AN ABSTRACT OF THE THESIS OF

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Title: A BIM-based Simulation Framework for Fire Evacuation Planning.

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Fire hazards threaten human life and property safety. Even though the number of deaths, injuries, and property damages due to fire hazards have decreased within the past decade, they are still significantly high. This leaves room for improvement in current fire safety management practices—specifically, high-efficiency evacuation, which tends to be the best approach for minimizing both mortality and property loss. Since it is unrealistic to study human behavior during a real fire hazard, computational tools are a better choice to computational tools are a better choice to simulate fire growth and human behavior for predicting evacuation performance in chaotic emergency situations. Although previous scholars have conducted a great amount of fire emergency simulation research, further studies are necessary to investigate the critical factors that impact human evacuation performance and improve simulation accuracy.

This research study aims to develop an interdisciplinary simulation framework that involves the three influential factors (physical building properties, characteristics of the fire, and characteristics of human behavior) that impact fire evacuation planning for high-occupancy buildings. The simulation system can better predict evacuation performance the more influential factors it considers. To elucidate, the fire growth process is simulated by using the Fire Dynamic Simulator (FDS) tool and the

evacuation simulation is designed from an Agent-based Modeling (ABM) system. BIM serves as the environment to conduct these simulations and visualize the results.

The objectives of this thesis are to investigate the reliabilities of (1) using BIM to offer a platform for conducting simulation design; (2) simulating fire growth via the FDS tool; (3) accounting for the characteristics of the building properties, fire conditions, and human behaviors in the agent-based evacuation design; and (4) applying the simulation outputs on a linear regression model used to investigate the relationship between building design and required safety egress time. And finally, 3D BIM serves as the environment to visualize the results of (1) the hazardous zones that reflected in the fire simulation; (2) the effective escape routes that are recommended by the evacuation scenario.

The research results from this thesis provide valuable information for design and education purposes related to fire evacuation planning and safety management and ultimately help to minimize fatalities and reduce the economic loss caused by building fire emergencies.

A BIM-based Simulation Framework for Fire Evacuation Planning

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Qi Sun, Author

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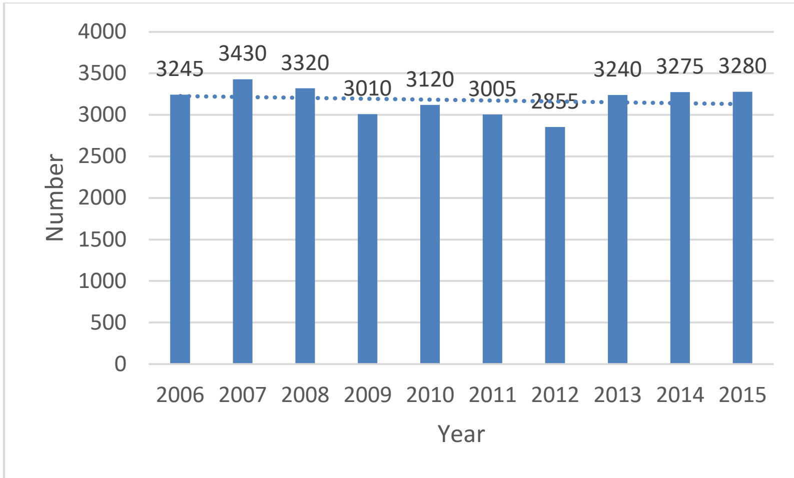
A BIM-BASED SIMULATION FRAMEWORK FOR FIRE EVACUATION PLANNING

1. INTRODUCTION

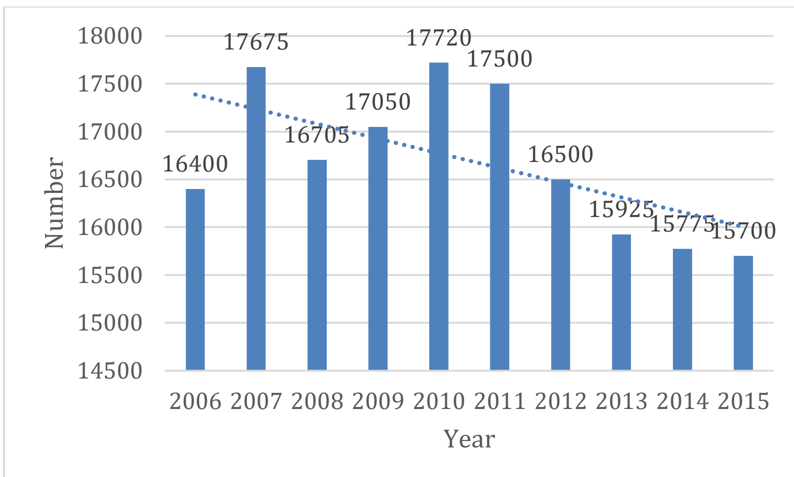
Fire hazards threaten human life and property safety. The fire statistics report published in 2015 by the U.S. Fire Administration reveals that in the United States, 129,800 fires caused 3,280 deaths and 15,700 injuries, which resulted in a loss of $14.3 billion [1]. Even though the number of deaths, injuries, and property damages due to fire hazards have decreased within the past decade (Figure 1.1), they are still significantly high. This leaves room for improvement in current fire safety management practices—specifically, high-efficiency evacuation, which tends to be the best approach for minimizing both mortality and property loss.

1.1. Problem Definition and Significance

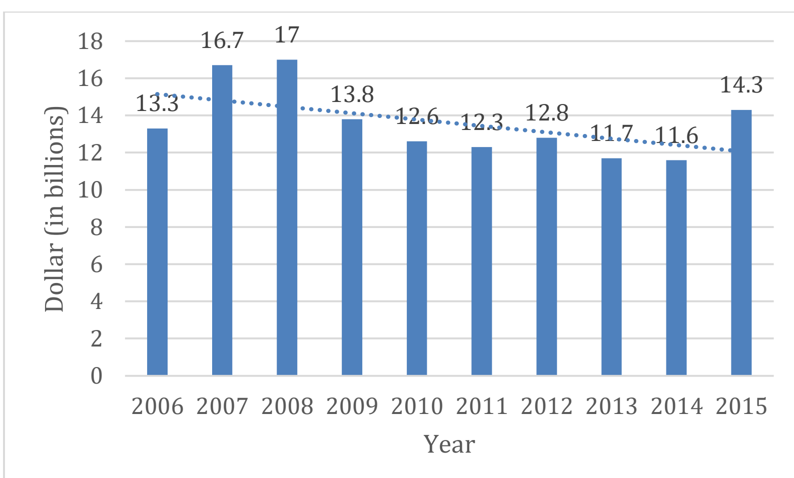
Besides the physical properties of buildings (alarm system, thermal properties of materials, and building layout), evacuation safety depends not only on the characteristics of the fire (smoke, toxicity, and heat generated) but also on characteristics of human behavior (both individual and social behaviors) [2]. Since it is unrealistic to study human behavior during a real fire hazard, computational tools are a better choice to simulate fire growth and human behavior for predicting evacuation performance in chaotic emergency situations.



(a) Trends in fire deaths



(b) Trends in fire injuries



(c) Trends in dollar loss

Figure 1.1 U.S. fire statistics from 2006 to 2015 (adopted from [1])

Fire emergencies in densely populated buildings carry features unique from other building emergencies, such as a high-density flow of pedestrians, rapid oxygen consumption, limited open space, and fixed exits. Although a significant amount of research has been conducted on using simulations for a variety of fire emergency scenarios, further studies are necessary to investigate the critical factors that affect human evacuation performance and to improve simulation accuracy. Plus, when considering building design optimization, proper and clear building exits are vital to improve evacuation efficiency while maximizing the usable area of a building. Therefore, it is of great significance to develop a computational scenario for fire evacuation planning that considers various evacuation factors to achieve both effective evacuation and building layout optimization.

1.2. Objectives and Motivation

The objectives of this thesis are to investigate the reliabilities of (1) using BIM to offer a platform for conducting simulation design; (2) simulating fire growth via the FDS tool; (3) accounting for the characteristics of the building properties, fire conditions, and human behavior in the agent-based evacuation design; and (4) applying the simulation outputs on a linear regression model used to investigate the relationship between building design and required safety egress time. The simulation framework can better predict evacuation performance. And finally, 3D BIM serves as the environment to visualize the results of (1) the hazardous zones that reflected in the fire simulation; (2) the effective escape routes that are recommended by the evacuation scenario. The research results from this thesis are expected to provide valuable information for building design and for fire evacuation planning and safety management and ultimately help minimize fatalities and reduce the economic loss caused by building fires.

1.3. Research Methodology

The research methodology is schematically outlined in Figure 1.2. This research study began with defining the problem and the preliminary objectives. This led to a comprehensive literature review that included studies related to building information modeling, fire dynamics simulator, agent-based modeling, human decision-making during fire emergencies, and the development of emergency simulations to date. Based on current techniques and acknowledging current emergency simulations, a new simulation framework was designed and implemented in the chosen software. Computational experiments were then conducted to implement the system. Specifically, the physical building properties used to establish emergency scenarios were based on the published report of the Station night club fire—a crowded fire emergency that resulted in a high number of mortalities and significant property loss—which occurred on February 20th, 2003, in West Warwick, Rhode Island. The experimental outcomes corresponded with the accident record, which validated the accuracy and feasibility of the proposed simulation framework. Finally, all the knowledge, experiments, and lessons learned were documented and presented along with recommendations for further studies.

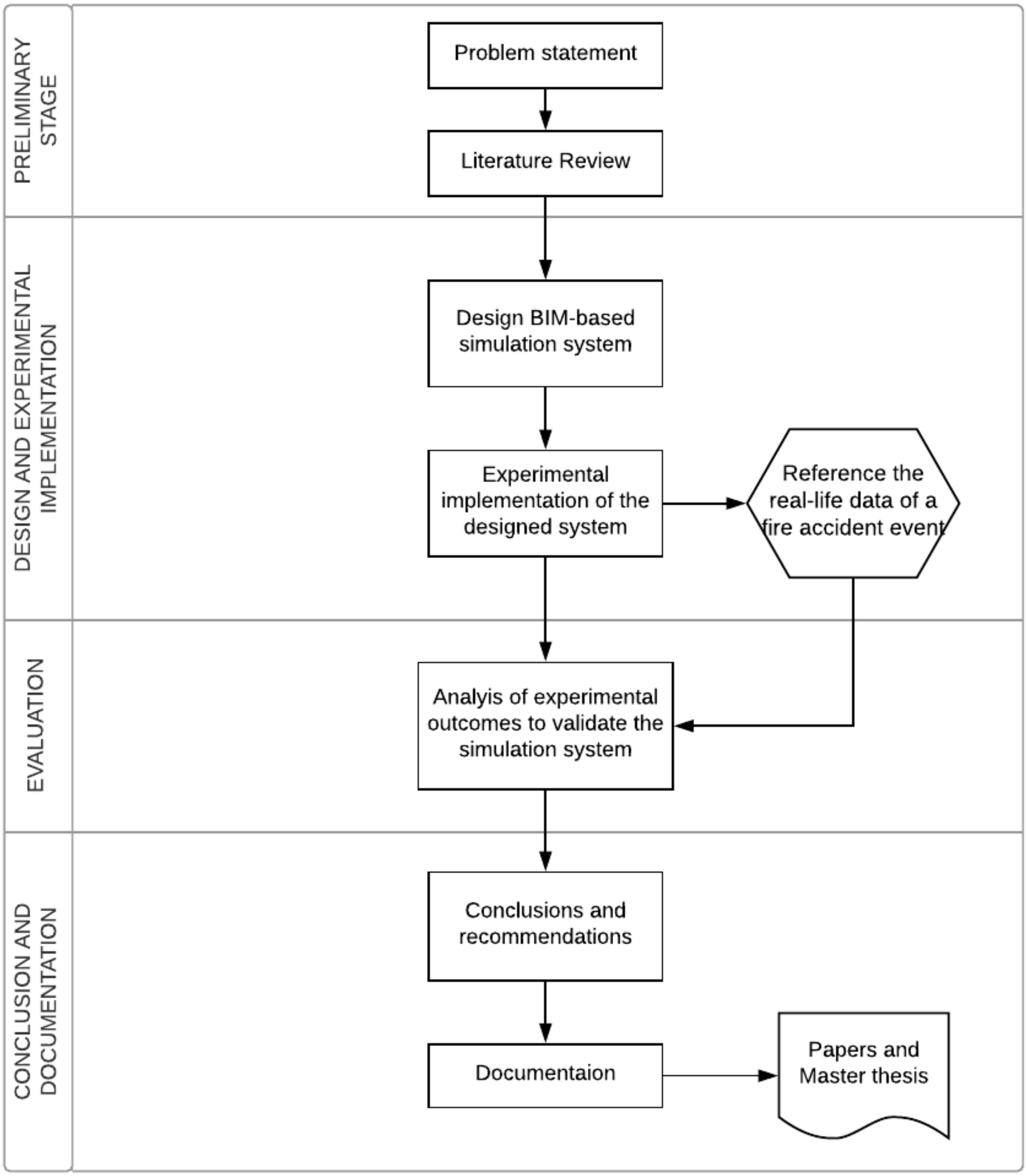


Figure 1.2 Research methodology

1.4. Thesis Organization

This thesis is organized into five sections. Section 1 provides an overview of the research problem and describes the research methodology. Section 2 introduces related simulation technologies and lists the critical factors that impact evacuation time in fire emergencies; previous works on developing emergency simulations are discussed here, as well. Section 3 details the simulation framework and methodology. The experimental implementation and results are evaluated and discussed in Section 4. Finally, conclusions and recommendations for future works are provided in Section 5. According to the results, this thesis summarizes a comprehensive framework for fire evacuation planning and proposes several future studies that will enhance fire safety management in high-occupancy buildings.

2. BACKGROUND AND LITERATURE REVIEW

This section summarizes the existing literature related to proposed simulation technologies, which include building information modeling, the Fire Dynamics Simulator, and agent-based modeling. The critical factors that impact evacuation time and life safety outcomes in building fire scenarios are then identified. Related works on fire emergency simulations are also discussed when proposing the new fire simulation framework design.

2.1. Building Information Modeling

Building Information Modeling (BIM) is an advanced 3D model-based process that has been used in the industry since the 1970s. In a Smart Market Report by Young et al. [3], BIM use in the Architectural/Engineering/Construction and Facility Management (AEC & FM) industry has increased tremendously within the last decade, as it has helped contractors to save time and money while improving project quality. Building information models can be networked to support decision-making regarding a building or other built asset. Since building fires are directly associated with casualties and asset security, BIM applications for building fire safety management include the design of a BIM-based serious game for fire safety evacuation simulations [4], a BIM-based system to check evacuation regulations in high-rise and complex buildings, and a BIM-based simulation of a fire emergency evacuation [6,7,8].

2.1.1. Introduction to Revit

Revit [9] is a 3D BIM tool that can assist in simulation designs through three features: interoperability, insightful analysis, and 3D visualization.

Interoperability: Revit supports information extraction or exchange with other software by importing/exporting common file formats, such as DWG and DXF [10]. In a study by Wang et al. [8], Revit offers a platform for linking other techniques that enable users to plan and design for emergency simulation intentions in the BIM environment. This contributes to improved coordination and less rework for contributors from multiple disciplines through the sharing and saving of their work to a centrally shared model.

