVAC, the user cannot adjust the evacuation strategies and the evacuation is always performed based on the shortest path. FDS and GIS data can further be used to incorporate fire phenomenon and the building environment in an agent-based evacuation simulation (Tang and Ren 2008). FDS combined with agent-based crowd simulation has also been used to assess strategies of evacuation in high-rise buildings (Mirahadi and McCabe 2020).

The quality of an evacuation process can be measured in several ways. The term, “evacuation time” was introduced in 1917 as the “maximum emptying time” (National Fire Protection Association 1917) and it eventually evolved to the time between the activation of an alarm and the completion of the evacuation (Ng and Chow 2006). Evacuation time derivatives such as average evacuation time, average travel distance, and average waiting time have also been used to assess and report the quality of evacuation (Owen et al. 1996). However, evaluation based on these measures neglects the delay between the hazard recognition and response times of individuals, and phenomena related to the dynamic nature of a fire hazard. Importantly, real-time management of crowds during emergencies demands that people be guided away from the hazard along the safest possible route. As such, finding the shortest path does not necessarily guarantee a safe evacuation.

Required safe egress time (RSET) and available safe egress time (ASET) were later introduced in fire safety engineering (Cooper 1983). RSET refers to the time for occupants to exit a building safely. The most comprehensive definition for RSET starts at the moment of fire ignition and covers the time for detection, alarm activation, occupant decision to take action, and the travel time for the occupant to reach a safe place out of the building (Nelson 2002b). ASET refers to the time it takes for a fire to make the building untenable. The objective in this approach is to keep ASET > RSET.

RSET/ASET has been adopted by several national organizations, including National Research Council of Canada (NRCC), International Organization of Standardization (ISO), and British Standard Institution (BSI) (Proulx et al. 2006, ISO 1999, ISO 2012, ISO 2009, BSI 2004). These organizations and standards have promoted the application of RSET/ ASET; however, they lack a comprehensive and clear procedure for the measurement and calculation of RSET/ASET (ISO 2009, ISO 2007). For instance, multiple definitions and tenability thresholds have been suggested to limit visibility, obstructions, poisonous gas concentrations, oxygen availability, and temperature (Hadjisophocleous and Benichou 1999). These varied definitions and thresholds demonstrate subjective life safety tolerances and explain the lack of objectivity on the quantification of RSET/ASET.

Route Risk Index (RRI), designed to quantify the risk of each egress route, was proposed to allow comparison between egress alternatives (Mirahadi et al. 2019). This index considers in its calculation the duration of an evacuation route and its proximity to hazards. Equation 1 shows the formula of RRI.

$$RRI = \int_{t=0}^{T} \frac{1}{ALET_{p(t)}}\ dt \qquad \text{Equation 1}$$

Where:

$ALET_{p(t)}$ (Available Local Egress Time) is the time it takes for a fire to reach $p_{(t)}$;

$p_{(t)}$ is the location (x,y,z) of an evacuee at time t;

T is the total travel time of an evacuee from their starting location to the end of the egress route; and,

t=0 represents the time for initiation of fire.

Given Equation 1, the risk of being at point $p_{(t)}$ is equal to 1/ALET, which is integrated over time to determine the risk for the entire evacuation path. Compared to the shortest path approach, RRI can provide results that are more reliable for the design of a performance-based evaluation model for building evacuations (Mirahadi et al. 2019).

The final exit strategy is useful only when the EMS can communicate with the evacuees and provide them with evacuation instructions. A sophisticated plan with all its details in a complex building layout is challenging to transmit to evacuees with traditional exit signage or garbled voice communication systems. ADSS refers to changeable exit signs in which the exit direction could be altered or negated during an evacuation. ADSS, dynamic signage system, or adaptive signage system, all refer to the same concept of changeable exit signs. Utilization of ADSS needs a control unit capable of updating the signs' directions and guiding evacuees toward safety. A case study in Sant Cugat Station, Barcelona proved that ADSS has a positive effect on route choice compared to the traditional static signs (Galea et al. 2017). It was also witnessed that a negated sign is not sufficiently effective to direct a user and it needs to be supplemented by a sign presenting an alternative direction. Empirical data shows that ADSS might extend the evacuation time; however, it is more successful in sending people away from the high-risk zones (Lin et al. 2017).

3. Model Development

EvacuSafe is presented as a powerful model that integrates network graphs, RRI, Dijkstra's algorithm, and ADSS (Figure 1). Because fire emergencies are the most frequent reason for building evacuations, EvacuSafe focuses on fire as the hazard. However, the same methods could be used for any hazard. In the model, BIM is employed to feed other modules with functional and physical characteristics of the facility. BIM is transformed into the IFC data structure to facilitate interoperability between the modules. IFC is parsed and the geometric network graph (GNG) is generated to visualize the simplified spatial information regarding available navigable connections between the spaces. Fire simulations are run in the pre-event stage and in that way, insights are acquired about the expansion and migration of fire products from different initiating locations. One crucial task is to detect the exact location of the hazard. The detection module, which is triggered by the fire alarm system, is set to an un-tenability threshold and is activated when the threshold is surpassed. Once the detection module locates the coordinates of the hazard, the GNG is complemented by semantic information inferred from the fire simulation and detection modules.

A risk factor is defined by combining geometric and semantic information of the GNG. Those risk factors are then assigned to the edges of the GNG to differentiate between the effectiveness of each evacuation route. Finally, Dijkstra's algorithm is applied to find the updated safest path of evacuation for each node. The guidance system can then be updated based on the safest paths.

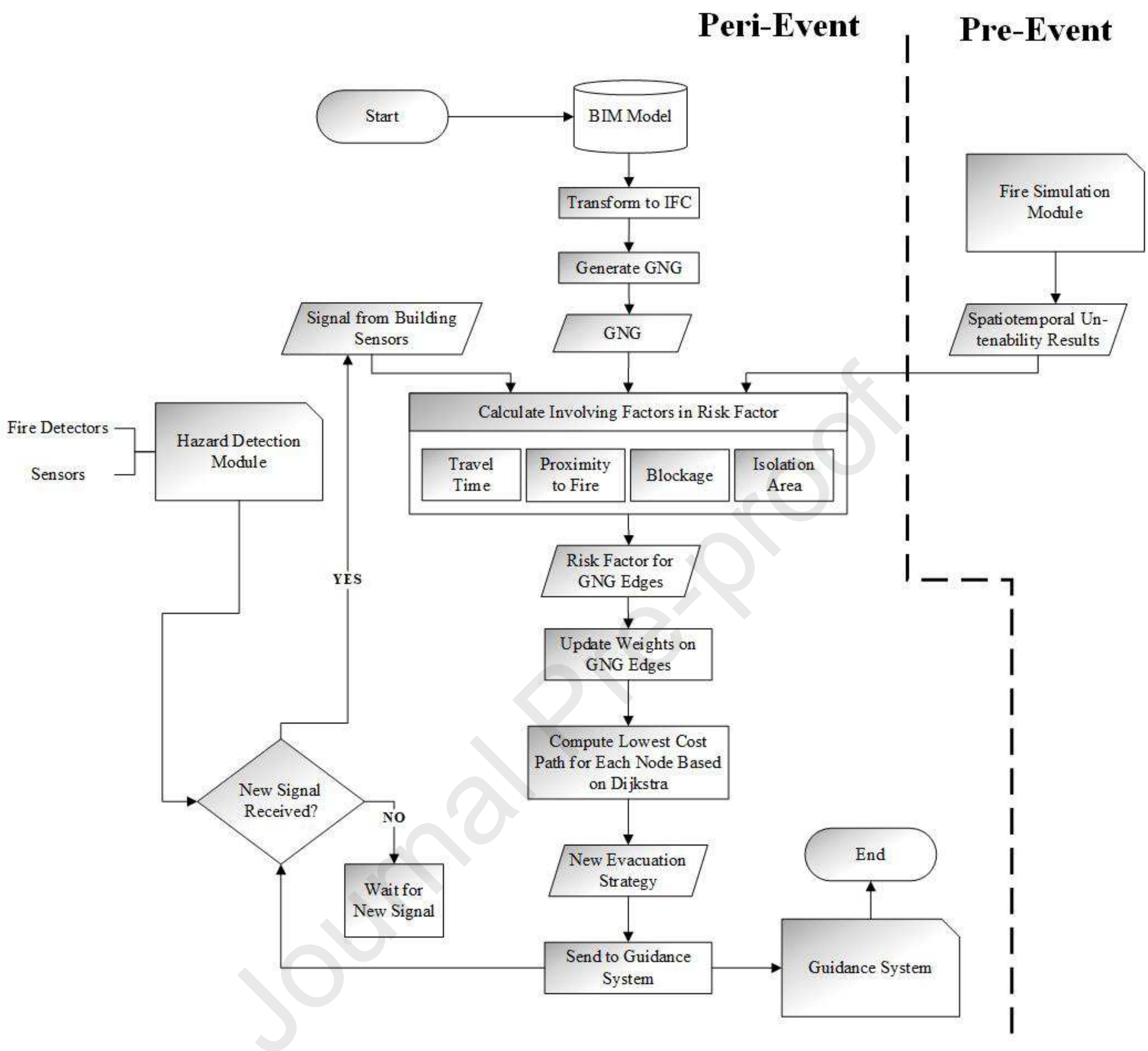


Figure 1: Flowchart of EvacuSafe

3.1 GNG

GNG is proposed as a 3D network graph representing the topology of navigable connections between the spaces in the building. GNG has to be defined in a way that it would present the geometric and spatial information related to the compartments and their interfaces. Although it does not mean that occupants strictly follow these simplified paths, it provides crucial information about the spatial sequence of evacuees' traverse and a rough estimation on the cost of each route. In GNG, coordinates of the nodes and lengths of the edges reflect the exact location of navigable building elements and their distances from each other, respectively. Each node stands for a space, door or virtual space delimiter. A space delimiter is a virtual element separating two adjacent compartments to semantically differentiate the identities of those spaces.

The graph is defined in continuous 3D space. Each node is positioned at the center of each space, door or space delimiter, and the length of each edge is proportional to the distance between those nodes. The conventional GNG is built by connecting the spaces through the doorways, which connect them. This approach causes some discrepancies in pathfinding by inaccurate intra-space pathfinding and overestimation of distances. This issue is illustrated in Figure 2.

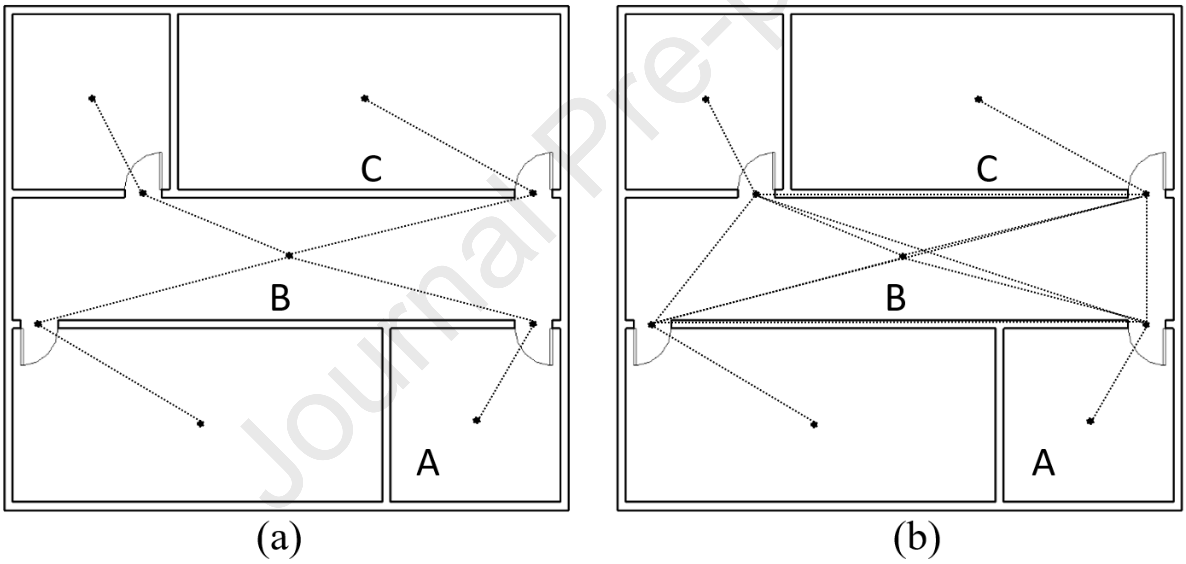


Figure 2: Conventional GNG (a) vs improved GNG (b)

Assume that an agent wants to travel from the center of room A to the center of room C using the shortest path. If the GNG is constructed only by connecting the spaces to the door, as shown in Figure 2 (a), the agent getting out of room A has to go to the center of room B and then return to enter room C. Therefore, the GNG cannot represent a realistic view of the movements in the building and over calculates the traversed distance. By connecting all the doors (or virtual space delimiters) within a space, a more efficient GNG is built, as shown in Figure 2 (b). This improved graph allows the agent to move directly between the doors going to the center of the intermediate room.

It is worth noting that the aforementioned issue of conventional GNG can be also fixed with the spatial discretization of the compartments. The unrealistic path-planning problem happens in high ratio compartments such as narrow or long corridors. Although it requires extra processing on the BIM model, spatial discretization of compartments to smaller squares can partially rectify the issue.

To generate this graph automatically, two sets of information are required: 1) the data related to the available connections between the spaces; and, 2) the data related to the location of each node in the space and the distance between the nodes. The IFC data structure can provide this information and remain independent of a specific BIM file extension, but requires some explanation.

ifcRelSpaceBoundary was first introduced in IFC release 1.5 and was later modified in the 2X release. This entity determines the physical or virtual relationship of each space with its surrounding elements. Two attributes of this entity are *RelatingSpace* and *RelatedBuildingElement*. *RelatedBuildingElement* specifies the elements, including walls, doors or virtual elements that are immediately connected to that space. *ifcDoor* and *ifcVirtualElement* matter here. In this terminology, a virtual element is a delimiter between the rooms or spaces. This element does not exist in the built environment and its only purpose is to allow decomposition of one space into smaller segments. The IFC file is parsed and a query is run to filter the spaces sharing common virtual elements or doors. Therefore, spaces sharing the same element of these two types are connected to each other. Also, the doors and virtual elements belonging to the same space are connected to each other. Gradually the graph of the entire building is constructed. This graph contains information about the characteristics of all connections between the spaces and doors.

The other element that needs to be extracted is the center of each building element. *ifcSpace* has two subtypes of *IfcProductDefinitionShape* and *ifcLocalPlacement*. *ifcLocalPlacement* defines the placement of the element, i.e. a space here, in the 3D space. *IfcProductDefinitionShape* describes the physical or topological representation of the product. What matters here is the footprint of the building element projected on the navigable surface. Each space's boundaries are represented by polylines and composite curves (Lin et al. 2013). The type of this projected shape on the surface combined with the information related to the coordinates of the boundaries facilitates the calculation of the centroid of each space. The same approach is adopted to find the centroid of doors and virtual elements. The combination of the network graph generated from navigable connections between the centroids of the spaces, doors and virtual elements generates a GNG in which the length of edges and coordinates of nodes exactly imitates the building dimensions in reality.