Insightful Analysis: BIM models contain not only the 3D data but also the object attributes [11]. Thus, Revit is not only a great visualization tool but it also provides data integration or design analysis support [10]. For example, it can be used to apply evacuation regulations on the application requirement scenarios when running a quality check on the building objects [5]. Furthermore, it enables the enhancement of model geometry and provides construction details or other information, such as marked hazardous areas and planned escape routes [8].

3D Visualization: During the design phase, the perspective and orthographic 3D views in Revit allow users to better visualize and more effectively communicate with the models. The function of a walkthrough [10]—a defined path created as a series of perspective views—is to display building layouts and planned escape routes to assist with fire education goals during the post-construction phase.

2.2. The Fire Dynamics Simulator

The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) simulation tool developed by NIST for modeling fire-driven flow and then displaying the result through the visualization program named Smokeview (SMV) [12]. It can help with various fire simulation goals, such as post-accident investigations [13,14] and fire safety assessments of existing buildings [6,15,16]. Moreover, it can assist in fire emergency planning by integrating with evacuation simulation tools like EVAC [17] to establish a continuous fire emergency and evacuation simulation scenario [18].

2.2.1. Introduction to PyroSim

PyroSim [19] is a program designed to act as a graphical user interface that quickly and accurately works with FDS models. Its stand-out properties of interoperability, property libraries, and post-processing enable users to effectively simulate fire emergencies.

Interoperability: PyroSim enables architectural building information exchange between FDS and BIM [20]. To be more precise, PyroSim converts the BIM-generated model into FDS files when conducting the fire simulation. During this process, the 3D face data from the imported BIM model are treated as obstructions, and different types of building materials will be automatically grouped. The thermal parameters of all materials must be customized in PyroSim for use in the FDS model.

Property Libraries: PyroSim provides model parameter property libraries, which include building materials, pyrolysis reactions, burning particles, detector devices, etc. [20]. Generally, the pre-defined property libraries are satisfactory when learning the software or when coaching others, but they are not explicit enough when conducting academic research or when gauging a building's fire resistance design. Even so, the property libraries outline the model parameters for FDS use, which enhances its user-friendliness and hastens model creation. Users can directly load the pre-defined libraries and create/delete libraries as needed. Figure 2.1 shows an example of accessing the materials library.

Post-processing: The SMV program in the FDS model is designed for visualizing the fire as a dynamic 3D animation, and dynamic 2D fire data can be attached as XY time history plots in the Static program [20]. PyroSim contains post-processing simulation outputs that allow these visualizations to be launched at any time during analysis (Figure 2.2). As a result, users can frequently access the results to check, review, or even terminate the designed situation if they are not satisfied with the results, all of which improve simulation efficiency and time-saving.

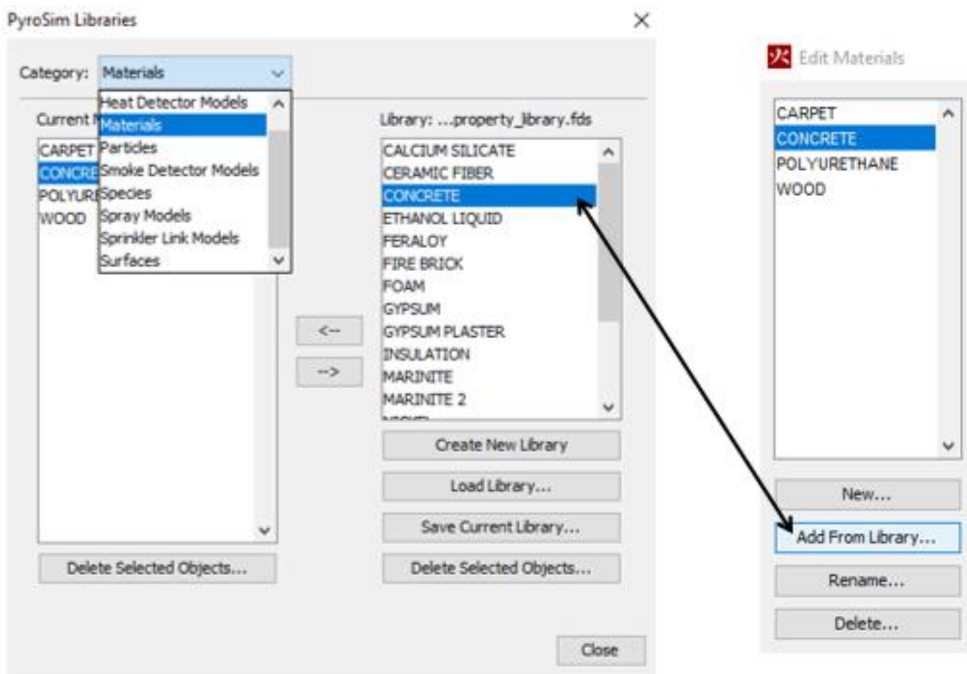


Figure 2.1 Loading the "Concrete" material property from the PyroSim libraries

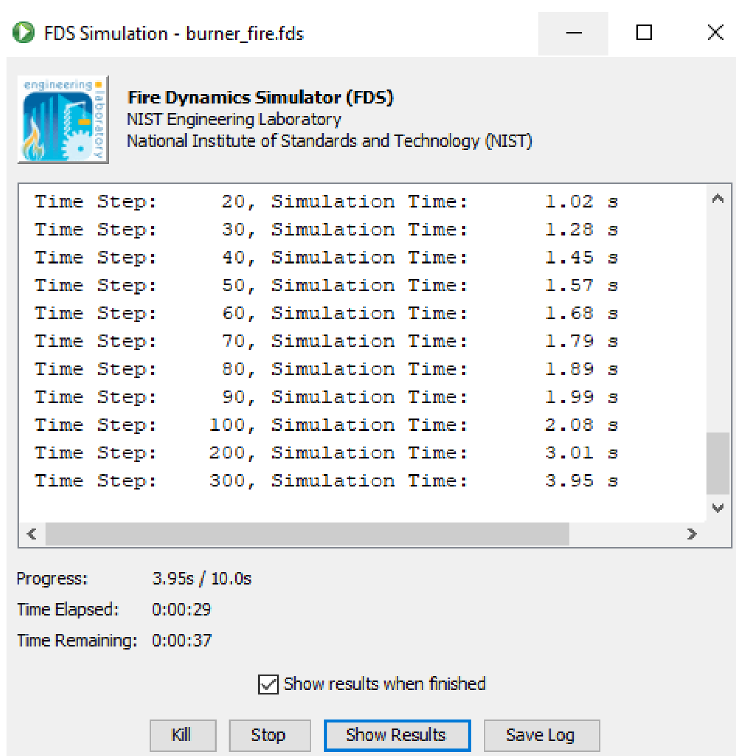


Figure 2.2 Results can be shown while a model is being processed

2.3. Agent-based Modeling

Agent-based Modeling (ABM) is one class of computational models used to simulate the interactions of autonomous agents, whose effects on the system as a whole are then assessed [21]. It is more of a mindset than a technology and can be applied across a wide range of research areas, such as economics, society, military, biology, crowds, etc. Agents can represent any type of individual besides human (transportation tools, animals, etc.) with behaviors that can be defined in mathematical, theoretical, or logical ways. Thus, an agent-based modeling simulation is a powerful technique to simulate and capture the emergent phenomena in individuals [21]. As shown in Figure 2.3, the applications of ABM on evacuation modeling covers a variety of hazards, including earthquakes, building fires, tsunamis, wildfires, hurricanes, and volcanic activity. When a fire hazard occurs, the evacuation performance of pedestrians depends heavily on their individual properties, such as observational abilities, responsibility for other people, and familiarity with the building [2]. Above all, it is feasible to use ABM models to simulate pedestrian behavioral responses to building fire scenarios.

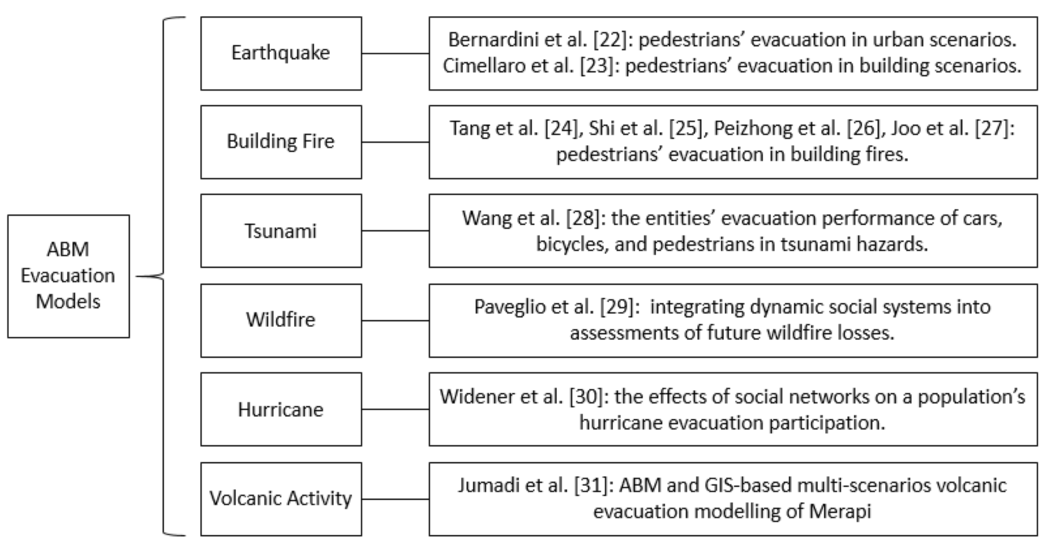


Figure 2.3 Related works of ABM evacuation models for varying hazards

2.3.1. Introduction to AnyLogic

To date, the modeling software that support agent-based evacuation simulations include AnyLogic [32], Netlogo [33], and Pathfinder [34]. After comparing these options (Figure 2.4), AnyLogic was adopted for this study because it has these exclusive and powerful functions: (1) it can interoperate with BIM-developed models by importing DXF files; (2) building the model does not require high-level Java skills or establishing meshes; (3) it can represent pedestrians as agents with individual parameters and behaviors; (4) it can simultaneously reflect pedestrian interactions and reactions with spectacular 3D graphics in pre-defined computational scenarios; and (5) it contains a pedestrian density map used to observe dynamic movement flow [35]. In conclusion, AnyLogic is user-friendly and functional enough to conduct an agent-based evacuation simulation.

	AnyLogic	Netlogo	Pathfinder
BIM model interoperability	YES	NO	YES
Does not require high-level Java skills	YES	NO	YES
Does not require the establishment of model meshes	YES	YES	NO
Allows for agent behavior personalization	YES	YES	YES
3D visualization	YES	NO	YES
Contains an observable pedestrian density map	YES	NO	NO

Figure 2.4 Evaluation of ABM software

2.3.2. AnyLogic Pedestrian Library

To carry out evacuation planning, the AnyLogic Pedestrian Library, which is designed as a crowd analysis tool, allows users to model, visualize, and analyze pedestrian movements in an emergency scenario [36]. The library's toolkit contains space markup elements for setting a physical environment and basic block elements for simulating pedestrian agents' movements within said environment (Figure 2.5). The simulation modeling procedure using these elements is described in Section 3 of this thesis.

Physical Environment: The physical environment defines the pedestrians' movement area. In this study, the simulated evacuation environment is established based on the imported Revit-developed building. Pedestrians within the building area will interact with the surrounding objects, avoid possible collisions (walls, columns, etc.), and make their own decisions on further movements [36].

Pedestrian Movements: The movement system is represented as a pedestrian flowchart that uses the block elements to define pedestrian behaviors, preferences, and states. To observe simulation outputs, users can quantify the pedestrian flow and measure movement time output statistics [36]. However, there is a default logical loop in which the pedestrians choose the shortest route when moving toward exits. To improve the applicability of the simulation design, it is essential to modify the pre-assigned movement logic and thoroughly consider the critical factors that may impact evacuation performance.

Figure 2.5 Modeling elements in the pedestrian library

2.4. Critical Factors Affecting Evacuation Time

Human behavior in disasters is generally unpredictable and heavily affects the evacuation time in response to fires. Kobes et al. [2] summarize that an indoor fire response performance system consists of three feature categories: human features, building features, and fire features, where each category consists of a few critical factors. Below, the critical factors (Figure 2.6) that affect decision-making performance and evacuation time in building fires are reviewed.

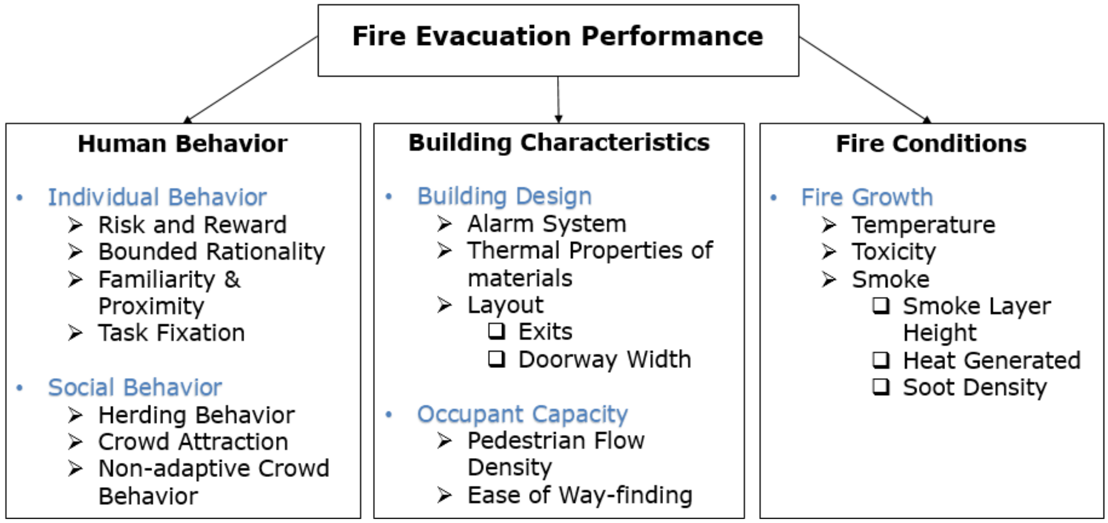


Figure 2.6 Fire evacuation performance model

2.4.1. Human Factors: Individual Behavior

The pedestrians' individual personalities will affect their evacuation performance. Knowledge of the building's layout and experience with fire emergencies are essential for people to make rational decisions about their egress routes [2].

Risk and Reward: The perception of risk and reward defined as a psychological process of risk assessment related to the current event [37]. In fire emergencies, it drives people to make an assessment of egress route selection before evacuating.

Bounded Rationality: The factor of bounded rationality prevents people from making rational decisions in an emergency, which requires a clear mind and a longer decision-making process [37,38]. According to previous experimental evidence and case studies, even after hearing an alarm as their first cue, people would not evacuate immediately due to: (1) their disbelief that it signals a real emergency [39]; or (2) they assume the fire will be contained and not dangerous [38,39].

Familiarity and Proximity: Pedestrians' egress route decisions are significantly driven by their familiarity with the building exits and results in them choosing their entry point as their exit [37,39,41,42]. Although proximity is also a driving factor, people may not be aware of all the surrounding exits if they are unfamiliar with the building's layout.