The GNG prepared in the previous step shows the navigable skeleton of the building. However, it does not present any information regarding the desired movement of the evacuees in the building. As will be explained in the next sections, the best path of evacuation will be selected by EvacuSafe. Merging the selected strategy with the GNG generates a directional GNG, which specifies the safest direction of evacuees' movements by inserting arrows on the edges of the GNG.

GNG is only the visual representation of space connections in the building. An adjacency matrix is the mathematical representation of the GNG. An adjacency matrix is an *n-by-n* matrix filled with 0 and 1 values, where *n* is the number of nodes. A value of 1 indicates that the pair of nodes are connected to each other. In the case of directional graphs, only one element of the pair is marked as 1.

3.2 Cost Function of Path-planning (C)

In this research, four factors are considered in the measurement and modeling of evacuation safety. The first is the travel time of the evacuee (τ). The second is the path's proximity to the fire (ρ). The third is blockages caused by malfunction of the doors or structural collapse, for example. And, the fourth is the isolation of areas anticipated to catch fire in the next step. It has to be mentioned that the effect of congestion is not considered in this research. It is assumed that the flow rates of building outlets are unlimited and they cannot hinder the evacuation flow.

Path-planning is an optimization problem and it requires a cost function that takes all of the factors into consideration. The cost function for the traversed path containing *n* nodes is defined in Equation 2.

$$C = \sum_{i=1}^{n-1} I_{i-i+1}\, \rho_{i-i+1}\, \tau_{i-i+1} \qquad \text{Equation 2}$$

where:

I_{i-i+1} is the isolation factor for the edge connecting node *i* to node *i+1*

ρ_{i-i+1} is the risk factor of the edge connecting node i to node i+1, due to proximity to fire

τ_{i-i+1} is the travel time between node i and node i+1

$$\tau_{i-i+1} = \frac{d_{i-i+1}}{\bar{V}} \qquad \text{Equation 3}$$

where:

$\bar{V}$ is the average speed of evacuees

d_{i-i+1} is the Euclidean distance between node *i* and node *i+1*

$$d_{i-i+1} = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \qquad \text{Equation 4}$$

Where:

x_i , y_i , z_i are the coordinates of the node i

x_{i+1} , y_{i+1} , z_{i+1} are the coordinates of the node i+1

Each of the aforementioned factors and details in Equation 2 is explained in the following sections.

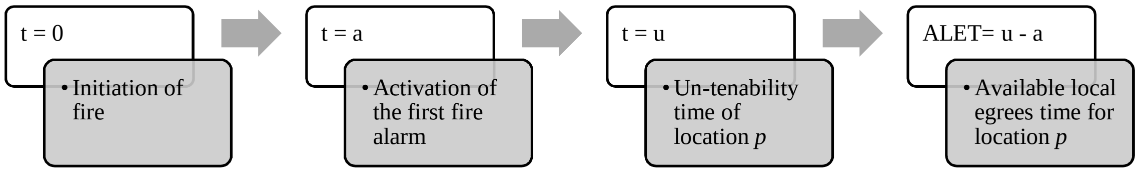
3.2.1 Proximity to Fire ($\boldsymbol{\rho}$)

When a fire is initiated in the building, each location in the building is subject to a level of risk. Herein, the risk factor is defined based on the philosophy of *RRI* (Eq. 1). $\rho_{p(t)}=1/ALET_{p(t)}$ represents the risk of being at any location *(x,y,z)* in the building at time *t*. $\rho_{p(t)}$ is based on the time that each location can remain tenable from the evidence of fire. $\rho_{p(t)}$ identifies which locations are in greater danger relative to the others. However, to compute *ALET*, we need the fire simulation.

The fire simulation module evaluates the characteristics and expansion pattern of a fire based on a number of inputs, which vary based on the selected fire simulation software. In this research, FDS is used as the fire simulation module. However, any other fire simulator that is able to provide tenability indices versus time and space and interface with other software can be applied here. Building geometry, building materials, fire loads such as furniture, location of doors and windows, ventilation type, and locations of sprinklers, smoke, and heat detectors are mandatory inputs for FDS. Herein, the IFC form of BIM is imported to initialize FDS. The detailed process of data transfer using IFC can be found in Mirahadi et al. (2019).

The output of the fire simulation module contains a report of smoke density, temperature, and dosage of noxious gas at every location and time. Herein, un-tenability is based on the activation of the smoke alarm system. The smoke alarm can provide residents with an early notification before an untenable condition dominates. This assumption might seem conservative, but the literature shows that smoke detectors normally provide sufficient time for residents to egress before untenable thermal and toxic gas conditions prevail (Mealy 2009). This assumption forces EvacuSafe to redirect the crowd before they encounter a serious condition that is dangerous to their health and functionality. Moreover, research shows that in 40.9 % of civilian fire injuries in residential buildings, the primary symptom of reported injuries was smoke inhalation (U.S. Fire Administration 2017). It is worthwhile to mention that the un-tenability threshold can be modified to represent the functionality and safety requirements of the specific facility.

Fire simulations are computationally heavy and cannot be performed within the tight time limits of an emergency situation. Thus, this process is performed within the pre-event stage of EvacuSafe as shown in Figure 1. Fortunately, real emergencies are not frequent and this provides the pre-event stage with benign time restrictions. During evacuation planning in the pre-event stage, the fires are initiated sequentially in the fire simulation. The results of the simulation contain the un-tenability times for all of the compartments associated with each initiating fire, with t=0 being when the fire is initiated. The occupants are notified about the fire when the first fire alarm is activated. Therefore, the ALET for occupants in each compartment is measured from the time of activation of the first detector. In other words, ALET in each compartment is equal to un-tenability time minus the time difference between the fire initiation and the first smoke detector activation.



In this way, ρ is assigned to each compartment of the building. If another fire occurs concurrently in the building, the ρ values are summed for each compartment in order to simulate the intensity of risk resulted from a larger fire covering all of the compartments that are on fire. Although this assumption might be different from the real risk of proximity to both sources of fire, it overestimates the risk and provides conservative results. Therefore, once a fire is sensed in the building, the risk of presence in other rooms is inversely related to the period that each room can remain free from evidence of the fire.

Practically, the tenability can be measured in some discrete points in the building. These points are where sensors, such as smoke and heat detectors, are installed. Therefore, tenability can be measured and reported at the scale of rooms. In the calculation of cost function, ALET of each space is associated with all the edges crossing within the borders of that space.

One of the challenges in calculating ALET is that there is no absolute number to define the threshold of un-tenability. Smoke and heat detectors are typically activated at 11% visibility obstruction (0.05 OD/m) and 57º C respectively; however, people can stay alive and mobile in worse situations. The definition of an untenable situation varies in the codes and regulations, which is why the thresholds are set based on the experts' opinion and the desired margin of safety, code values, or default values in the sensors.

3.2.2 Travel Time ($\boldsymbol{\tau}$)

Travel time is an important criterion in an evacuation, and it is reasonable to send occupants out of the building as soon as possible. The travel time of an occupant from point A to point B depends on speed, acceleration, congestion, terrain, toxicity of the space, and visibility. For simplification, if the speed of an agent is assumed constant during the egress, the travel time is linearly proportional to the distance of the travel. The Euclidean distance of each edge is calculated during the development of the GNG. The target is to minimize $\frac{d}{v}$ and find the shortest safe path to a building exit.

3.2.3 Blockage

In emergencies, obstructions or blockages can occur not only because of the fire itself, but due to the malfunction of doors or to a structural collapse, which means that the evacuees cannot pass through the desired route and must take a detour. The early detection of blockages can save significant time and counter flow by guiding people toward other routes. Previous research to detect blockages using CCTV cameras and CCC sensors (Ergen et al. 2015) allows the current authors to focus on how the identification of blockages can be fed into EvacuSafe, rather than on how blockages are identified.