Task Fixation: Task fixation means that people in emergencies are likely to continue their movement toward a chosen egress route even when it proves ineffective [2]. Without task fixation, people will reconsider their movement decisions.

2.4.2. Human Factors: Social Behavior

The sociality of humans affects their behavior in emergencies as well. Due to an affiliation or sense of responsibility toward others, pedestrians who have partners tend to warn and assist each other to ensure they evacuate together [2,38]. As for the pedestrians who do not have partners, they must make their own decisions, although their movements are still influenced by others.

Herding Behavior: Herding behavior describes how individuals in a group can act collectively without centralized direction. That means people are attracted to a surrounded guide's instructions under an emergency [38]. Even so, they must judge the guide's authority and then decide whether to follow them [40]. If a fire occurs in a commercial building, people will follow the instructions of an employee who is familiar with the building layout instead of a fellow consumer.

Crowd Attraction Factor: Unique from herding behavior, crowd attraction occurs among two or more groups. Being attracted by crowd, people will unconsciously choose the egress direction that several others are observed to have chosen [38]. Reviewing the function of familiarity, it is assumed that the primary main entrance is the most likely point to become crowded.

Non-adaptive Crowd Behavior: Non-adaptive crowd behavior refers to destructive actions performed in crowd dynamics, such as stampeding, pushing, or trampling on others [38]. This causes the counter-flow effect, which is a forward flow negatively impacts evacuation efficiency [43].

2.4.3. The Effect of Fire Conditions

Fire conditions heavily impact pedestrian evacuation efficiency as well since their movement depends on their physical tolerance and psychological status while suffering from hazards. During a fire hazard, the most threatening element is smoke, rather than fire, and can cause body pain or impaired vision [42]. Generally, smoke consists of airborne solids, liquid particulates, and gases released during the pyrolysis process. The heat generated, radiation temperature, soot density, and concentration of CO are used to measure smoke severity.

According to the research results currently available in fire safety engineering analysis [24,25,42,44], the heat generated will begin to harm the human body when (1) its upper layer radiation strength reaches 180 ℃ and (2) the layer of direct contact reaches 60 ℃. The soot density will reduce movement speed (1) as a 0.9 coefficient when the lower air layer reaches 1.5 m and (2) as a 0.6 coefficient when the lower layer reaches 1.2 m [24,25]. The toxicity concentration of CO will begin to harm humans when it reaches 2500 ppm [44]. Furthermore, humans will experience impaired visibility and mobility when the smoke density reaches above 85% [42]. Thus, when designing computational simulation framework, the FDS measurements of heat generated, toxicity concentration, and soot density should be considered as factors that impact pedestrian movement.

2.4.4. Building Characteristics

The characteristics of the building are closely associated with the human decision-making process and fire growth. Although International Building Code (IBC) offers regulations for typical types of buildings, each buildings has its own engineered and situational attributes that impact on fire outcomes. The engineered attributes are generally associated with the perspectives of building design and the situational attributes are typically the environmental effects on evacuation performance [2].

Building Layout Design: First, the building layout will impact familiarity and proximity for pedestrians when they make their egress route decision [2,38]. After the fire has ignited, people need time to observe fire signals, which will depend on the location of fire cues and the sensitivity of the building's alarm system. Plus, the level of fire resistance and ability for the flames to spread directly correlate with the materials' thermal properties and the ventilation system inside buildings [42].

Building Capacity: The incapacity of a building to support pedestrian density will result in frequent congestion during emergencies. On the one hand, the destructive actions caused by congestion will affect pedestrians' movement. On the other hand, a high flow density will reduce pedestrian visibility while they choose their egress routes.

Therefore, it is helpful to investigate the relationship between building capacity and evacuation performance to reduce the frequency of congestion during an evacuation.

2.5. Related Works on Fire Evacuation Design

Fire evacuation has already become the core when discussing human behavior during an indoor emergency scenario since fires account for a great loss of human life and property [1]. Since it is unethical to record occupant reactions by putting real people through a real fire incident, computational tools have become the ideal simulation method. To date, many researchers have attempted to conduct indoor fire evacuation modeling that reflects true human reactions (Figure 2.7).

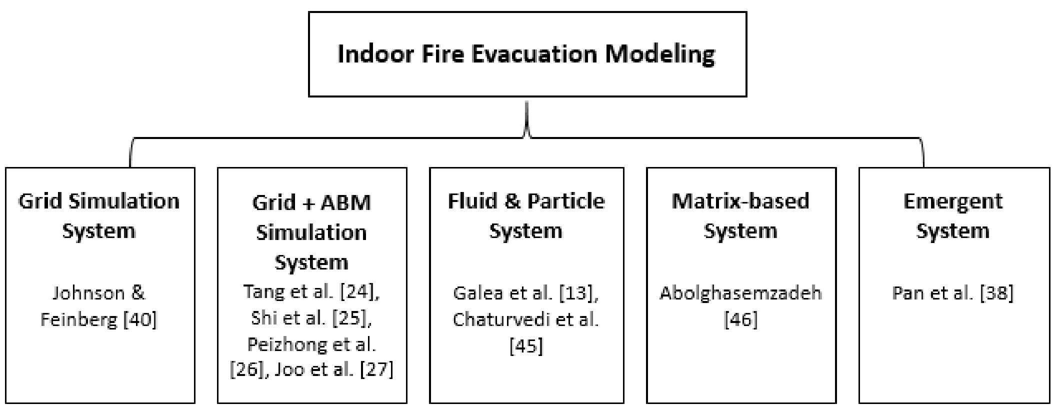


Figure 2.7 Previous designs on fire evacuation systems

Grid Simulation System: One of the most pioneering attempts involving the consideration of evacuation behavior was conducted by Johnson & Feinberg in 1997 [40]. They divided a simulated room into hundreds of grids to investigate their hypothesis about the relationship among the number of building exits, egress routes chosen, and human mortality. Although the egress route simulation was limited by the computational abilities of that time, the attempt can be seen as a precursor to the grid simulation system.

Grid System and Agent-based System: More than a decade later, Tang et al. [24], Shi et al. [25], Peizhong et al. [26], and Joo et al. [27] successfully combined the ideas of the grid system and agent-based system that involved the impact of individual occupant behaviors and social behaviors. However, none of them considered a delayed evacuation caused by the pedestrians observing fire signals. Moreover, Tan et al. ignored the impact of smoke density on occupants' walking speed, whereas Shi et al. and Peizhong et al. mentioned the lowered walking speed and impaired vision caused by the higher generated temperature and soot mass during a fire.

Fluid and Particle System: Galea et al. [13] and Chaturvedi et al. [45] combined building properties and human properties together by using the fluid and particle system, which uses a discrete event-based flow that contains sequential periods for each model. Although they simulated separate models for fire and agents, their research design failed to take fire effects into account, which would heavily impact the evacuators' performance.

Matrix-based System: Abolghasemzadeh [46] used the matrix-based system to develop an effective wayfinding simulation design so that various types of building users could shorten their egress time under fire scenarios. Considering the diversity of building users and applying both human properties and a fire's effects on evacuation behavior were positive approaches. Even so, the matrix system is not a good choice for a crowded scenario, as the system struggles to simulate the occurrence of counter-flow.

Fire Emergent System: Another modeling method summarized by Pan et al. [38], which is named the emergent system, can be used to simulate crowded phenomena, especially the counter-flow effect. However, fire evacuation phenomena are closely associated with human psychonomics [2], and even though behaviors during an incident can be predicted, it is hard to discern the motivations behind the human decision-making process given multiple route selections.

By analyzing the current developments and limitations on fire evacuation simulation designs, it is important to generate all mentioned influential factors to improve the accuracy of simulation outcomes. The designed evacuation process in this study will consist of four periods: the pre-alarm period, alarm period, pre-evacuation period, and evacuation period. The movement of agents will be based on the influence of human properties (individual and social behaviors), fire properties (temperature, toxicity, and soot density), and building properties (alarm system, material thermal properties, and building design). By also considering the factor of task fixation, this study will create a "re-decision model" for testing the effect of pedestrians who are impatient about queuing toward crowded exits. To determine physical building characteristics, the number of exits, pathway width, and building capacity will all be investigated to assist in fire evacuation planning. The designed purpose of this research is to establish a comprehensive BIM-based modeling system that involves FDS and ABM for investigating the relationship between these influential properties and evacuation efficiency.

3. SIMULATION FRAMEWORK AND METHODOLOGY

3.1. BIM-based Simulation Framework

BIM's interoperability function enables users to import the model into other software for conducting the fire simulation and evacuation simulation. As shown in Figure 3.1, the start of this simulation framework is meant to establish an architectural model in Revit for simulation use. By importing the Revit-generated model into PyroSim, it turns into an FDS model for testing the building's Available Safe Egress Time (ASET) for pedestrians during a fire. The agent-based simulation is designed based on the critical factors (building, fire, and human characteristics) on pedestrian evacuation behavior in order to predict the Required Safe Egress Time (RSET) in AnyLogic. Along with differing the building exit designs, pathway widths, and occupant capacity, the RSET in different building scenarios will be changed as well. Acceptable building designs are defined by a smaller RSET number compared to ASET. In other words, the building design needs to be adjusted to achieve the intended level of fire safety. The expected situation is to ensure that the RSET equals ASET to achieve maximum building utilization without human death. Finally, information about hazardous fire zones and recommended egress routes are stored in the 3D-BIM environment and visualized through mobile devices. The intention of this system is to apply BIM on fire evacuation planning and safety management for design and education purposes, and the simulation results can be used to minimize fatalities and reduce the economic loss caused by building fire emergencies.

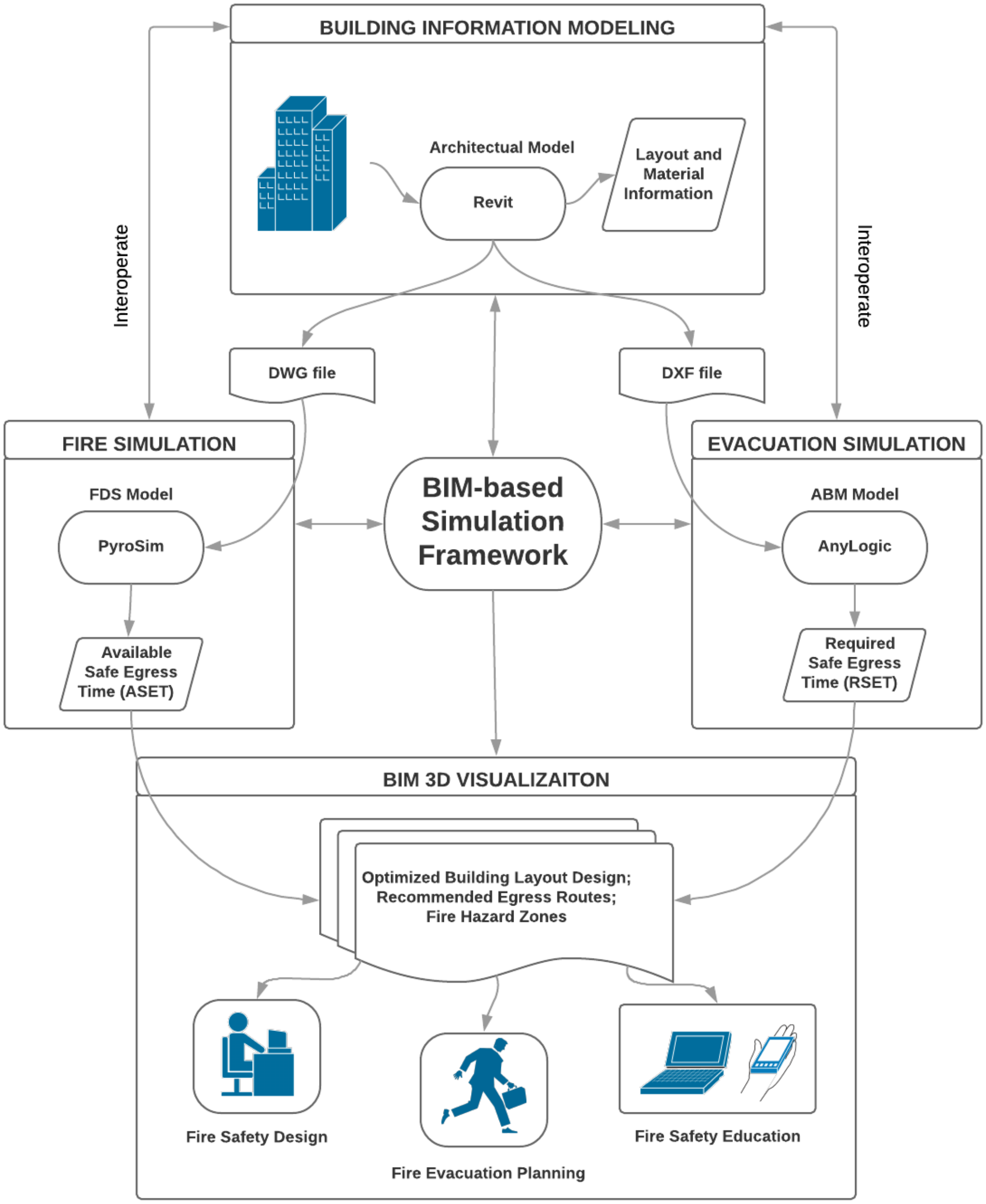


Figure 3.1 The BIM-based simulation framework

3.2. Fire Simulation Design

The first step of conducting the fire simulation is to build the 3D-BIM model and import it into PyroSim. Figure 3.2 and the procedure description below describe how to develop a fire simulation through PyroSim.