To model a blockage in GNG, the impacted doors or spaces are eliminated from the GNG. Two situations could be imagined. First, if the blockage is caused by a door malfunction, the corresponding door node is removed from the GNG. Second, if the blockage is caused by a collapse in a space, the node related to the corresponding space and all of the doors connected to that space have to be eliminated from the GNG. In this way, the blocked locations are not used in finding the lowest cost path.

3.2.4 Isolation Factor (I)

There are some areas in the building, such as rooms immediately connected to the fire room that evacuees should not pass through unless there is no way around them. Even if the evidence of fire has not yet exceeded the tenability threshold, their high potential for being the next untenable spaces should take them out of the immediately available routes. Therefore, isolation factor I is defined. In safe spaces, I = 1. But in areas immediately connected to the fire location, I is set to a very large number (e.g.

1E+12), which escalates the cost of routes consisting of the selected rooms. In this manner, those routes are neglected until they will be the only way out for the occupants.

3.3 Dijkstra's Algorithm

The Dijkstra's algorithm is a widely used graph search algorithm in navigation and robotics. The algorithm can be modified to calculate the cost rather than the length of each path. In EvacuSafe, the GNG is used as the target graph for the Dijkstra's search and the cost of each edge is measured using Equation 1.

In Dijkstra's, the start node is tagged first. Then, the cost of travel to all the connected nodes is calculated. The node with the smallest value is tagged. Then, the costs of travels to all of its connected nodes are calculated. The cost of unvisited nodes is updated if it is less than their previous cost. This process continues until the end node is achieved.

The target is to find the lowest cost escape route for each space in the building. Therefore, the Dijkstra's algorithm is run multiple times as each space is tagged as the start node and repeated until the lowest cost routes for all of the spaces in the building are found. Because large facilities and high-rise buildings typically have multiple exit doors, there exist multiple goals in this optimization problem. The Dijkstra's algorithm is therefore solved for multiple end nodes and the minimum of those is the final solution. As an alternative approach, one pseudo-node with edges holding similar weights and connected to all exits can be defined as the end node. In this way, Dijkstra's can be run once to evaluate all the exits at the same time. Merging the result of the Dijkstra's search with the GNG produces a directional graph to specify the safest route.

3.4 Guidance System

The final evacuation routes must be communicated to evacuees during the emergency. The quality of this communication is very important, as it defines the efficiency of the model. In this paper, ADSS is used to guide and divert the crowd. ADSS can provide continuous local instruction along every evacuation route. In addition, ADSS signs are controlled by an automated control system, which eliminates the risk of human errors, confusion, and inefficiencies in controlling the crowd.

The locations of dynamic signs are determined by the floor plans. Signs must be installed such that they are visible to evacuees and effectively redirect their flow when conditions change. Decision making about the location of active dynamic signs needs thorough knowledge about the evacuation safety and technical specifications of the ADSS control unit. Thus, once the safest evacuation routes are chosen, they will be transmitted to the ADSS control unit. The control unit is responsible for putting all the signs in order. Signs can direct evacuees to the right, left, or be dissuasive.

Assuming that the location of every active dynamic sign is identified in the floor plan, an algorithm in the control unit can translate the directional GNG to the visual signs of the ADSS. This can be achieved by relating each active dynamic sign to the nearest node in the GNG. This node can represent a space, door or virtual element. Therefore, the direction of the dynamic sign will follow the direction of the exiting edge of the associated node in directional GNG. Figure 3 illustrates this method with an example.

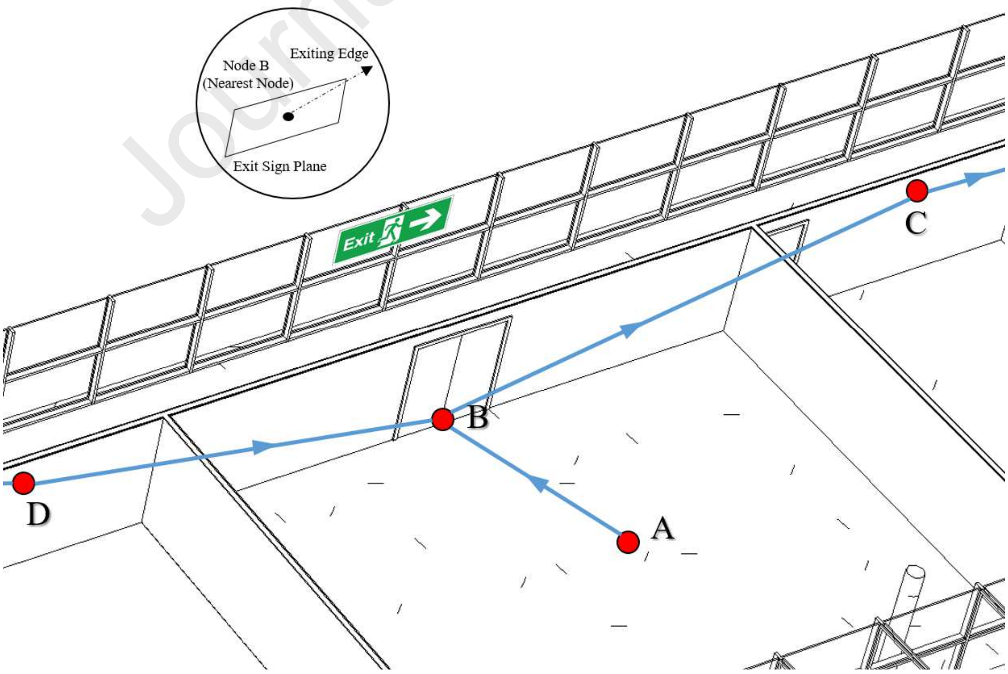


Figure 3: Nearest node method for updating ADSS

3.5 System Iteration

The final routes and path-planning sent to the guidance system are valid until a new signal is received from the hazard detection module. A new signal means a change in the initial parameters of the modelling. The change could be the result of a new blockage, a new compartment affected by fire, another source of fire, or related to currently available accesses for egress. Repeating the process of path-planning can lead to a very different safest solution. Therefore, the initial egress routes concluded in the previous run are no longer reliable for the safe egress of evacuees. EvacuSafe can provide continuous real-time guidance to evacuees only when the path-planning procedure is repeated after each significant change in the building. To that, EvacuSafe goes to another iteration of GNG cost calculation, Dijkstra's optimization and guidance system update once it receives a new signal from the hazard detection module.

Any change to the evacuation strategy can affect the integrity of the evacuation process. Significant changes to egress routes can confuse the evacuees and lower the chance of obedience from the prescribed evacuation strategy. Therefore, a tolerance is required to check the value of strategy change. If the cost of the new egress route is within that tolerance, e.g. ±5 % of the cost of the current route, route change is not justified or needed.

4. Implementation and Discussion

This case study involves a two-story office building to demonstrate the proposed framework. The floor plans of the 1st floor (a) and the 2nd floor (b) are extracted from BIM and shown in Figure 4. The building has three staircases, two of which are connected to outdoor spaces; the third one connects the two floors but does not exit at the ground floor. The first floor has three exits. The rooms, corridors, and staircases are divided into 59 compartments. Photoelectric smoke detectors and heat detectors are installed in every compartment.

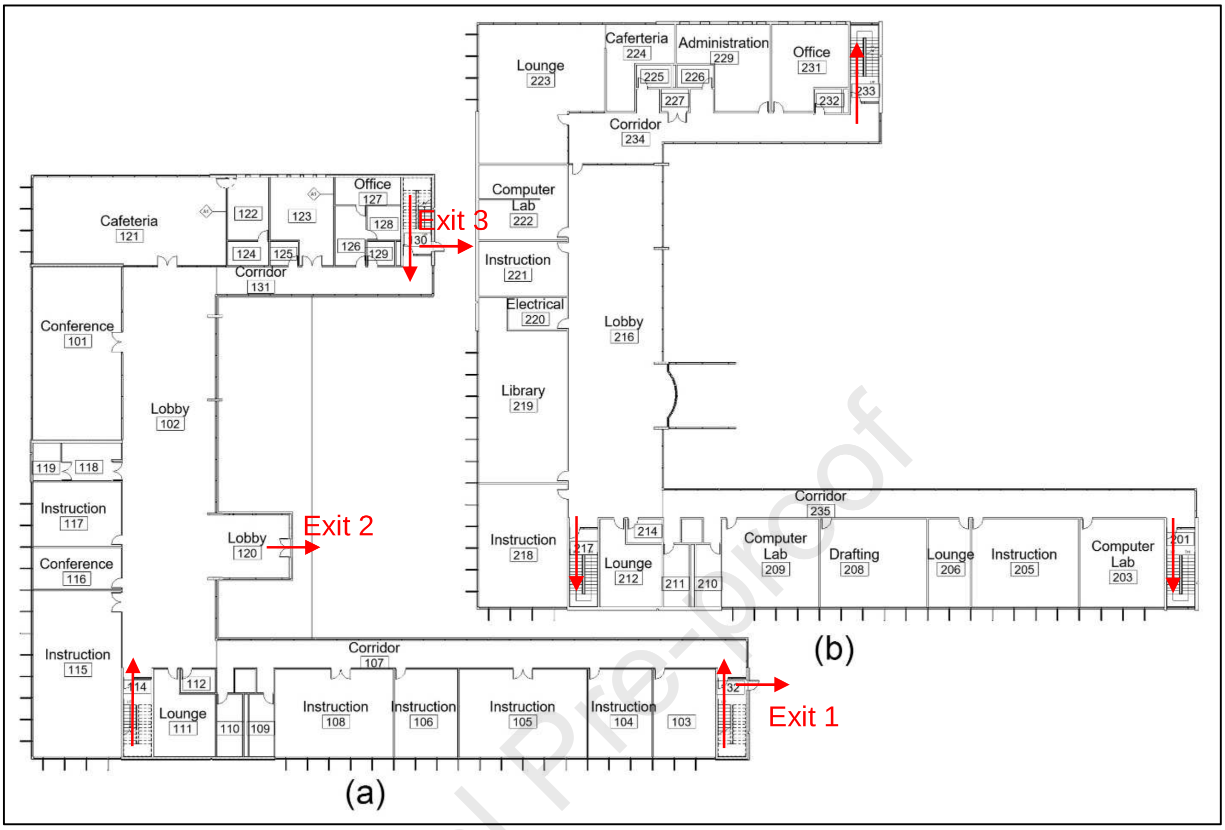


Figure 4: Floor plan of the building (a): First Floor, (b): Second Floor

The BIM of the building is transformed into IFC data structure and the IFC file is parsed. Based on the method using *ifcRelSpaceBoundry*, *IfcProductDefinitionShape* and *ifcLocalPlacement* described in 3.1, the improved GNG is extracted (Figure 5). The nodes corresponding to the exit doors are annotated in the figure.

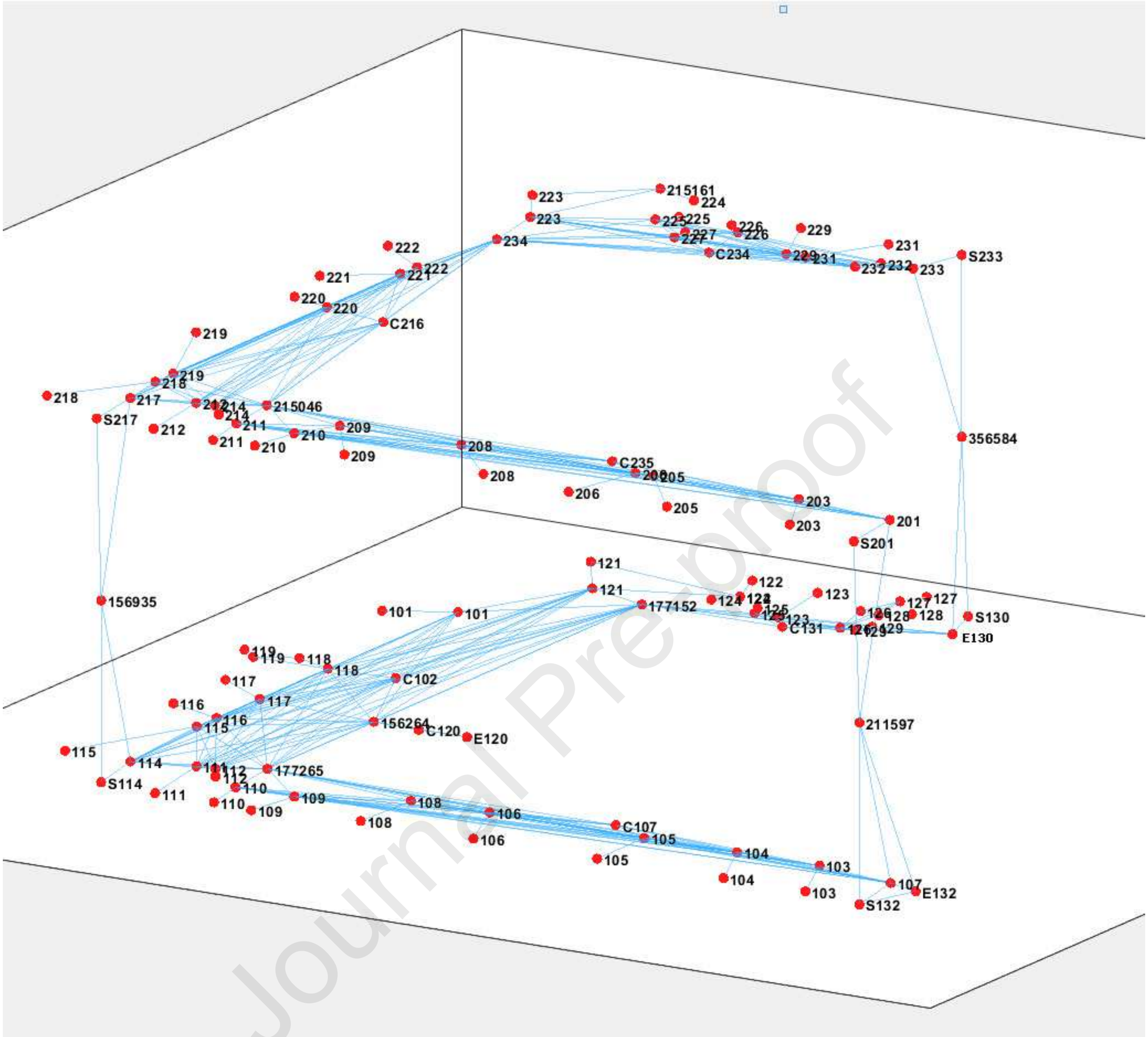


Figure 5: Improved GNG of the building

FDS is used to simulate the fire initiation and expansion. Geometric attributes, materials, locations of detectors and sensors, ventilation system properties, and potential furniture and fixtures as fire loads are imported directly from IFC to FDS to initialize the fire simulation parameters. This seamless connection can significantly enhance the efficiency and robustness of the data transfer. It is assumed that the fire-initiating element is a piece of household furniture, represented by a 1 cubic meter block of wood. The early alert of un-tenability or an approaching fire has a visibility threshold of 11% obstruction. Due to the computational heaviness of FDS, the fire simulations are run for a large number of scenarios during the pre-event stage, i.e. well before the emergency happens. The initiating point of fire is modeled in all of the compartments and the resulting un-tenability times for the remaining rooms are calculated. Each fire scenario was run 10 times and the average results were used as final un-tenability times. These un-tenability times are resulted from the activation times of smoke detectors initialized in the fire simulation. The simulation results are then stored for access during the peri-event stage of an emergency.