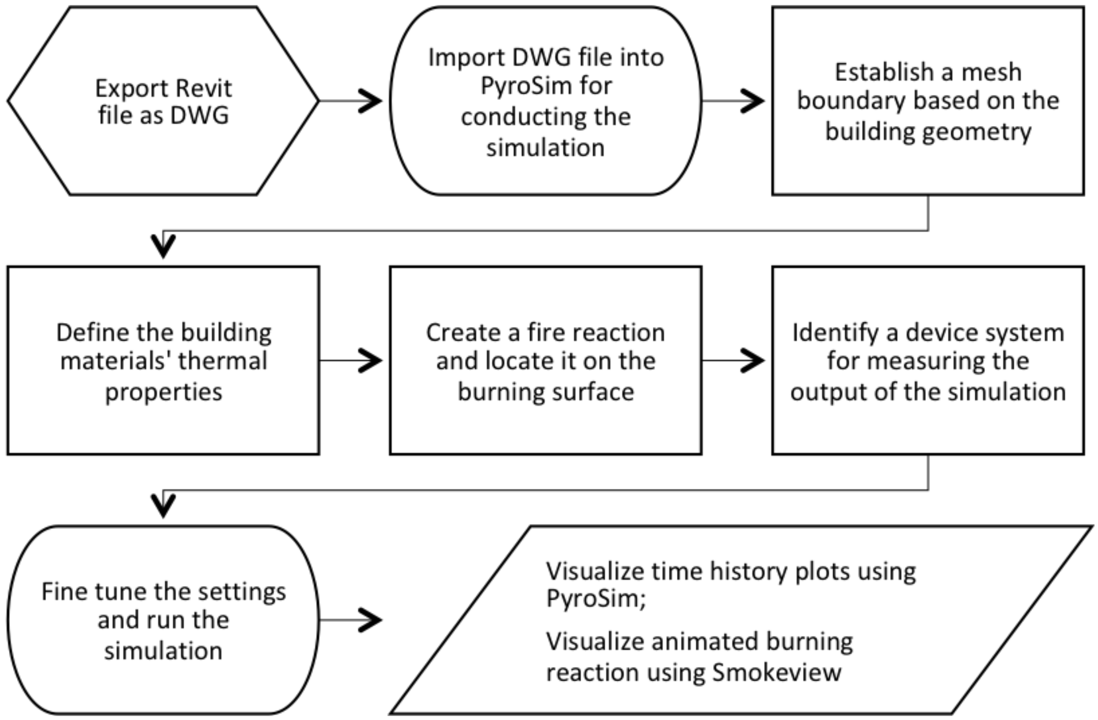


Figure 3.2 Fire simulation design flowchart

Building Geometry and Mesh Boundary: The Revit model is first resampled into the pre-defined 3-D cubic mesh in FDS. The increased mesh resolution helps to obtain a more accurate simulation. However, according to the FDS Technical Guide [47], reducing the mesh size by a factor of 2 will result in the computation time increasing by a factor of 16. To balance the computation time and accuracy, the mesh size should be around 1/5 to 1/20 of the characteristic fire D*, which is known as

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T \sqrt{g}}\right)^{\frac{2}{5}} \tag{1}$$

where $\bar{Q}$ is the range of peak heat release rates, p is the material density, c_p is the specific heat, T is the reference temperature, and g is the standard gravity. The information about material properties corresponds to the building details.

Materials and Surfaces: To simulate the fire reaction of a building made with heat-conducting materials, it is essential to specify each material and describe their specific thermal properties and pyrolysis behaviors. Surfaces can be used to make a connection between the thermal properties of materials and the simulation domain's solid object. When a solid object's thermal properties need to be governed by one or more materials, it becomes a layered surface comprising all the related materials' properties. As mentioned, PyroSim offers pre-defined thermal properties for common building materials. Even so, uncommonly used materials must be created manually, and their thermal properties are derived from the material's information supplied in the ASTM Fire Standards [48].

Fire Reaction: In the FDS model, a fire reaction is created by a burner surface with a specific Heat Release Rate (kW/m^2) and Net Heat Flux (kW/m^2), which are known as the power of fire and the rate of heat energy transferred per surface unit area, respectively. After creating a fire, it is better to define the pyrolysis process and the reaction's byproducts. In the FDS analysis, a "simple chemistry" combustion model is based on the chemical components (C, H, O, and N) of a single fuel species that reacts with oxygen (O^2) in one mixing-controlled step to produce H_2O, CO^2, soot, and CO [47]. These byproducts are the outputs measured to ascertain the building's fire-resistant properties throughout the burning process.

The Device System: Devices are used to record output measurements that include (1) the surrounding gas temperature (℃) measured by either a thermocouple device or a heat detector; (2) gas density defined as the occupied percent per meter (%/m) as shown on the gas detector; and (3) the smoke layer height (m) measured by a layer zoning device. Thus, to measure and monitor dynamic fire growth changes during the simulation, the device system is composed of three device types: heat detectors, gas detectors, and layer zoning devices. Moreover, gas phase data can be displayed as a dynamic flow on three axis-aligned slice planes (1.5 m, 2.0 m, 2.5 m), which can reflect changes in temperature, visibility, and gas density at different heights.

Outputs and Results: After fine-tuning the simulation parameters, the model is run and the outputs are obtained. All the data measured by the device system are placed into time history plots and then viewed as 2D charts, while the burning animation is displayed in PyroSim Smokeview. As a result, an analysis of the temperature, visibility, and gas density will prove helpful when developing an evacuation model and the final investigation to determine fire safety management.

3.3. New Evacuation Simulation System

The Revit-established model is imported into AnyLogic as the movement area for agents. The agents' behaviors are presented in a Pedestrian Flow designed based on the new evacuation system (Figure 3.3). The procedure for establishing the agent-based evacuation model in the AnyLogic Pedestrian Library are described below.

Pedestrian Source: An agent group is defined as the pedestrian source and then distributed randomly within the pre-defined movement area. The basic pedestrian flow starts at "PedSource" and ends at "PedSink" (Figure 3.4). In this evacuation simulation design, the agents' initial walking speed is 0.95–1.55 m/s, and their body diameters range from 0.22–0.29 m, which are based on the unimpeded average walking speed and body dimension of adults, respectively [43].

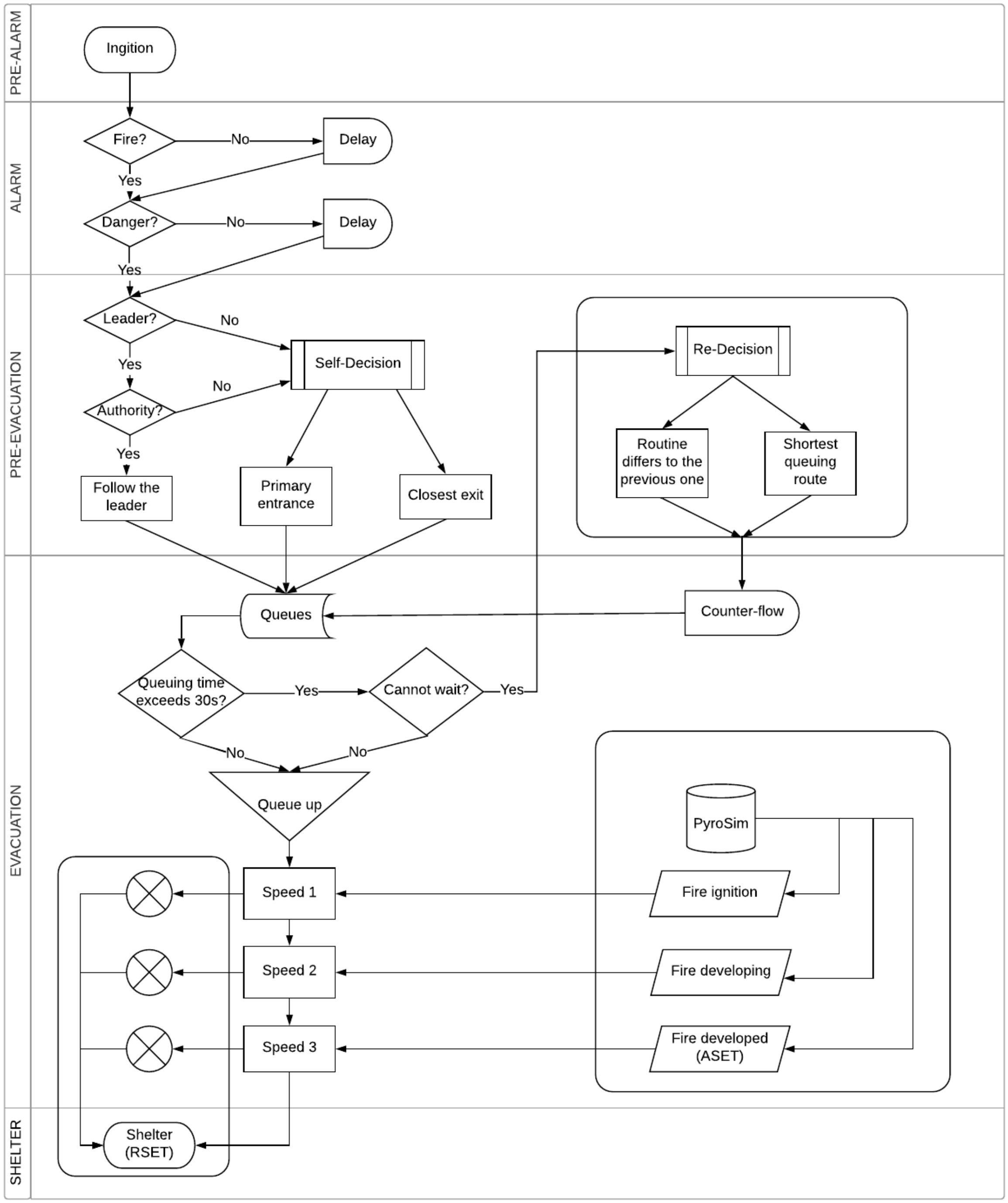


Figure 3.3 Designed system of pedestrian flow

Pre-alarm Period: Fire ignition is defined in the model as the start time of 0 s. The pre-alarm period is measured by the time necessary to receive a fire signal, which depends on the location of fire cues and the sensitivity of the alarm system.

Alarm Period: Pedestrians would not evacuate immediately if they determine the fire is non-threatening, even after the first cue of the fire alarm [26]. Thus, after the fire ignites, the agents' evacuation will be delayed 0–60 s due to the time needed for the signal to be received and the risk assessed. The block of "pedWait" is used to represent these periods of delay in the pedestrian flow system (Figure 3.5).

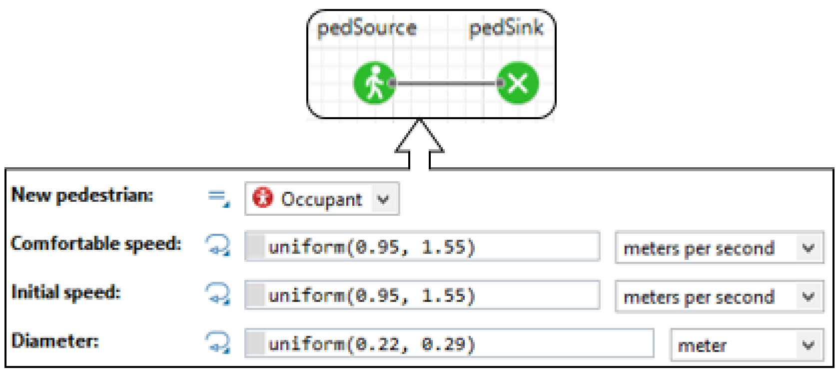


Figure 3.4 The basic pedestrian flow and property setup

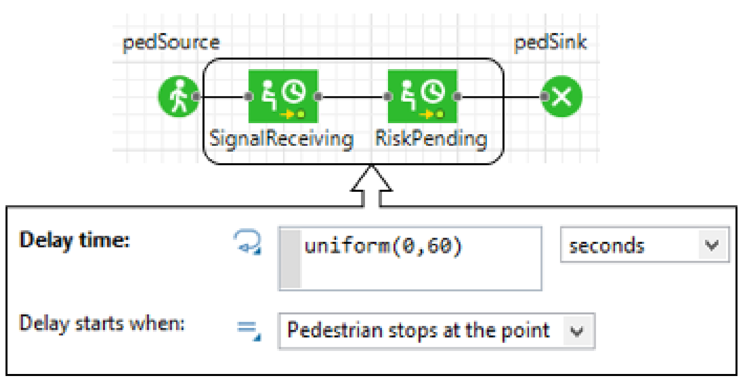


Figure 3.5 The presentation of PedWait flow and property setup

Pre-evacuation Period: The egress route selections are driven by the perception of risk and reward. When considering the guide effect, a portion of agents defined as guides who are familiar with the layout and affect the movement direction of surrounding agents to select the shortest route toward exits. However, agents may not be able to search for guides or effective egress routes due to the factor of bounded rationality. Moreover, due to the function of familiarity, people will generally not recognize side doors and instead crowd and block the main entrance [37,39,41,42]. Thus, the remaining agents will choose the main door as the egress route. Figure 3.6b shows the decision-making flow that replaces the basic pedestrian selection flow (Figure 3.6a). The number of exits can be increased/decreased as needed.

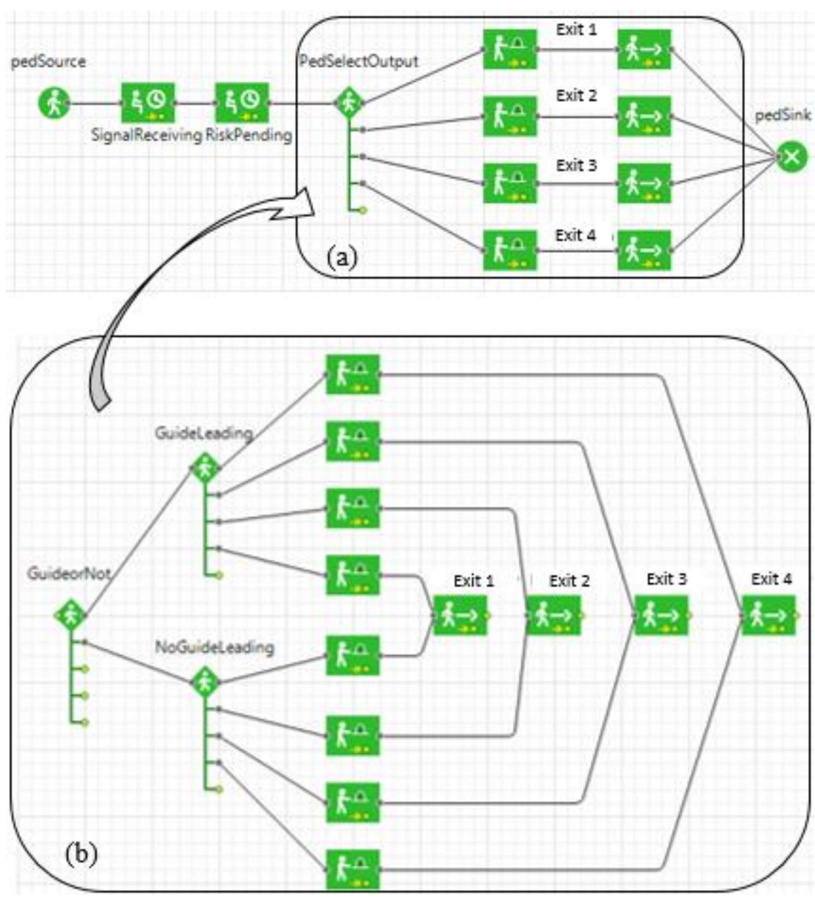


Figure 3.6 Egress selection flow with or without guide leadership

Re-decision and Counter-flow: The typical capacity of doorways allows for 60 people per minute to pass through [38], therefore an incapable doorway would become jammed and require people to queue for shelter. As for those who are too impatient to wait longer than 30 s, they will make a re-decision regarding their route selection (Figure 3.7). In Anylogic, agents cannot automatically deal with counter-flow, instead requiring users to manually define its influence. Thus, in this study, once agents decided to alter their route, a 0.81 coefficient of speed deduction would impact their movement [43]. This value refers to the destructive actions performed in counter-flow dynamics.

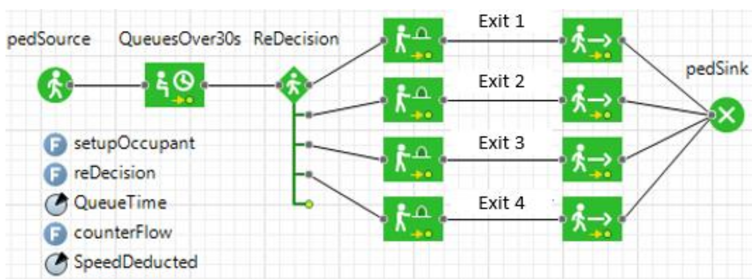


Figure 3.7 The re-decision flow and function setup

Evacuation Period: During the evacuation period, the speeds of agents will be affected by fire conditions. As mentioned before, the FDS outputs regarding fire condition can be divided into three levels: (1) the initial stage when the height of smoke is above 1.5 m; (2) the process between 1.5 m and 1.2 m in height is the developing stage; and (3) finally reaching 1.2 m marks the fire developed stage. This model creates multiple speed parameters to represent agents' changing speed during the evacuation process (Figure 3.8). For more detail, the default speed of any agent is defined as an adult's average walking speed of 1.25±0.3 m/s. When considering the influence of smoke density, that speed will be reduced to 1.125±0.27 m/s during the fire developing stage, and then be reduced further to 0.75±0.18 m/s once the fire has fully developed.

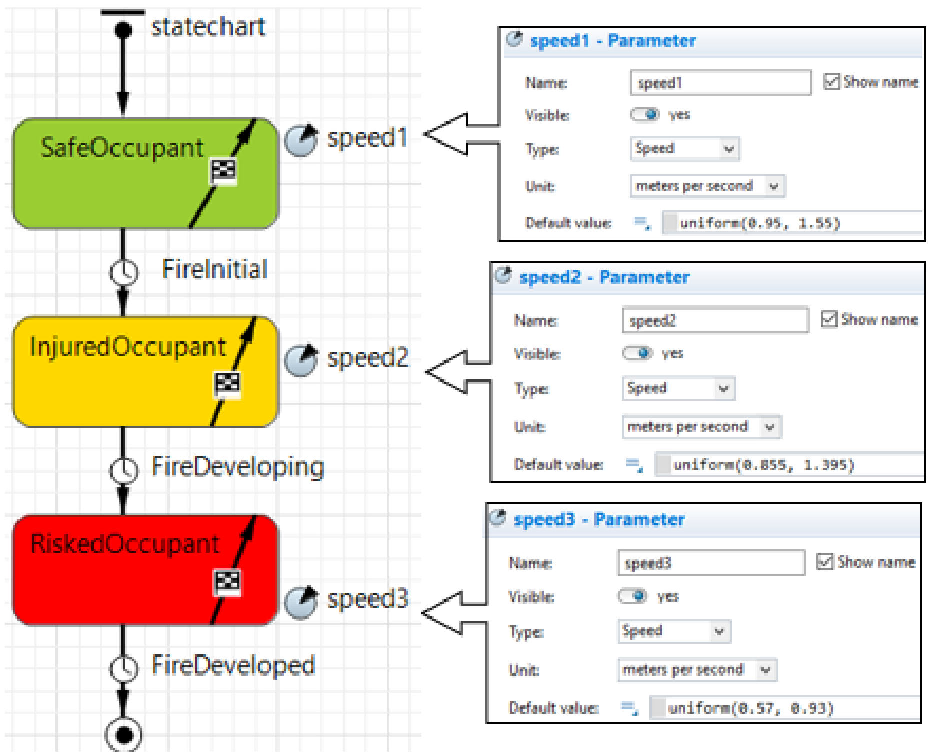


Figure 3.8 The parameters of leveled speeds

To include all the flow functions, a simplified version of the model is shown in Figure 3.9. The movement condition of agents will be reflected in real-time in the AnyLogic model. RSET is represented by the time required for all agents to reach shelter.

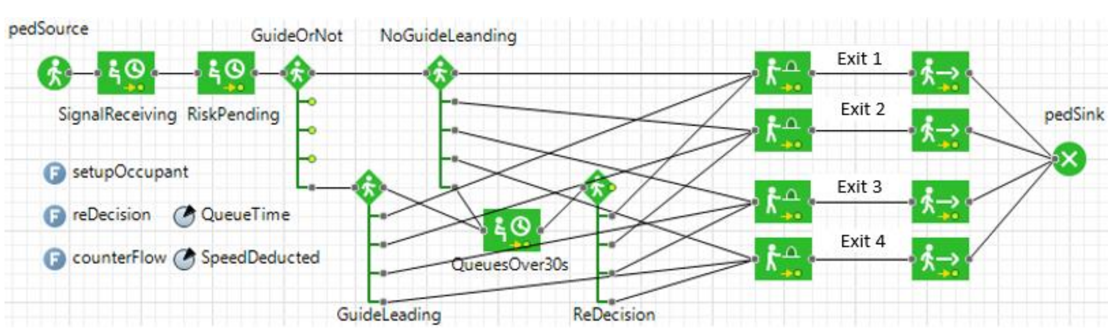


Figure 3.9 The entire pedestrian flow for evacuation modeling

3.4. Application for Fire Safety Management

As mentioned above, the Available Safe Egress Time (ASET) represents the time before people begin to get hurt during the fire developed period. The time needed for all people to find shelter is known as the Required Safe Egress Time (RSET). The FDS output results are divided into the three milestones of fire developing, fire developed, and time to hurt occupants; the ABM evacuation process consists of four periods that include the pre-alarm period, alarm period, pre-evacuation period, and evacuation period (Figure 3.10).

The optimal situation for fire safety and building economy is to ensure the RSET is same as the ASET—that is, all agents will reach the exits effectively without suffering any harm while maximizing the building usable area. Otherwise, the building layout (number of exits, doorway width) and allowed occupant capacity must be adjusted to achieve the expected fire safety design. Statistical analysis via R Studio [49] can be applied to investigate the relationship between building design and RSET value in building fire scenarios. The optimized design can then be adopted for fire safety design intentions, and fire hazard zones or recommended egress routes will be displayed in a 3D BIM environment via the walkthrough function for fire safety education intentions.

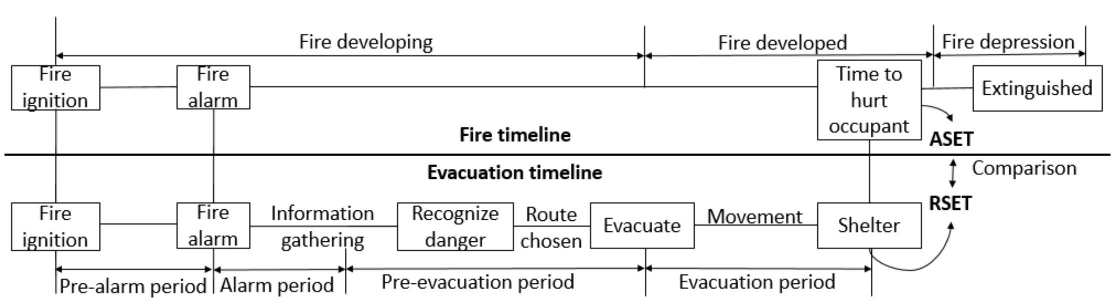


Figure 3.10 Comparison of the timelines

4. EVALUATION AND RESULTS

This section introduces an experimental implementation of the designed fire evacuation planning methodology. This experiment does not aim to cover accident investigation, rather, it concentrates on the feasibility and accuracy of the designed simulation framework by comparing it to accident timelines. The resulting analysis and system evaluation will be discussed at the end of this section.

4.1. Experimental Implementation

4.1.1. Overview of the Experiment

To validate the designed simulation framework, the chosen experimental case study is named the Station Nightclub Fire, which occurred on the night of February 20th, 2003, in West Warwick, Rhode Island. It was the fourth-deadliest nightclub fire in US history and killed 100 people, injured 230, and only 132 escaped uninjured [50]. According to the accident investigation: (1) the fire was ignited by the pyrotechnics, which ignited the non-fire retardant polyurethane foam during the band's performance; (2) wood panels accounted for 95% of the fuel load that resulted in a quick fire spread; and (3) during the evacuation period, a majority of pedestrians did not identify the side doors, instead congesting and crowding the main entrance [50].

After generating the architectural model in Revit, the interoperation process among BIM-FDS-ABM is shown in Figure 4.1. There are four exits in the building area: (1) the front door is the primary entrance for consumers; (2) the right-side door is the exit for the platform area; (3) the left-side door is the main exit on the bar side; and (4) the last exit is found in the kitchen.

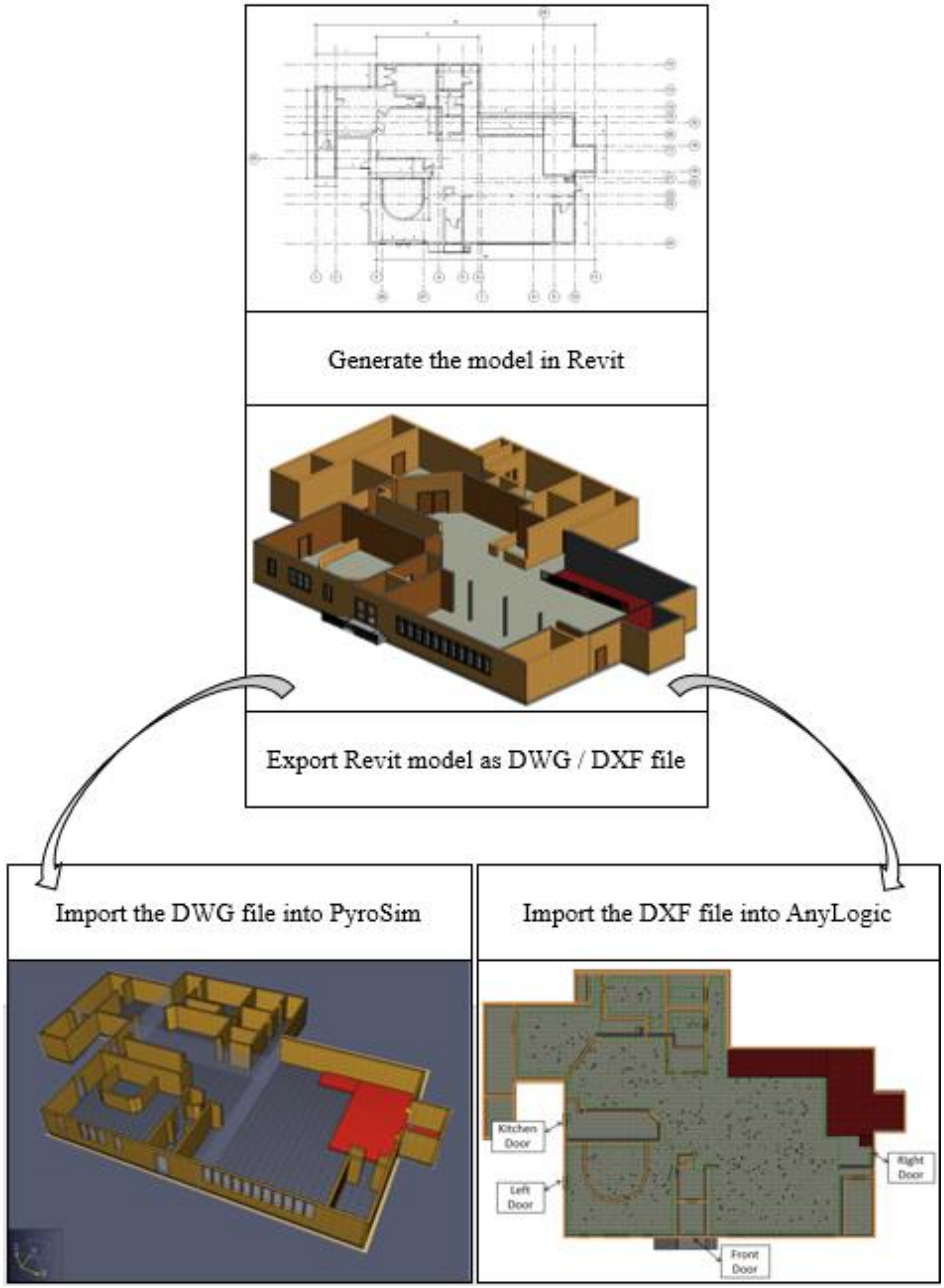


Figure 4.1 The process of model interoperation

4.1.2. Parameter Setup for Simulation Design

Fire Simulation: By using Eq.1 to balance between computation time and accuracy, 45,000 kW peak heat release rate and 0.25 m length of cubic-mesh cells are used. The building materials are based on the fire investigation report published by NIST in 2005 [50] and the thermal properties are based on ASTM E84 [51] (Table 4.1). By referring to the accident video record [51], the simulated ignitions are located at the same place as those mentioned in the fire accident record (Figure 4.2). The device system consists of devices and axis-aligned slice planes for measuring and presenting the fire dynamic changes on temperature, visibility, and toxicity density.

Evacuation Simulation: During the evacuation process, 462 agents are randomly distributed within the building area (Figure 4.3) and follow the designed pedestrian flow framework. This case assumed 2% of agents are club officers and 10% are frequent customers who are more familiar with the building layout and can affect surrounding agents' movement direction. Others move toward the front door as their egress route. The number of agents who reach shelter agents will be reflected in real-time.

Table 4.1 Thermal properties for building materials

Material Name	Density (kg/m^3)	Specific Heat ($kJ/(kg \cdot K)$)	Conductivity ($W/(m \cdot K)$)
Wood Panel	513	1.38	0.115
Concrete	1600	0.84	0.79
Nylon Carpet	128	1.42	0.1
Polyurethane Foam	22	1.4	0.034