In scenario A, it is assumed that the fire is initiated in compartment 103 in the south-east corner of the first floor. From the fire simulation module, un-tenability times of the compartments associated with the fire initiated in compartment 103 are recalled from the fire simulation module. Un-tenability time defines ALET and ALET defines ρ in Equation 2. Using this equation, the risk factor R of each compartment due to the proximity to the fire is equal to 1/ALET. The risk factor of each edge is defined based on the compartment in which the edge lies. The average speed of evacuees is assumed at 1.35 m/s based on a study of commuters of varying genders and ages (Fruin 1971). In this example, no blockage or isolated area is considered in path-planning. The Dijkstra's algorithm is later run for each space-node based on the cost function of Equation 2. The graph in Figure 6 shows the lowest cost path associated with each compartment. As seen in the graph, the cost (C) associated with compartment 103 is very high at more than 1000. By the time the smoke detector in compartment 103 is activated, the ALET for this compartment is equal to 0. However, $ALET=0$ placed at the dominator of Equation 2 will result in an error. Therefore, a very small number e.g. 1E-12 is adopted as the ALET of compartment 103, which will lead to a very high-cost value for the route passed through compartment 103.

The selected path for each space is calculated and presented in the form of arrays, showing the sequence of to-be-traversed nodes. In Figure 7, the selected path for each space-node is visualized by defining different zones. Each zone is assigned an exit route. As shown in Figure 6, room 103 is already un-tenable and that is why the value of cost function associated with it is very high. In this case, the evacuee cannot avoid the fire and the algorithm looks for the route with the shortest travel time within the untenable zone.

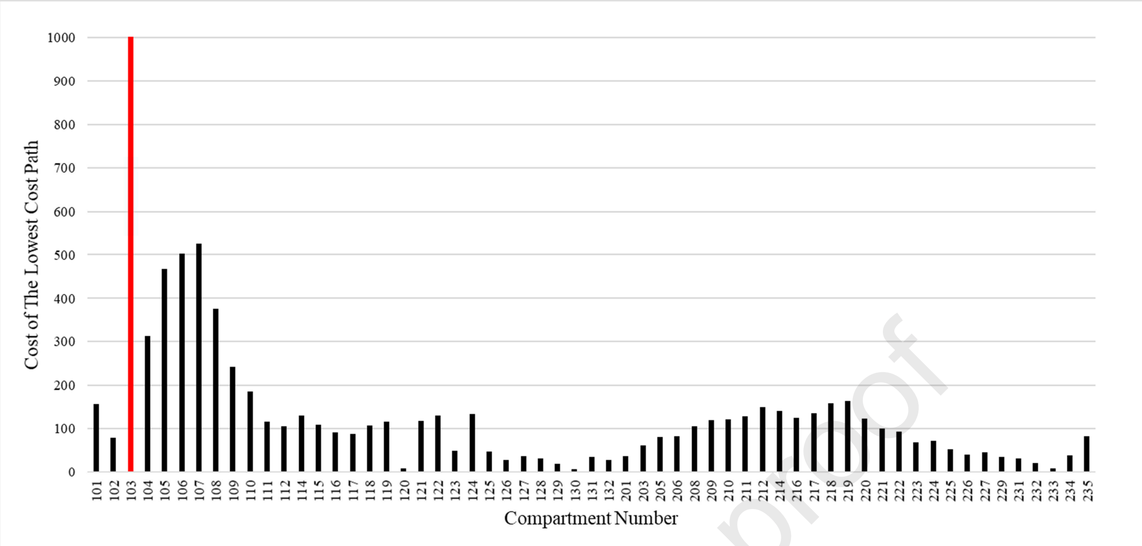


Figure 6: Scenario A: The Cost of the Lowest Cost Path vs. Compartment Number

In floorplans with large compartments, such as lobbies or long corridors, treating the compartment as one unit can cause confusion in path-planning. Since the optimized route is calculated only based on the center of the compartment, the selected route might be improper for marginal zones of the compartment. For example, in Figure 7, corridor 107 is inside the blue zone, directed toward exit 132. This path is concluded based on the center-point of the compartment. However, this decision does not make sense for the left side of the corridor, where compartments 106, 108, 109 and 110 are directed to the left and toward exit 120. The corridor is therefore shown in blue and orange checkered pattern. Such discrepancy can be avoided by discretizing the compartment to smaller compartments in BIM using virtual elements. For simplification, it is assumed that once the egress direction of a corridor is different from the room immediately connected to it, the direction has to be modified to comply with the room. Future research should focus on how corridors and lobbies should be discretized to address this issue.

The graph exploration and cost optimization of Scenario A, which must be performed during the evacuation process, took less than 1.0 second on a Core i-7 dual core 2.7 GHz. This quick computation time satisfies the need for an algorithm that could reliably perform during an emergency.

Figure 1: Scenario A: Escape route plan fire initiating in compartment 103

In Scenario B, we assume that a fire initiating in compartment 103 has not been restrained and the smoke and heat will be sensed in room 107. The alarm from the smoke detector of compartment 107 forces the system to update and recalculate all of the routes. Once the system receives a signal indicating a change in the assumptions of path-planning, it recalculates the paths. The risk of proximity to fire in this case is calculated by adding 1/ALET caused by the fire in room 107 to 1/ALET caused by the fire in room 103. Therefore, the new cost for each edge is determined and the Dijkstra's algorithm is run to find the lowest cost routes. The result of the analysis is shown in Figure 8 and Figure 9.

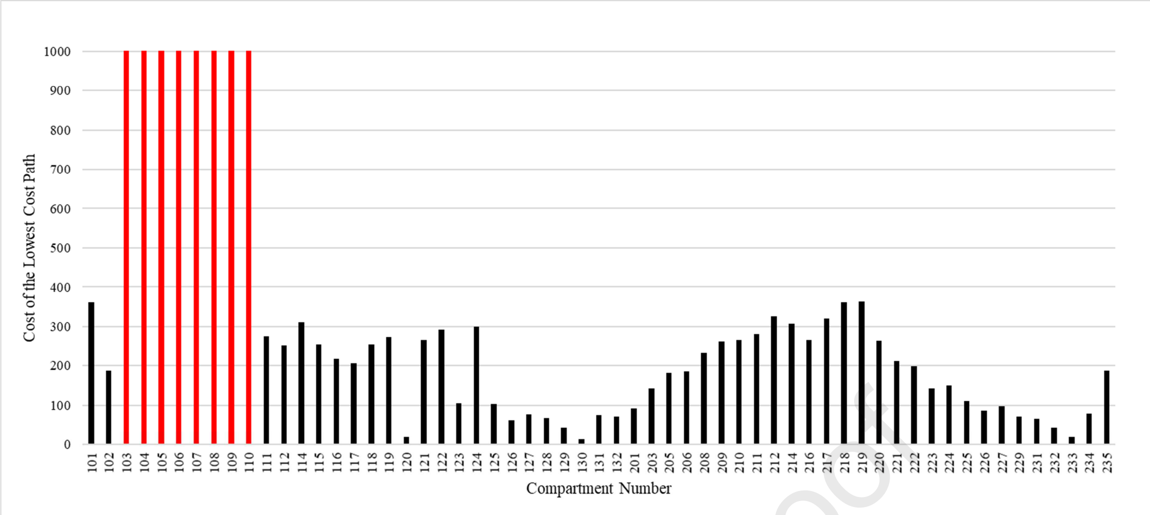


Figure 8: Scenario B: The Cost of the lowest cost path vs. compartment number

Comparing Figure 9 with Figure 7 shows that the violet area on the second floor in Figure 7, which used compartment 217 to go downstairs and exit from compartment 120, disappeared. Instead, those compartments are now using staircase 201 and then exiting by compartment 132. This change recognizes that there is no barrier between compartment 107 and 102, therefore, room 102 will be filled with smoke earlier than compartment 132. From the mathematical perspective, 1/ALET in 132 is smaller than that of 102; therefore, Dijkstra's suggested the route passing through compartment 132.