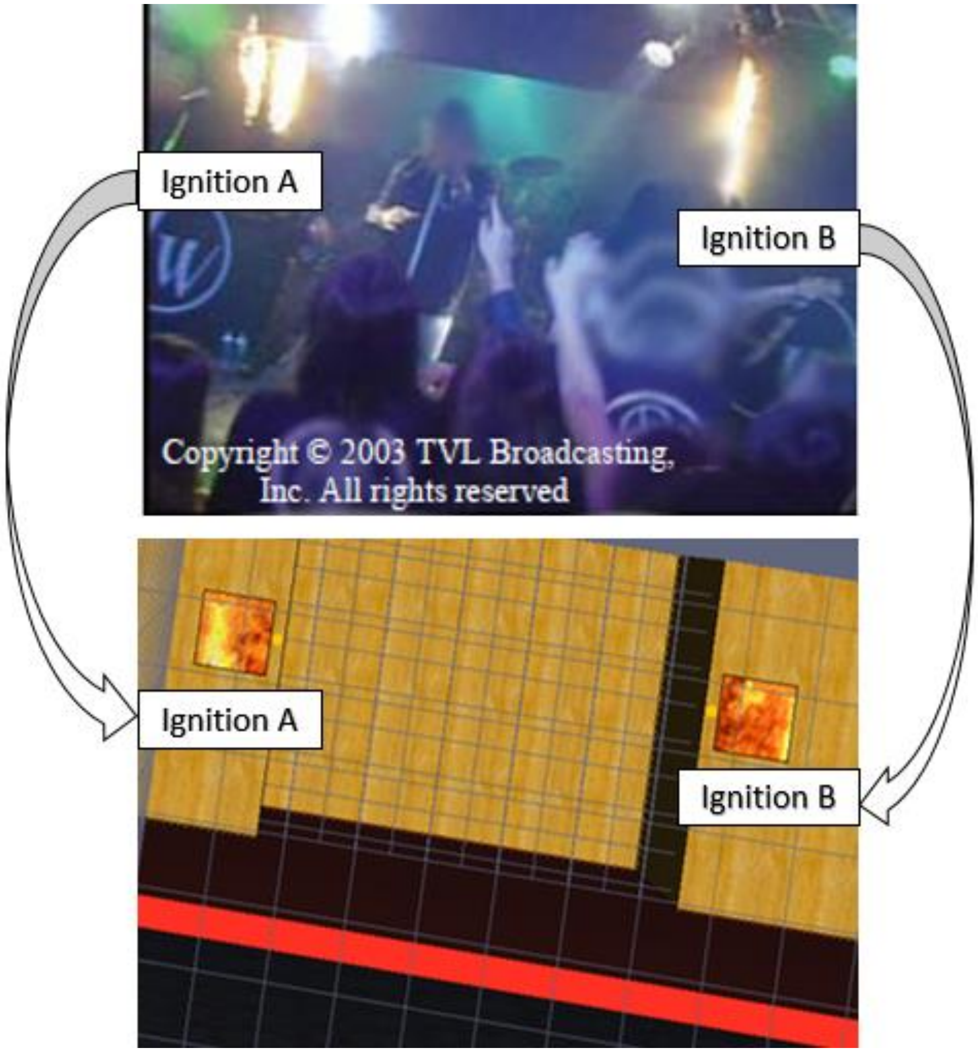


Figure 4.2 Simulated ignition locations in PyroSim

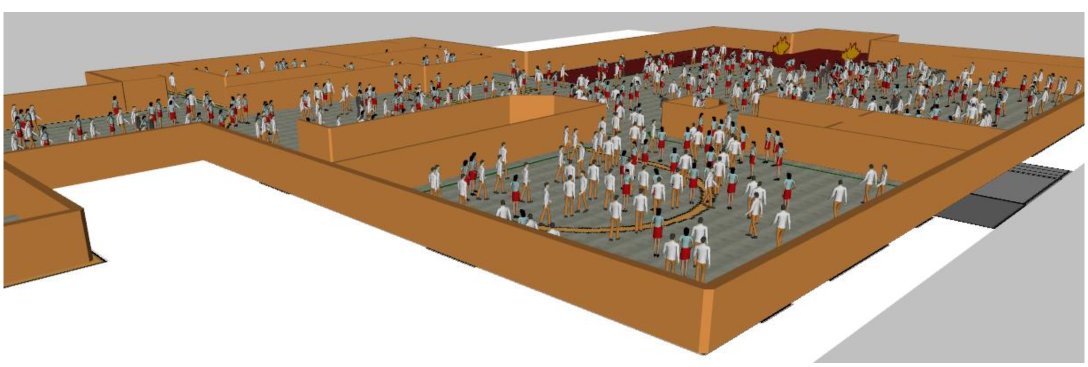


Figure 4.3 3D view of pedestrian agents in AnyLogic

4.1.3. Experiment Assumptions

The assumptions for conducting the experiment are: (1) each experimental scenario is independent of the others; (2) in the FDS model, the fire growth is exponential; (3) at the beginning of evacuation, agents are randomly distributed in the building area; and (4) all modeling parameters and functions are randomly assigned to each agent.

4.2. Evaluation and Validation

4.2.1. Fire Simulation Results

The simulation timeline of fire growth corresponds to the accident timeline, which validates the accuracy of the FDS model (Figure 4.4). According to the time history plots, the smoke layer reaches 1.5 m at 180 s and reaches 1.2 m at 300 s (Figure 4.5a), which causes a reduction in agent walking speed of 10% and 40%, respectively. The smoke density reaches 85% at 380 s (Figure 4.5b) and occurs earlier than other human physical limitations in fire simulation outputs. In conclusion, the ASET for total uninjured escape is 180 s, the ASET for injured escape without deaths is between 180–300 s, and the ASET for living is 380 s.

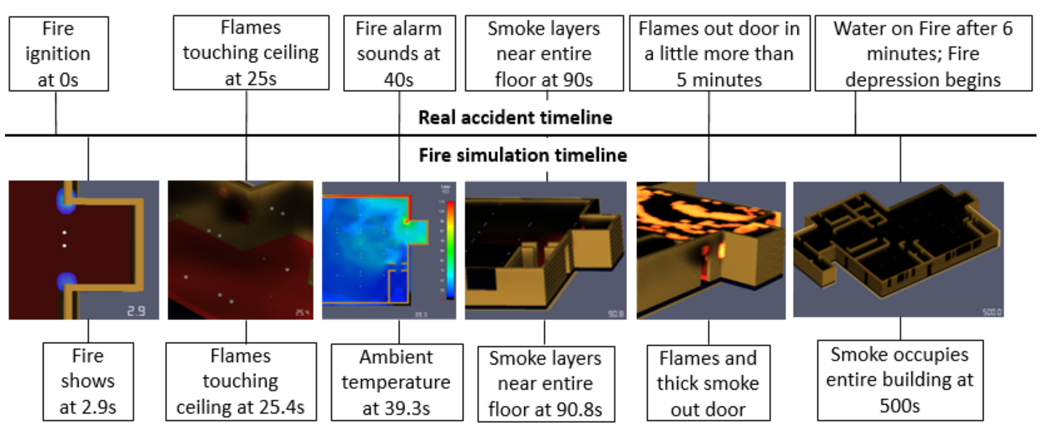
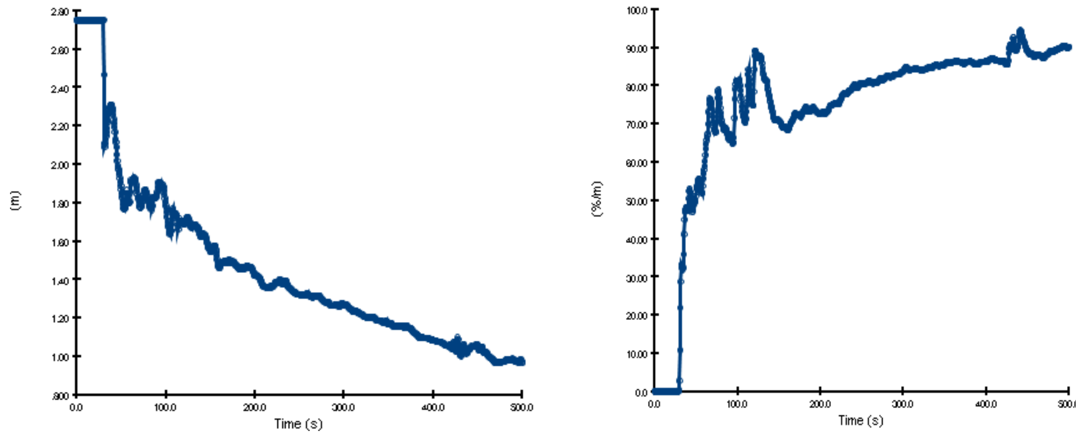


Figure 4.4 Fire growth timelines (ceilings are hidden for better visualization)



(a) Smoke layer height (b) Smoke density

Figure 4.5 Time history plots of the fire simulation results in PyroSim

4.2.2. Evacuation Simulation Results

This study of the evacuation simulation was conducted 10 times for the given scenario and the average value of outputs were used to eliminate singular result bias. The record of all simulation outputs is listed in Table 4.2.

Based on the simulation outputs: (1) the average number of sheltered agents at 180 s is 127, which means there are 127 people who escaped uninjured; (2) the average number of sheltered agents at 300 s is 342, which means there are 215 people who escaped with injuries; (3) the average number of sheltered agents at 380 s is 370 and there are 92 unsheltered agents, which means there are 370 people who escaped without dying and 92 who died; (4) the average RSET is 510 s, which means the people required at least 510 s to ensure that all of them could escape without losing their lives.

The numbers of sheltered agents correspond to the accident investigation about the numbers of injuries and deaths (Figure 4.6), which validates the accuracy of the evacuation simulation design.

Table 4.2 Evacuation simulation outputs

Tests	Number of sheltered agents			RSET(s)
	ASET at 180s	ASET at 300s	ASET at 380s	
1	120	324	356	532
2	136	340	374	498
3	123	339	368	517
4	130	360	380	507
5	136	344	367	528
6	136	348	373	524
7	109	349	382	480
8	130	338	369	494
9	127	344	376	503
10	122	332	351	511
Average	127	342	370	510
Escaped, uninjured agents			127	
Escaped, injured agents			342 – 127 = 215	
Escaped, living agents			370	
Dead agents			462 – 370 = 92	

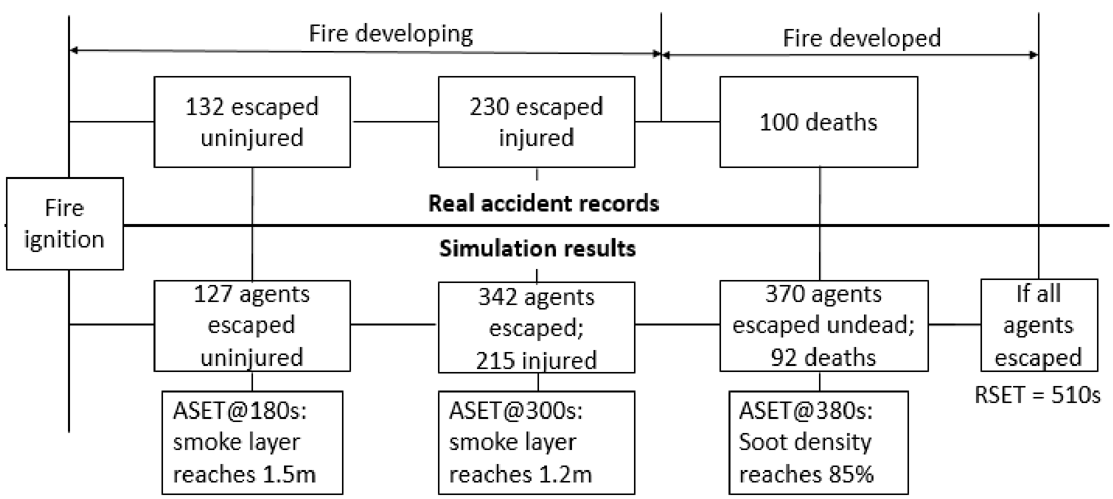


Figure 4.6 The comparison of injuries and deaths

4.2.3. Statistical Analysis

A statistical t-test was applied to investigate the relationship between RSET and building design. The testing model consists of one response variable (RSET) and three explanatory variables (number of exits, doorway width, and occupant capacity). Each explanatory variable has three levels—thus, a total of 27 scenarios must be conducted (Table 4.3). All simulations were assumed to be independent and normally distributed. The result carries a 95% confidence level that small p-values (< 0.01) significantly suggest a linear relationship between RSET and those three factors (Figure 4.7a). The residual plots verify the reliability of the fitting model (Figure 4.7b). The estimated model equation can be written as

$$\text{RSET} = 265.60 - 32.78a - 46.78b + 0.93c \qquad (2)$$

where factor a is the number of exits, factor b is the width of doorways, and factor c is the capacity of occupants. This equation can be used to predict RSET with different building designs.

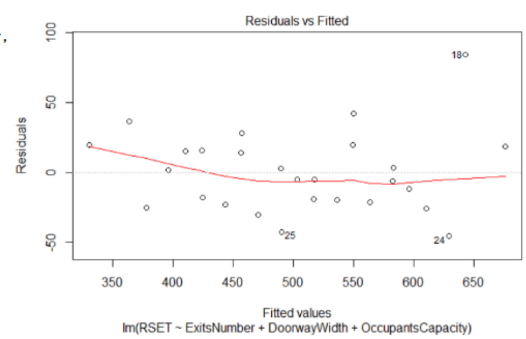
```
Call:
lm(formula = RSET ~ ExitsNumber + DoorwayWidth + OccupantsCapacity,
    data = rset)

Residuals:
    Min      1Q  Median      3Q     Max
-45.833 -20.583  -5.111  16.917  84.167

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)       265.59667   42.38666   6.266 2.15e-06 ***
ExitsNumber       -32.77778    7.16352  -4.576 0.000134 ***
DoorwayWidth      -46.77778    7.16352  -6.530 1.16e-06 ***
OccupantsCapacity   0.92944    0.07164  12.975 4.58e-12 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 30.39 on 23 degrees of freedom
Multiple R-squared:  0.9098,    Adjusted R-squared:  0.898
F-statistic: 77.31 on 3 and 23 DF,  p-value: 3.664e-12
```

(a) P-values and estimated coefficients



(b) Residual plots

Figure 4.7 Linear regression model for fitting the data

Table 4.3 Evacuation simulation results with different variable values

Variables			Sheltered agents' number			Injuries and deaths			
a	b	c	ASET at 180s	ASET at 300s	ASET at 380s	Escaped uninjured	Escaped injuries	Deaths	RSET(s)
4	3	362	117	317	362	117	200	0	350
4	3	462	127	336	409	127	209	53	439
4	3	562	131	391	457	131	260	105	497
4	2	362	111	317	362	111	206	0	352
4	2	462	133	345	411	133	212	51	440
4	2	562	121	339	429	121	218	133	542
4	1	362	108	298	343	108	190	19	406
4	1	462	127	342	370	127	215	92	510
4	1	562	126	352	430	126	226	132	584
3	3	362	104	271	343	104	167	19	400
3	3	462	101	305	382	101	204	80	470
3	3	562	116	302	399	116	186	163	569
3	2	362	95	262	327	95	167	35	425
3	2	462	107	291	365	107	184	97	498
3	2	562	113	321	394	113	208	168	584
3	1	362	85	239	296	85	154	66	485
3	1	462	101	262	318	101	161	144	592
3	1	562	97	276	333	97	179	229	727
2	3	362	98	270	345	98	172	17	398
2	3	462	97	278	358	97	181	104	492
2	3	562	108	290	390	108	182	172	576
2	2	362	99	258	329	99	159	33	420
2	2	462	101	265	339	101	164	123	516
2	2	562	101	271	383	101	170	179	583
2	1	362	88	238	314	88	150	48	447
2	1	462	84	231	316	84	147	146	586
2	1	562	97	248	344	97	151	218	694

4.2.4. Application for Fire Safety Management

Optimize Building Design: Using Eq.2, there are several building design suggestions that change just one variable compared to the original building design (4 exits, 1 m doorway width, and a 462-occupant capacity) (Table 4.4). The optimal building design would be to keep the original layout, but lower the occupant capacity to 323.

Table 4.4 Suggested building design for fire safety

Number of exits (n)	Doorway width (m)	Occupant capacity (n)	RSET	ASET (living)	RSET ≤ ASET?
4	1	323	380	380	Yes
8	1	462	378	380	Yes
4	4	462	369	380	Yes

Fire Evacuation Planning: The Smokeview in PyroSim suggests that the dancing and stage area account for the fastest burn rate. One possible explanation for this is that the building uses non-fire retardant foam as wall insulation and the nylon carpet speeds up the spread of flames (Figure 4.8). The pedestrian density flow shown in AnyLogic indicates that the agents crowd and congest the main entrance while evacuating (Figure 4.9). This is caused by the fact that most pedestrians are not aware of the side-door exits and instead select the primary entrance door as their egress selection. Thus, based on the simulation outputs, the stage area should be marked as the fire hazard zone, which needs to be improved and fireproofed (Figure 4.10). The side exits should also be more clearly represented as recommended egress options (Figure 4.11). Finally, 3D-BIM will serve as the environment to visualize the results.

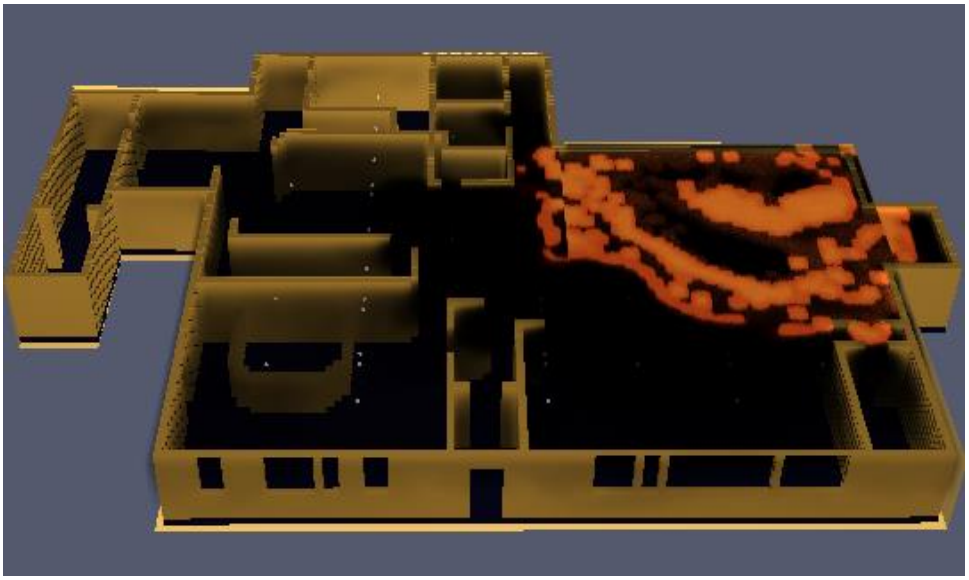


Figure 4.8 Fire spreads fast within the stage area

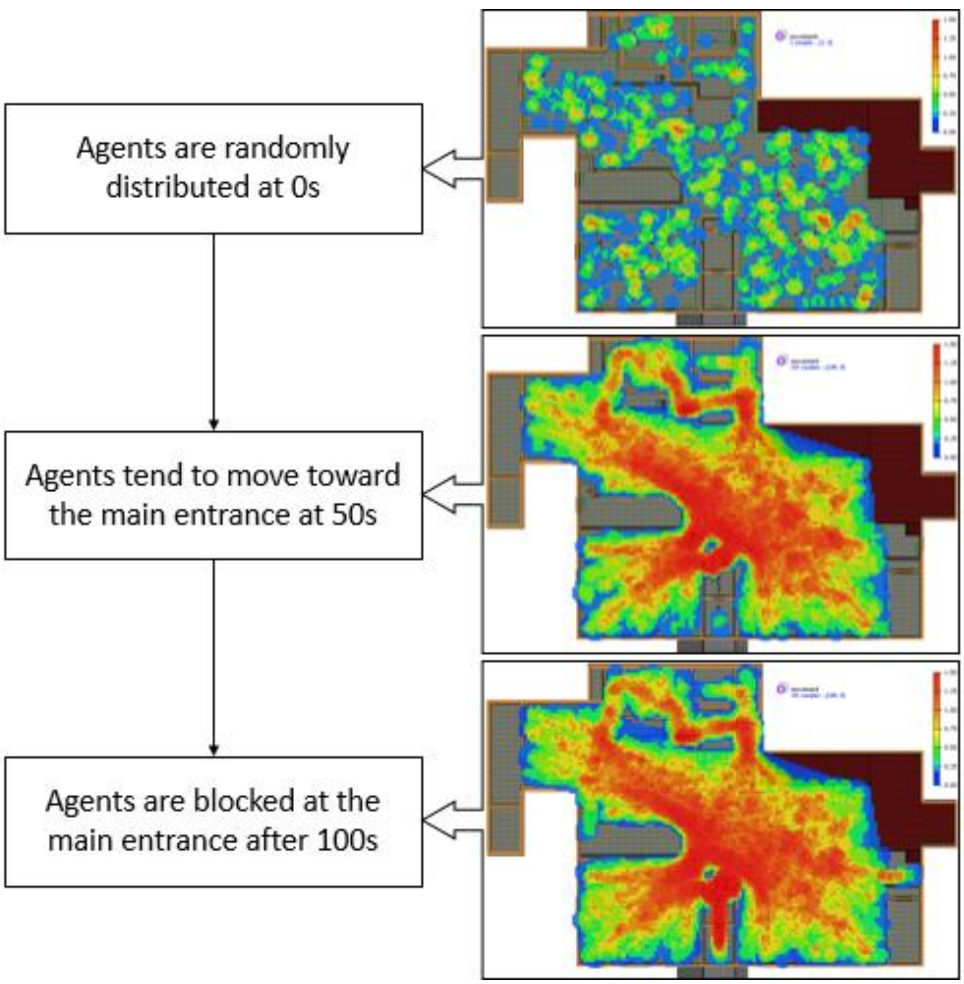


Figure 4.9 Pedestrian density maps in AnyLogic

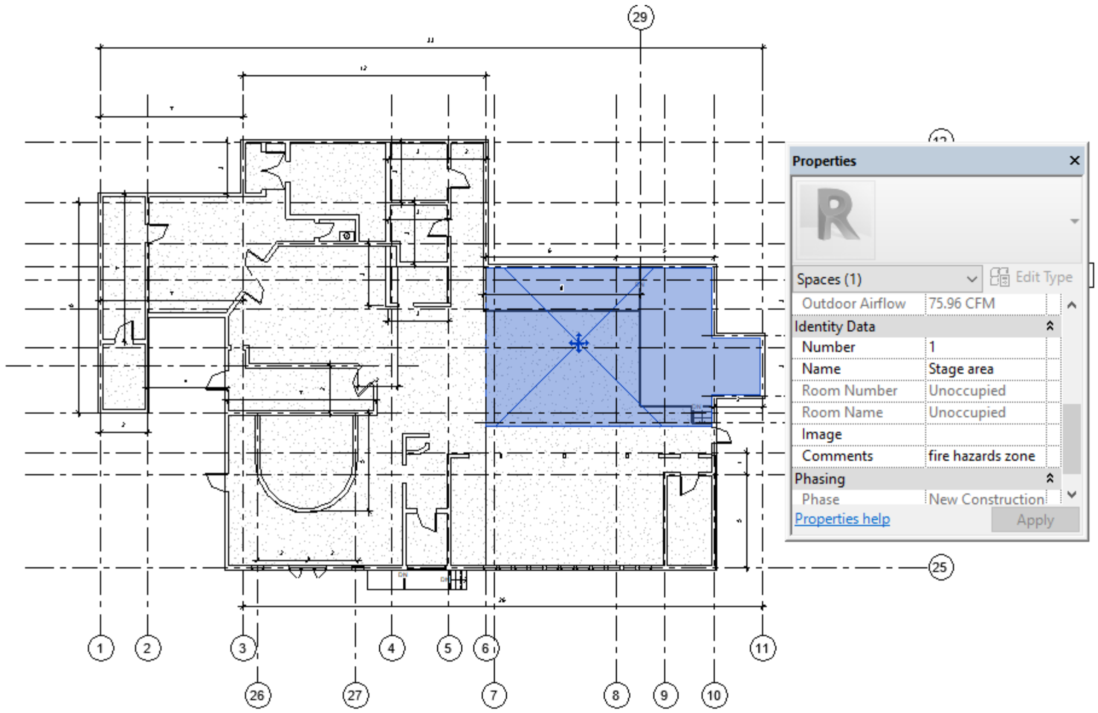


Figure 4.10 Marking the stage area as a fire hazard zone in Revit

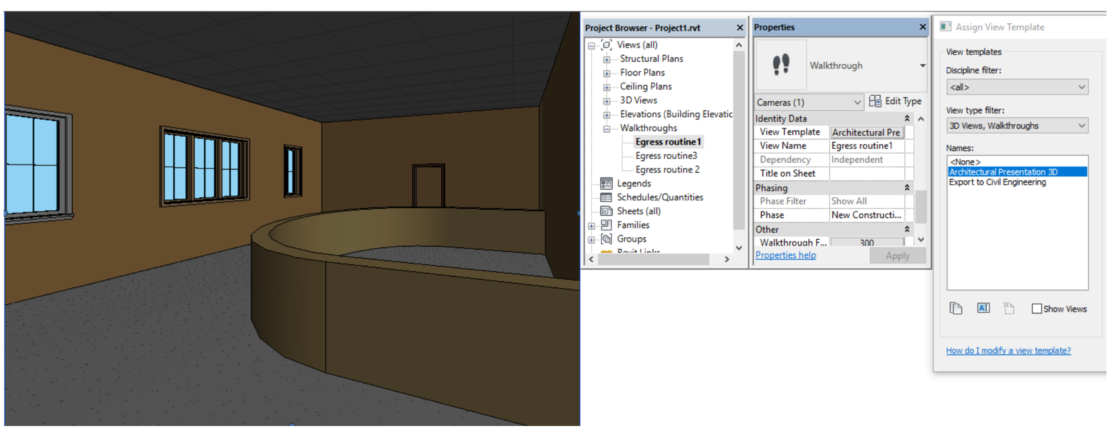


Figure 4.11 Egress route displayed as a 3D walkthrough in Revit

4.3. Sensitivity Analysis of Net Heat Flux

Net heat flux is known as the rate of heat energy transferred per surface unit area, which can impact the size and burn speed of a fire [8]. It is difficult to predict the size of fires in the real world, so this study instead conducts a sensitive analysis to test the effect of net heat flux on fire growth.

Test Compartment: There are four levels of net heat flux (35 kW/m^2, 40 kW/m^2, 45 kW/m^2, 50 kW/m^2) being used to test the time required before reaching the following situations: (1) smoke layer reaches 1.5 m; (2) smoke layer reaches 1.2 m; (3) temperature reaches 60 ℃; (4) temperature reaches 120 ℃; and (5) the toxicity density reaches 2500 ppm.

Results Analysis: According to the histogram shown in Figure 4.12, there is a decreasing trend of required time before reaching the aforementioned situations along with an increasing net heat flux. Based on the boxplots shown in Figure 4.13, the vertical boundary heights roughly decrease, which can be assumed as an exponential relationship between fire growth and net heat flux. This validates previous research that claimed fires have an exponential model for growth [52,53,54].

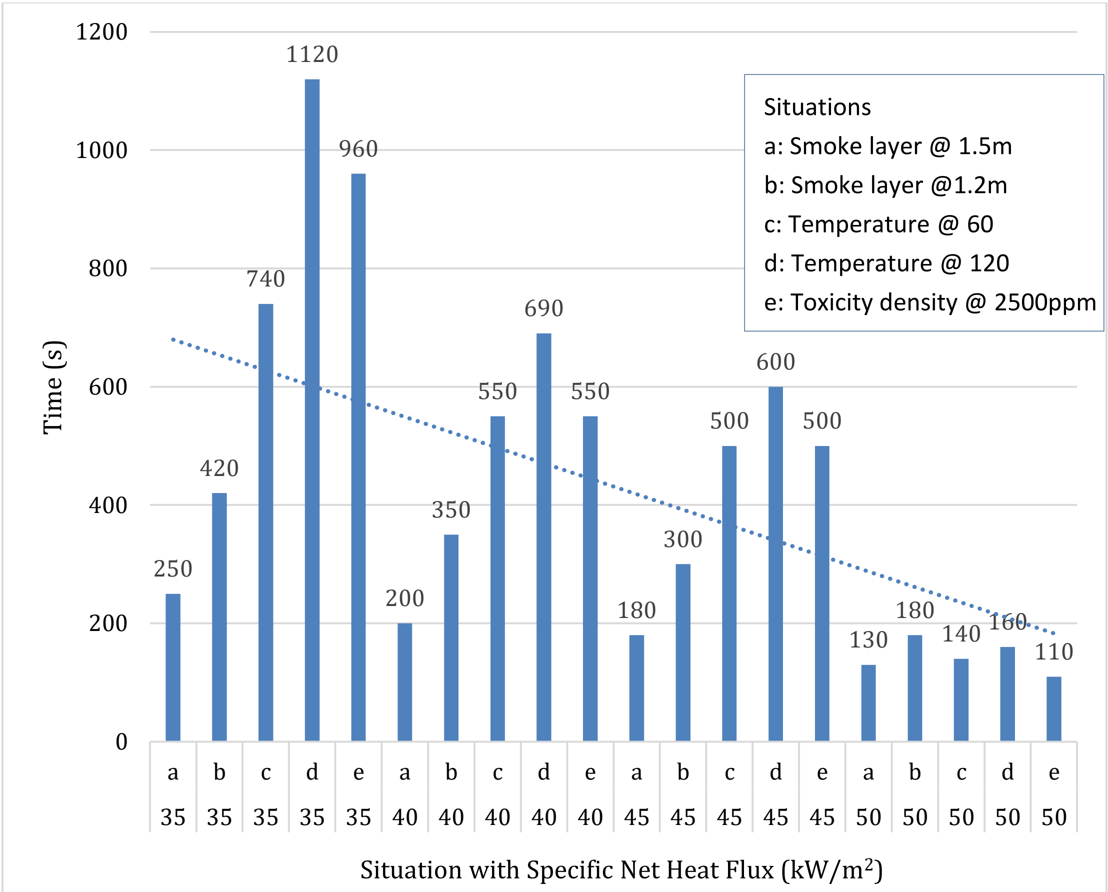


Figure 4.12 Fire conditions with net heat fluxes (kW/m^2) of 35, 40, 45, 50

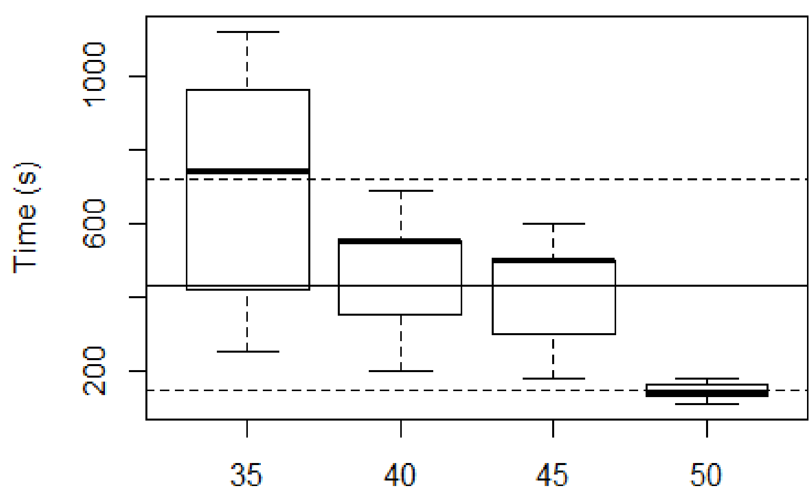


Figure 4.13 The boundary heights of the boxes decrease

4.4. System Evaluation

To test the effectiveness of specific functions in the pedestrian flow system, the method is to compare the modified scenario with the regular one used for the evacuation simulation. When testing the effect of one parameter, all other parameters must be fixed. Each scenario is run ten times and the average mean is extracted to eliminate any bias. All test results are applied in RStudio to analyze the boxplot and conduct statistical t-tests. The simulation outputs for all scenarios are shown below (Table 4.5).