Looking at the two emergency scenarios, the algorithm works in terms of diverting the crowd from the un-tenable compartments toward safer zones. However, the algorithm may not be effective in terms of anticipating fire growth directions. In both situations, compartment 132 is too close to the source of fire, but people were unfavorably routed through that compartment. The isolation factor may be helpful at this stage. A large number e.g. 1E+12 is assigned to the spaces that are immediately surrounding the fire initiating compartment. In the scenario where the fire started in compartment 103, the following compartments will be isolated: 132, 104 and 107. Let's also assume that there is a structural collapse in exit 120. This is Scenario C. Thus, all of the edges of the GNG within compartment 120 are eliminated. After performing the calculations and visualizing the selected routes, Figure 10 results.

Figure 9: Scenario B: Escape route plan fire initiating in compartment 103 and spread to compartment 107

Figure 10: Scenario C: Escape route plan for fire initiating in compartment 103, blockage in compartment 120, and isolated compartments: 104, 107, and 132

Figure 10 shows that in Scenario C, the majority of occupants are guided toward the north exit of the building. The exit at compartment 120 is inaccessible due to structural collapse and the exit at compartment 132 is expected to receive fire products imminently. Only compartments 103, 104 and 132 are evacuated from exit 132 because their distance to exit 132 is very short and compartment 107 is already isolated as a high-risk zone. If the evacuees originating from compartments 103, 104 and 132 decide to turn left and escape from compartment 130, they would spend more time inside the isolated high-risk zone of 107. This decision would raise their travelling cost. As such, they are directed toward exit 132.

As discussed in the model development section, path-planning and finding the safest strategy of evacuation is more beneficial when there is a guidance system to communicate with the evacuees. Complex and dynamic path-planning can be handled with ADSS. Based on the floor plans, the placement of the exit doors, and the staircase locations, Figure 11 shows suggested locations of active dynamic signs.

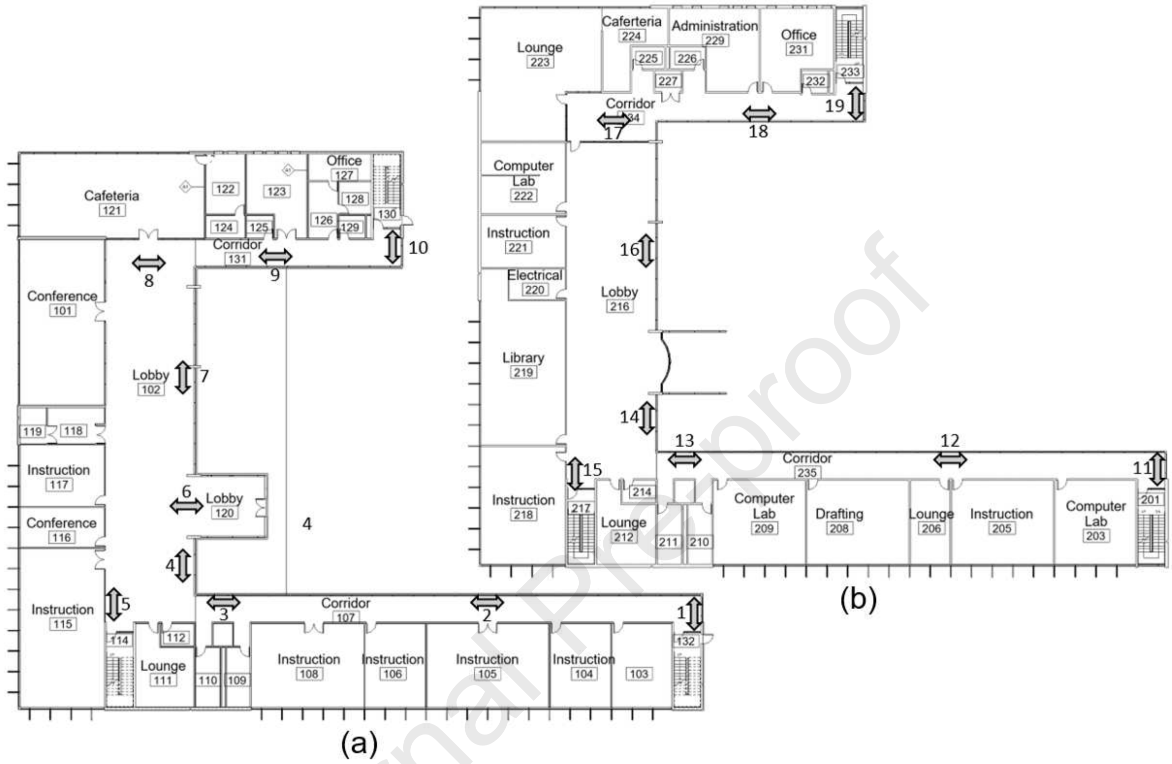


Figure 11: Suggested locations of ADSS signs

Once the ADSS signs are installed, the most important action is to update the direction of the ADSS signs in real-time during an evacuation. As described in Section 3.4, the nearest node approach is used to determine the correct direction of the ADSS at each point in time based on the updated directional GNG. The directional GNG is continuously developed based on the inferred routes of the Dijkstra's algorithm. Table 1 shows the images of the ADSS signs in Scenario C based on the floorplan in Figure 11.

Table 1: Images of the ADSS signs in Scenario C

	Facing	Nearest Node	Direction	Image of the Sign
1		Door 107	Right	
2		Door 105	Left	
3		Virtual Element 177265	Left	
4		Virtual Element 177265	Left	
5		Door 114	Right	
6		Virtual Element 156264	Negated Right	
7		Scape 102	Left	
8	North Side	Door 121	Left	
	South Side		Right	
9		Door 123	Left	
10		Door 131	Left	
11		Door 201	Negated Right	
12		Door 206	Left	
13		Virtual Element 215046	Left	
14		Virtual Element 215046	Left	
15		Door 217	Right	
16		Space 216	Left	
17	North Side	Door 216	Left	
	South Side		Right	
18		Door 229	Left	
19		Door 233	Left	

The proposed model has to be validated to evaluate the degree to which the safety of evacuees improved. For this purpose, Scenario A is used as a benchmark. Then we assume that the fire expands and by each state change in any detector/sensor, the path-planning gets updated. Unfortunately, in this subject of research, there is no possibility to test the scenario with a real case of fire to evaluate the consequences. Thus, ABM techniques are used.

The Ontario building code (OBC) recommends 9.3 m^2/person occupant load for office spaces and 3.7 m^2/person for corridors (Building Code Act 1992). The total area of both floors is 2920 m^2 including 367 m^2 of corridors and 2553 m^2 of offices, resulting in 99 agents in corridors and 275 in offices; this is rounded up to 400 agents distributed in these two floors. MassMotion© software is used to implement the ABM for crowd simulation. This software is verified and validated for modeling building evacuations as per NIST technical note 1822 (Ronchi et al. 2013). The interval between the first fire alarm and the evacuee's movement towards exits is called pre-movement time. However, none of the codes prescribes a firm pre-movement time. Herein, a pre-movement time of 50 s is based on the data collected via video cameras in 3 office buildings in Canada (Proulx and Pineau 1996).