Table 4.5 Outputs of RSET(s) in different evacuation scenarios

	Regular model	Modified models (without tested function)					
		Signal receiving stage	Risk pending stage	Guide effect	Re-decision system	Counter-flow effect	Fire condition effect
1	532	492	480	595	697	489	354
2	498	470	496	550	669	500	386
3	517	520	455	514	636	484	408
4	507	480	489	560	716	496	410
5	528	470	503	569	658	469	368
6	524	456	475	565	676	467	423
7	480	447	493	546	645	489	396
8	494	476	502	566	672	514	401
9	503	428	487	535	686	483	367
10	511	462	494	556	704	478	375
Mean	509.4	470.1	487.4	555.6	675.9	486.9	388.8

4.4.1. Effect of the Signal Receiving Stage

The boxplot shown in Figure 4.14 indicates there are different RSET means between the regular and modified model. Moreover, in the two-sample t-test, a small p-value (= 0.0008085) strongly rejects the null hypothesis that there is no difference between the two models, and the estimated value of the mean difference is 39.3 s within a 95% confidence interval from 19.1–59.4 s (Table 4.6). According to the fire accident report, people received the fire signal around 30 s after the fire ignited, and the crowd then began to evacuate [38]. This verifies that evacuation time is influenced by the factors of physical building properties, such as the thermal properties of materials, the location of fire cues, and the sensitivity of the building's alarm system.

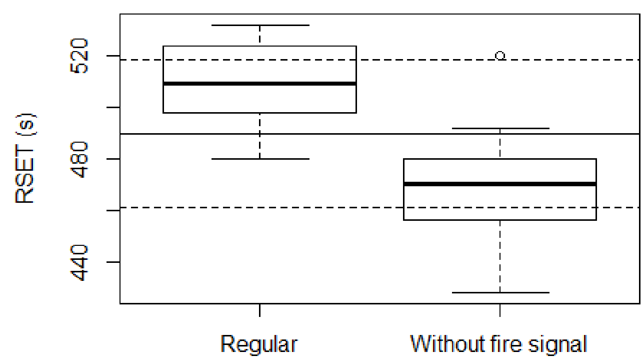


Figure 4.14 Boxplot of models with and without the alarm-system effect

Table 4.6 Two-sample t-test on the alarm system effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	470.1
95% Confidence interval: (19.15649, 59.44351)		
t = 4.1474, df = 15.475, p-value = 0.0008085		
Alternative Hypothesis: true difference in means is not equal to 0		

4.4.2. Effect of the Risk Pending Stage

Both the boxplots (Figure 4.15) and the two-sample t-test (Table 4.7) clearly indicate a difference in RSET values ranging from 7.5–36.5 s between these two models. A small p-value (= 0.005127) supports the alternative hypothesis. The estimated time difference for the models with or without the risk pending stage is 22 s, which confirms that the evacuation time is influenced by agents' decision-making ability. Recall that people will not evacuate immediately if they do not recognize the fire as a threat. Even when they do, they will attempt to warn and assist their partners before evacuating. Thus, the risk pending stage impacts evacuation time in this simulation design.

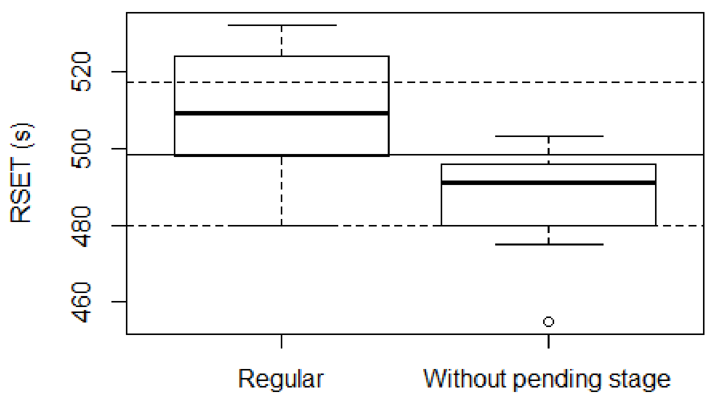


Figure 4.15 Boxplot of models with or without the pending stage effect

Table 4.7 Two-sample t-test on the pending stage effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	487.4
95% Confidence interval: (7.50403, 36.49597)		
t = 3.1922, df = 17.715, p-value = 0.005127		
Alternative Hypothesis: true difference in means is not equal to 0		

4.4.3. Effect of the Guide Leading System

Without the guide effect, the RSETs values are greater than the regular model (Figure 4.16). The t-test uses a small p-value (= 5.244e-05) to strongly reject the null hypothesis that there is no difference between the two models, and the estimated value is 46.2 s within a 95% confidence interval from 28.1–64.3 s (Table 4.8). Due to herding behaviors, the agents defined as club officers or frequent consumers will guide the surrounding agents and egress effectively. However, due to bounded rationality, not all agents are able to search for a guide or make good decisions based on proximity. Thus, the remaining agents are influenced by the factors of familiarity and crowd attraction behavior to choose the front door as their egress option, which decreases evacuation efficiency due to congestion.

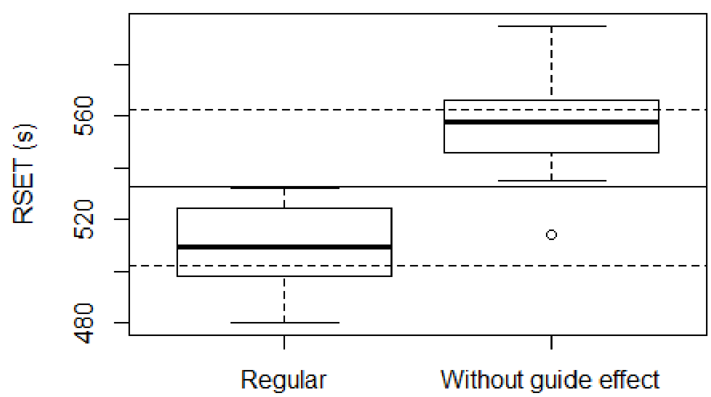


Figure 4.16 Boxplot of models with or without the guide effect

Table 4.8 Two-sample t-test on the guide effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	555.6
95% Confidence interval: (-64.33616, -28.06384)		
t = -5.3808, df = 16.743, p-value = 5.244e-05		
Alternative Hypothesis: true difference in means is not equal to 0		

4.4.4. Effect of the Re-decision System

The mean RSET value without the re-decision system is significantly greater than the result from the regular model (Figure 4.17). According to the t-test outputs, a small p-value (= 1.733e-11) strongly rejects the null hypothesis that there is no difference between the two models, and the estimated mean difference 66.4 s within the 95% confidence interval from 146.1–186.9 s (Table 4.9). Without the re-decision system, many agents will queue toward the primary entrance and ignore the different egress routes, which is caused by the human factor of task fixation. However, based on the fire accident report [38], some people tried to change their egress route, but were blocked by the congestion at the main entrance doorway. That is why this study designed the system of egress route re-decision. Future studies are needed to investigate the effect of re-decision in real cases.

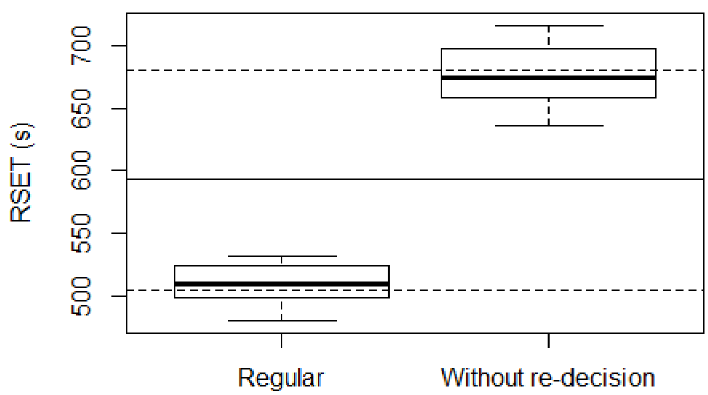


Figure 4.17 Boxplot of models with or without the re-decision effect

Table 4.9 Two-sample t-test on the re-decision effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	675.9
95% Confidence interval: (-186.9114, -146.0886)		
t = -17.355, df = 15.317, p-value = 1.733e-11		
Alternative Hypothesis: true difference in means is not equal to 0		

4.4.5. Effect of Counter-flow

Counter-flow functions as a destructive flow in the evacuation process. According to the boxplots (Figure 4.18) and the t-test results (Table 4.10), the 0.81 speed reduction coefficient due to the counter-flow effect alters the mean RSET values. The p-value (= 0.00421) strongly rejects the null hypothesis that there is no difference between the two models, and the estimated mean difference is 22.5 s within the 95% confidence interval from 8.1–36.9 s (Table 4.6). Without counter-flow, the modeled scenario indicates a shorter time required for all agents to reach shelter compared to the regular scenario. This result verifies the negative effect of the counter-flow function in this simulation design.

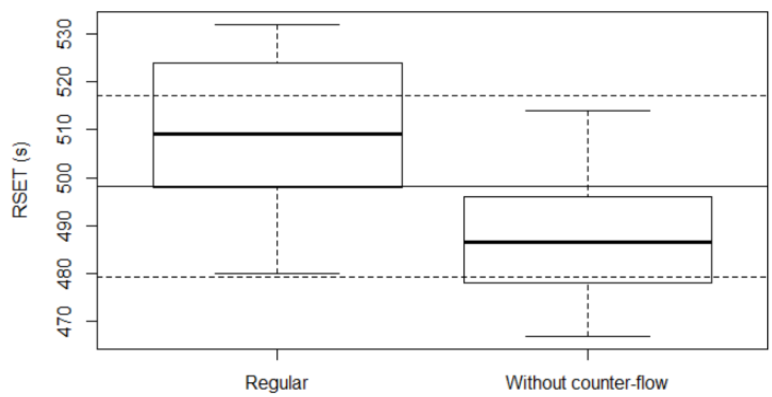


Figure 4.18 Boxplot of models with or without the counter-flow effect

Table 4.10 Two-sample t-test on the counter-flow effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	486.9
95% Confidence interval: (8.08456, 36.91544)		
t = 3.2838, df = 17.654, p-value = 0.00421		
Alternative Hypothesis: true difference in means is not equal to 0		

4.4.6. Effect of Fire Conditions

The gap between mean RSET values for these two boxplots (Figure 4.19) are plain to see. Based on the t-test output, a tiny p-value (= 1.848e-10) strongly supports the alternative hypothesis (Table 4.11). In this simulation design, the model with a different fire status influences movement speed, which corresponds to the effect of temperature, smoke density and toxicity, and human visibility and mobility while evacuating. As a result, the scenario without speed changes indicates a much shorter time requirement for RSET, and the estimated mean difference when compared against the regular model is 120.6 s with individual values ranging between 102.1–139.1s. Thus, the ABM model in this study successfully integrates the fire's effects while simulating the evacuation process of pedestrians.

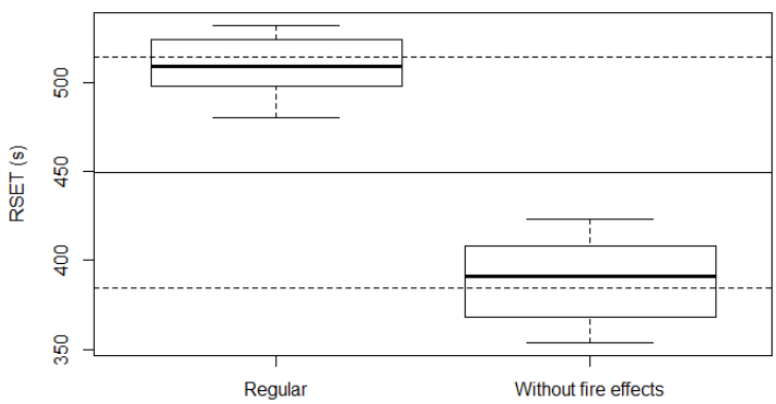


Figure 4.19 Boxplot of models with or without the fire condition effect

Table 4.11 Two-sample t-test on the fire condition effect

Two-sample t-test		
	Regular model	Modified model
RSET mean	509.4	388.8
95% Confidence interval: (102.0636, 139.1364)		
t = 13.76, df = 16.483, p-value = 1.848e-10		
Alternative Hypothesis: true difference in means is not equal to 0		

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study proposed a comprehensive BIM-based simulation design that combines FDS and ABM to improve building fire safety management. The simulation framework summarizes the critical factors for evacuation planning that include physical building properties (alarm system, material thermal properties, and building layout), characteristics of fire (smoke, toxicity, and heat generated), and characteristics of human behavior (both individual and social behavior patterns). To validate the proposed simulation design, an implementation of the "Station Night Club Fire" case is conducted. The analysis of the experimental results verifies the reliabilities of: (1) using the BIM technique to offer a platform for conducting simulation design; (2) simulating fire growth via the FDS tool; (3) accounting for the characteristics of the building properties, fire conditions, and human behavior in the agent-based evacuation design; and (4) applying the simulation outputs on a linear regression model used to investigate the relationship between building design and required safety egress time. These results can be used to optimize the building design and fire evacuation planning, and the 3D BIM serves as an environment to visualize the results of (1) the hazardous zones reflected in the fire simulation and (2) the effective escape routes recommended by the evacuation scenario. A sensitivity test on the fire simulation is conducted to study the proposed exponential relationship between fire growth rate and net heat flux, and to use statistical tools to test the critical factors' effects on evacuation time and evaluate the designed system.

5.2. Limitations

There are few limitations of current simulation framework design to be improved in the future. First, the experimental implementation of the evacuation simulation indicates fewer injuries and deaths compared to the real accident records. However, it is expected to predict conservative results that can ensure human evacuation safety in real emergencies. Second, although the simulation framework design in this study offers valuable information for fire evacuation planning during the building design phase, it is expected to assist in fire safety management throughout the entire construction life cycle, that includes the design phase, the construction phase, and the maintenance phase. Besides, human evacuation performance closely associates with psychological status while suffering from hazards. Even though pedestrians' evacuation actions can be predicted, it is hard to investigate their motivation. Thus, future studies and investigation on emergency behavior are essential.

5.3. Suggestions for Future Studies

Although this study contains all three factor categories critical for fire evacuation planning, there is room to improve the simulation design. This section lists a few recommendations for future research below.

- The ignition location in this experimental case relies on the fire investigation report. However, the ignition location of a fire is hard to predict in real life. Thus, it is recommended to test the effect of different ignition locations on the fire growth rate.

- In more complex building systems, a time-controlled device must be implemented in the fire simulation process, such as a sprinkler system being triggered at a specific time. Therefore, in future works, it is suggested to consider the effect of sprinkler systems on fire growth.
- The experimental study investigates only the single-story building type. In future fire safety and evacuation studies, multi-story building structures should be studied to conduct more complex fire evacuation planning.
- To assist in fire safety management through the entire construction life cycle, it is feasible to develop and apply the framework design on construction phase and maintenance phase, such as assisting in fire safety assessment of the construction site and fire safety equipment maintenance.

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