A body ellipse of 0.6 m by 0.4 m (Fruin 1971) is suggested for the agents. However, it is simplified to a body circle of 0.25 m, which constitutes the same area while significantly reducing the computational load in simulating agents' movements and interactions (Kinsey 2015). A normal distribution with a mean of 1.35 m/s and a standard deviation of 0.25 m/s represents the speed of the agents. The maximum and minimum of the speed are 2.05 m/s and 0.65 m/s, respectively (Fruin 1971).

It is not realistic to assume that all of the evacuees will follow the signs. Some of the evacuees might become distracted or choose not to follow the signs. Therefore, it is assumed that the obedience of evacuees from ADSS signs is 90%, which was recommended based on field evaluation of ADSS (Galea et al. 2014).

The evacuation is simulated in MassMotion. In one scenario of simultaneous evacuation, all of the agents evacuate the building at once and they independently choose their shortest exit path. This represents the conventional evacuation process that asks evacuees to use the nearest exit. In the second scenario, it is assumed that the building is equipped with ADSS and the locations of the signs are based on Figure 11.

Meanwhile, FDS simulates the distribution of smoke density and temperature in the building. The movements of all the evacuees are tracked and it will be registered to the time-dependent distribution of smoke from FDS. The maximum level of exposure to smoke along the path of each evacuee are measured. In this experiment, FDS and MassMotion are run 10 times. Figure 12: compares the result of an evacuation led by EvacuSafe-RT with the result of the same emergency scenario, but accompanied by a simultaneous evacuation.

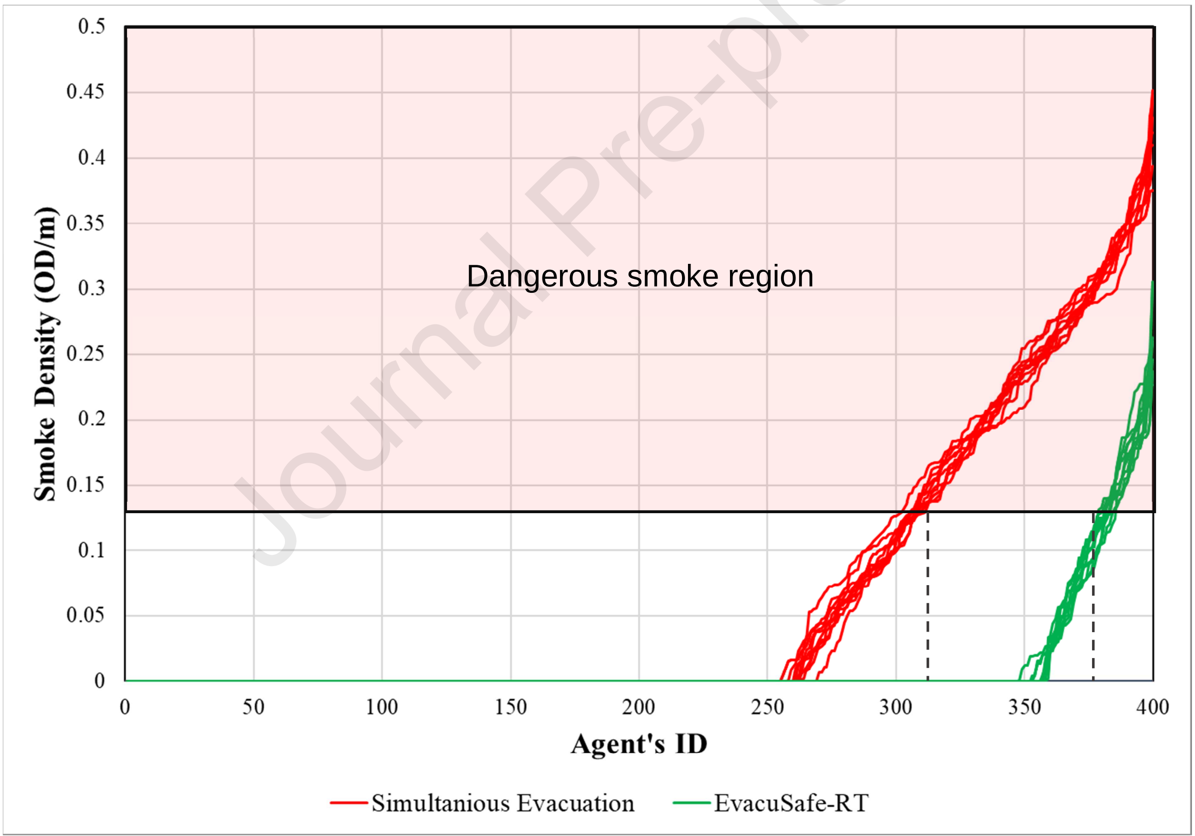


Figure 12: Maximum exposure of the agents to smoke in simultaneous evacuation vs. EvacuSafe (results of 10 simulation runs)

Previous studies show that smoke density of more than 0.13 OD/m can affect the movement functionality of evacuees (Poh 2011). Figure 12: shows that in 10 runs, at least 91 simultaneous evacuation agents are exposed to these high smoke densities, whereas the maximum number of exposed EvacuSafe agents is 22. Also, the maximum exposure in simultaneous evacuation (0.452) is 48% higher than the maximum in the EvacuSafe model (0.306).

5. Conclusion

EvacuSafe was proposed as a real-time model for building evacuation management. EvacuSafe comprises three modules that work together to build a real-time path-planning model for guiding evacuees toward safety during emergencies. In this model, the hazard detection module locates the initiating location of the fire, and then combines with the fire simulation, which is run in the pre-event stage of operation. EvacuSafe calculates the risk of being present at each location in the building. Geometric information available in BIM is extracted to generate the geometric network graph (GNG) of the building. Dijkstra's graph search algorithm is used to find the egress path starting from each compartment of the building with the lowest risk. Dijkstra's cost function considers travel time, proximity to the fire, blockage, and near future forecasts of fire expansion in its computation of the optimal path.

Unlike conventional path-planning approaches, which are based on crowd simulation methods, EvacuSafe can efficiently operate and respond within the time constraints of emergency situations. The model is alerted of changes to the status of the building and the emergency and updates the strategy of evacuation after each status change. Active dynamic signage system (ADSS) was adopted to demonstrate the potential effectiveness of EvacuSafe in improving the overall safety of occupants using agent-based crowd simulation. A two-story office building case study with 59 compartments demonstrates the research outcomes. Implementation results showed that the application of EvacuSafe combined with ADSS can lower the maximum exposure of evacuees to fire products. EvacuSafe also provides a safer evacuation by keeping more evacuees away from critical levels of exposure to dangerous fire products.

The main limitations of EvacuSafe can be summarized as: 1. Inability to consider the effect of congestion in path-planning, and 2. Inability to quantify the complexity cost of each strategy. Herein, the path-planning was based on graph exploration methods and there was no crowd simulation module to investigate the effect of crowd congestion in the building. Further research by incorporating the capacity of outlets or application of computer vision techniques can fill this gap. Moreover, the best evacuation strategy, which is mathematically calculated, might not be necessarily the most practical one. The simplicity of the evacuation strategy itself can increase the chance of obedience to the evacuation plan. More research in this area can allow us to quantify the practicality of each evacuation strategy.

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Highlights

- EvacuSafe was proposed as a real-time model for building evacuation management.
- Geometric network graph (GNG) of the building is extracted from BIM model.
- Proximity to fire, travel time, blockage and isolated areas are loaded to GNG as some weights.
- The safest path of evacuation is dynamically calculated based on Dijkstra's algorithm

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: