A BIM Based Simulation Framework for Fire Evacuation Planning

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Abstract

This study implements Building Information Modeling (BIM) for conducting a simulation design involving the technologies of Fire Dynamics Simulator (FDS) and Agent Based Modeling (ABM) to foresee the relationship between evacuators' mortality and building layout design. The goals of this paper are to investigate (1) how to predict the building's Available Safe Egress Time (ASET) by using FDS software; (2) how to reflect the evacuation behavior within an ABM simulation; (3) how would the Required Safe Egress Time (RSET) be impacted by the building properties, fire properties, and human behavior. By making a comparison between ASET and RSET, the optimized building layout design that reflects minimum RSET can be chosen. And finally, 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. These results can be used to improve fire safety management for both fire education and construction design. Following the results, this paper concludes with a description of challenges associated with building fire and agent-based evacuation simulations that would arise from developing a BIM-based framework for highly occupied building fires.

Keywords

Fire safety management • Building information modeling (BIM) • Fire dynamic simulator (FDS) • Agent-based modeling (ABM)

51.1 Introduction

51.1.1 Background and Motivation

Fire hazards pose threat to human life and property safety. The fire statistics report published in 2015 by the U.S. fire administration reveals that only in the United States, 129,800 of fires caused 3280 deaths and 15,700 injuries, which resulted in 14.3 billion dollars loss [1]. Even though the number of fire hazards, thus deaths, injuries and property damages due to fire hazards have decreased within the past decade, the numbers are still significantly high, and there is room to improve current fire safety management practice. More specifically, human behavior during a fire hazard should be further studied.

Therefore, this paper focuses on the issue of safe evacuation. Other than the physical building properties, evacuation safety not only depends on characteristics of fire, but also closely associates with characteristics of human behavior [2]. It would be unrealistic to study human behavior during a fire hazard. Computational tools are a better choice to simulate the fire growth and human behavior under such conditions. This study attempts to develop a Building Information Modeling (BIM) based platform for conducting fire simulations using Fire Dynamics Simulator (FDS) and Agent-Based Modeling (ABM).

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This paper is organized as follows. The next section introduces the related works on BIM, FDS, ABM and critical factors on the evacuation time in fires. Section 51.3 details the research methodology and implementation. The preliminary experimental results of a case study are described in Sect. 51.4. Finally, conclusions and recommendations for future work are provided in Sect. 51.5.

51.2 Literature Review

This section summarizes the existing literature related to emergency simulation technologies including BIM, FDS, ABM. Then, the critical factors that affect the evacuation time and life safety outcome in building fire scenarios including the physical properties of the building, the characteristics of fire, and human behaviors are identified.

51.2.1 Simulation Technologies

Building Information Modeling. BIM use in the construction industry has increased tremendously within the last decade as it helps contractors save time and money while improving project quality [3–6]. It is essential to apply BIM on fire simulations since building fires are directly associated with human safety and property security [4, 6]. In this case, Revit [8] is a 3D BIM tool that allows users to visualize better and communicate more effectively with simulation designs. First, Revit enables information sharing and linking with other software by importing/exporting commonly file formats, such as DWG and DXF. Second, Revit models contain not only the 3D data but also the object attributes that provide data integration or design analysis support. Besides, 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 [7]—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.

Fire Dynamic Simulator. FDS is a computational tool developed by NIST for modeling fire-driven flow with predicting burning products [9]. To quickly and accurately work with FDS models, PyroSim [10] is a particular software that enables importing DXF/DWG files from Revit for helping with various fire simulation goals. Galea et al. [11], Shen et al. [12] reconstruct fires by PyroSim for post-accident investigation. Glasa et al. [13], Glasa et al. [14], and Wang et al. [15] use PyroSim as a tool to evaluate fire safety of existing buildings. Besides, Tingyong et al. [16] combine PyroSim and EVAC [17] to establish a continuous FDS&EVAC model for assisting in building fire evacuation, and they demonstrate that FDS is an accurate and comprehensive simulation tool in fire safety field.

Agent-Based Modeling. ABM is one of a class of microscope agents for simulating the interactions of autonomous agents with a view to assess their effects on the system as a whole [18]. It is more of a mindset than a technology and can be applied across a wide range of research areas, such as economics, military, biology [19–21]. Thus, an agent-based modeling simulation is a powerful technique to simulate and capture the emergent behavior in individuals [22–25]. This study uses AnyLogic [26], which is a professional ABM software, to conduct the evacuation simulation since: (1) it can be integrated with Revit-developed buildings and structures by importing DXF file; (2) it can represent pedestrians as agents with individual parameters and behaviors; (3) it can simultaneously reflect the agents' interactions and reactions with spectacular 3D graphic [27]. 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 [28].

51.2.2 Critical Factors Affecting the Evacuation Time

Building Physical Properties. The physical characteristics of a building are closely associated with human decision-making process and fire growth. Although International Building Code (IBC) offers regulations for typical types of buildings, each building has its own engineered and situational attributes that affect fire outcomes. The engineered attributes are generally associated with the perspectives of building design and the situational attributes that are typically the environmental effects on evacuation performance [2, 25]. The building layout affect familiarity and proximity for pedestrians when they make their egress route decision. The capacity of a building to support pedestrian density will result in frequent congestion during emergencies.

Human Behavior. The pedestrians' individual personalities will affect their evacuation performance. The perception of risk and reward defined as a psychological process of risk assessment related to the current event [29]. It drives people to make an assessment of egress route selection before evacuating. However, 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 [25, 29]. Due to the human characteristic of herding behavior, the escape decision-making will be attracted by the instruction of someone who is familiar with the building layout [30]. Also, the escape route selection would be significantly driven by the factors of familiarity that results in choosing the same exit as the one they entered into [31]. Besides, with congestions happening, people will encounter with destructive actions, such as stampede, pushing, or trampling on others [25]. Due to these destructive actions, the counter-flow will be functional as the negative forward flow to negatively impact on the evacuation efficiency [32].

The Characteristics of Fire. During a fire hazard, the most threatening element is smoke, rather than fire, and can cause body pain or impaired vision [33]. According to the research results currently available in fire safety engineering analysis, the heat generated will begin to harm the human body when (1) its upper layer radiation strength reaches 180 °C and (2) the layer of direct contact reaches 60 °C [19, 33]. The smoke 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 [19, 22]. The toxicity concentration of CO will begin to harm humans when it reaches 2500 ppm [33]. Furthermore, humans will experience impaired visibility and mobility when the smoke density reaches above 85% [34]. 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.

51.2.3 Related Works on Fire Evacuation Design

To date, several researchers have conducted indoor fire evacuation simulation that reflects true human reactions. One of the pioneering studies in this domain was the grid simulation system that divided a simulated room into hundreds of grids [35], however human behavior simulation was limited by the computational abilities of that time. More than a decade later, Shi et al. [19], Peizhong et al. [20], Joo et al. [21] and Tang and Ren [22] successfully combined the ideas of the grid system and agent-based system that involved the impact of human evacuation behavior. However, none of them considered a delayed evacuation caused by building properties, such as the sensitivity of alarm system. Galea et al. [10] and Chaturvedi et al. [23] combined building properties and human properties together using the fluid and particle systems. However, they failed to consider fire effects. Abolghasemzadeh [24] used the matrix-based system to investigate the effect of building design on fire evacuation. Nonetheless, the matrix system is not a good choice for a crowded scenario, as the system struggles to simulate the effect of counter-flow.

By analyzing the current developments and limitations on fire evacuation simulation design, it is important to include all influential factors mentioned above to improve the accuracy of simulation outcomes. In this study, the movement of agents is based on the influence of human behavior (both individual and social behavior patterns), fire condition (temperature, toxicity, and smoke density), and building properties (alarm system, material thermal properties, and building layout). Moreover, this study develops a "re-decision model" for testing the effect of pedestrians who are impatient about queuing toward crowded exits. Besides, the effect of counter-flow will have an impact on agents' movement speed as a 0.81 coefficient of speed deduction [32], which refers to the destructive actions performed in counter-flow dynamics. To determine the effectiveness of building design, the number of exits, pathway width, and building capacity is adjusted to assist in optimizing the fire evacuation planning.

51.3 Research Methodology and Implementation

Revit software is used to established the architectural BIM model. BIM's interoperability function enables users to import the model into other software to conduct both the fire and evacuation simulations. PyroSim can be used to test the building's fire resistance and indicate the Available Safe Egress Time (ASET). The evacuation simulation is based on human physical limitation in fires to predict the Required Safe Egress Time (REST) by using AnyLogic.

To validate the designed simulation framework, the data collected from the Station Nightclub Fire, which occurred on the night of February 20th, 2003, in West Warwick, Rhode Island is used [36]. It was the fourth-deadliest nightclub fire in US history and killed 100 people, injured 230, and only 132 escaped uninjured [36].

51.3.1 Fire Simulation Design

Figure 51.1 shows the procedures of how to develop a fire simulation through PyroSim. The Revit model is first export as DWG file then resampled into the pre-defined 3D cubic mesh in PyroSim. The 2D drawings and material information for establishing the models are mainly obtained from the fire investigation report [36]. With an increased resolution of the mesh, a higher accuracy of the simulation can be obtained. However, reducing the mesh size as a factor of 2 will result in about a factor of 16 more computation time [29]. To balance the computation time and accuracy, 0.25 m length cubic mesh cells are used in this case. Moreover, nylon carpet, wood panels, and foam insulation account for the majority of fuel material that results in a quick fire spread [36]. These materials' thermal properties are referenced to the ASTM E84 [37]. Besides, the fire reaction is defined by creating the ignitor with 45 kW/m^2 Net Heat Flux, which is known as the heat energy transferred per surface unit area [9]. To measure and monitor the dynamic fire growth, the device system is composed by three types of devices (detectors of smoke, heat, and soot) and three layers of 2D slices (1.5, 2.0 and 2.5 m), which can reflect the changes of fire conditions in different heights. And finally, the outputs results of temperature, visibility and toxicity density will be visualized as time history plots in PyroSim, and the burning animation can be displayed in Smokeview [29]. The Available Safe Egress Time (ASET) represents the time before people begin to get hurt during the fire growth period.

51.3.2 Evacuation Simulation Design

The designed evacuation simulation in this study consist of four periods: the pre-alarm period, alarm period, pre-evacuation period, and evacuation period (Fig. 51.2). Fire ignition is defined in the model as the start time of 0 s. The pre-alarm period is the time necessary to receive a fire signal, which depends on the location of fire cues and the sensitivity of the alarm system. After the fire ignites, the agents' evacuation is delayed 0–60 s due to the time needed for the signal to be received and the risk assessed. In this design, 2% of agents are assumed as club officers who are familiar with the effective egress routes. And they will affect the movement direction of nearby agents. However, people may not be able to search for guided routes caused by the factor of bounded rationality. Unleaded agents will move to the main entrance initially due to the function of familiarity. The typical capacity of doorways allows 60 people per minute [34], thus the incapable doorway would be jammed and require people to queue for sheltering. As for the people who are impatience to wait longer than 30 s, they will make a re-decision of route selection. During the evacuation period, the default speed of agents is defined as adults' average walking speed of 1.25 ± 0.3 m/s [35]. By considering the influence of smoke density, their speeds will reduce to

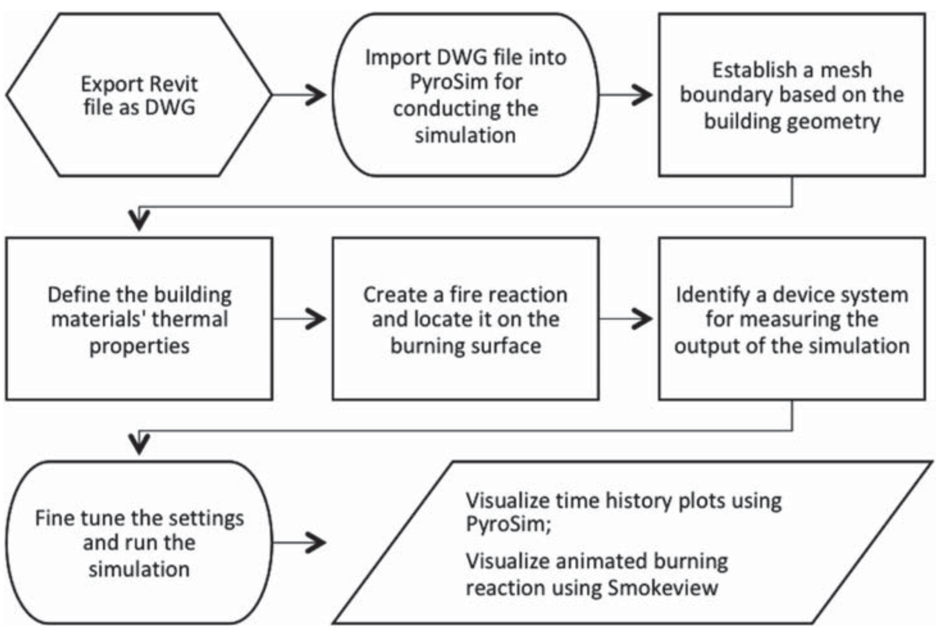

Fig. 51.1 Fire simulation design flowchart

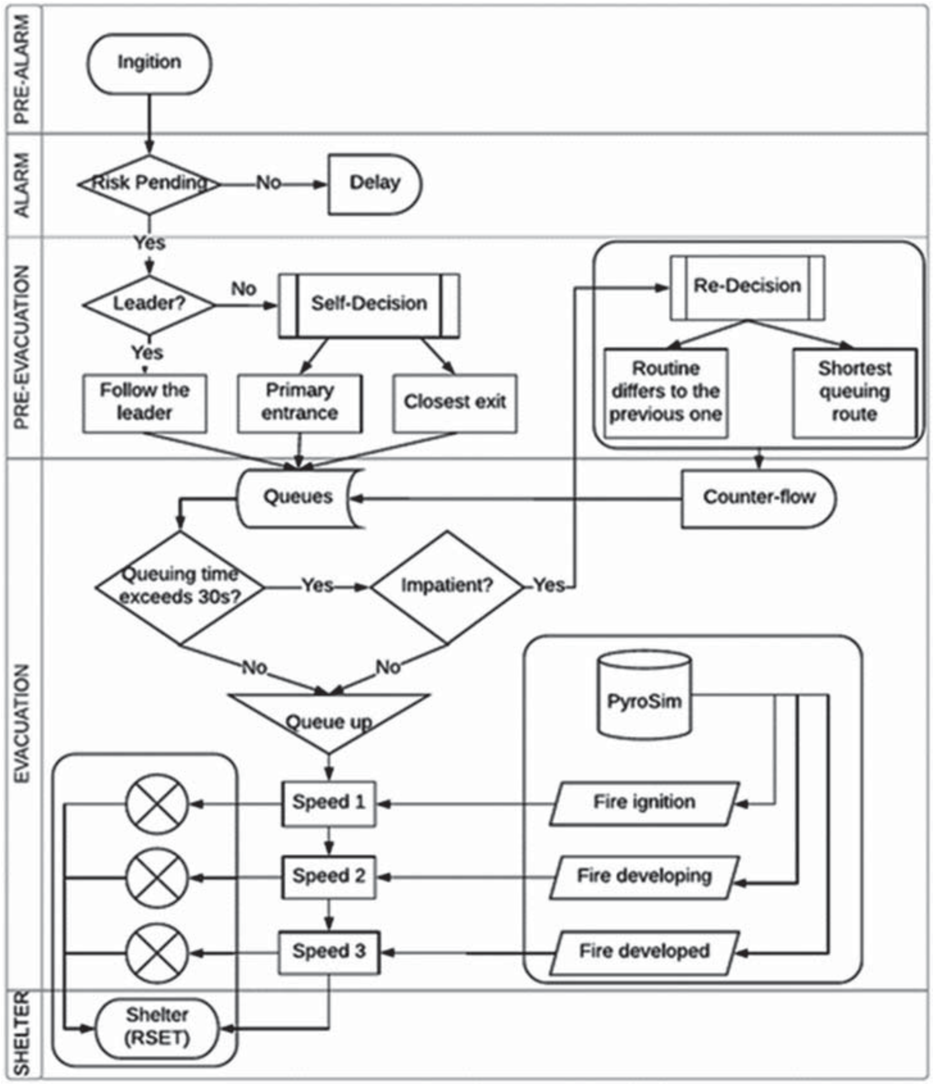

Fig. 51.2 Evacuation system flowchart

1.125 ± 0.27 m/s during the fire developing stage, and then reduce to 0.75 ± 0.18 m/s while the fire is fully developed. In the end, the time needed for sheltering all agents is used to represent the Required Safe Egress Time (REST).

51.4 Preliminary Results

51.4.1 Simulation Results

The fire simulation timeline approximately corresponds to the real accident timeline (Fig. 51.3). The smoke layer reaches 1.5 m at 180 s and reaches 1.2 m at 300 s, thus the agents' walking speed should deduct 10 and 40% respectively. Besides, the smoke density reaches 85% at 380 s, which happened earlier than other human physical limitations in fires. As a result, the ASET for uninjured, injured and severely injured escape are 180, 300, and 380 s respectively. Based on the evacuation simulation outputs: (1) 127 agents escaped uninjured; (2) 215 agents escaped with injuries; (3) 370 agents escaped with severe injuries and 92 died; (4) the RSET for all agents escaped without losing lives is 510 s. The numbers of sheltered

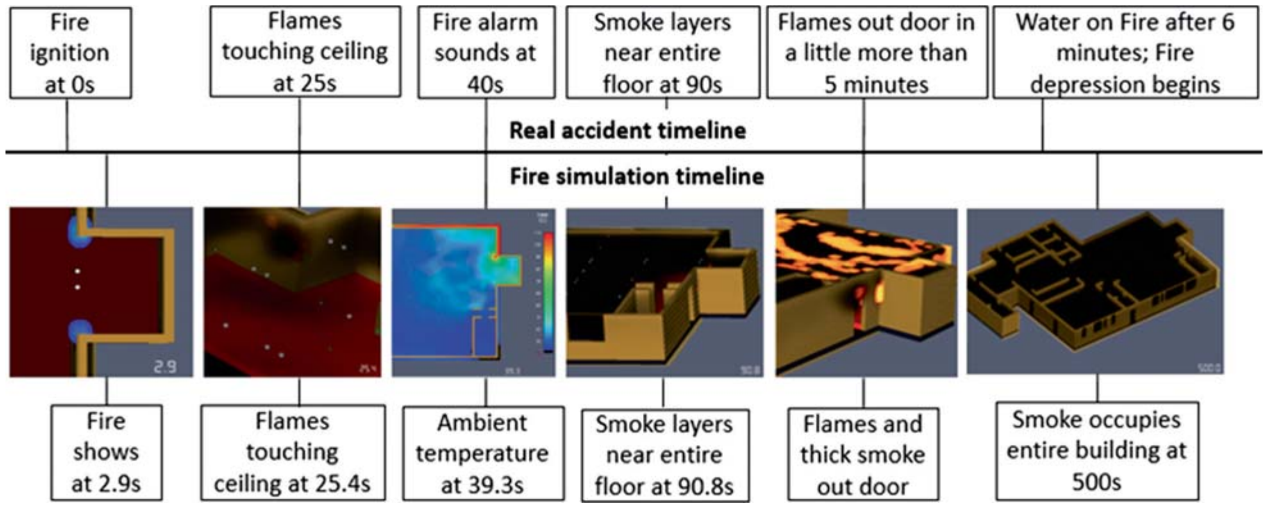

Fig. 51.3 Comparing timelines (ceilings are hided for better visualization)

Table 51.1 Suggested building designs for fire safety

Exits' number	Doorways' width (m)	Occupants' capacity	RSET	ASET	RSET $\leq$ ASET?
4	1	323	380	380	Yes
8	1	462	378	380	Yes
4	4	462	369	380	Yes

agents correspond to the accident records of injuries and deaths, which validates the accuracy of the evacuation simulation design.

Statistical Analysis. A statistical t-test is applied to investigate the relationship between RSET and building layout design. All of the simulations are assumed to be independent and normally distributed. As a result, with a 95% confidence level, small p-values (<0.01) significantly suggest a linear relationship between RSET and those three factors. The estimated model equation can be written as:

$$\text{RSET} = 265.60 - 32.78a - 46.78b + 0.93c \tag{51.1}$$

where factor a is the exit number, factor b is the doorway width, and factor c is the occupant capacity. This equation can be used to predict RSET for different building designs.

51.4.2 Application of Simulation Results

Acceptable building layout designs are defined by a smaller RSET number compared to ASET. Using Eq. 51.1, there are several building design suggestions that changes one variable only compared to the original building design (4 exits, 1 m doorway width, 462 occupant capacity) (Table 51.1). In order to achieve the maximized building utilization without human death, the optimal building design would be to keep the original layout design but lower the occupant capacity to 323.

Visualized through BIM. 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. The pedestrian density flow shown in AnyLogic indicates that the agents crowd and congest the main entrance while evacuating. This is caused by the fact that most pedestrians are not aware of the side-door exits and instead select the main 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. The side exits should also be more clearly represented as recommended egress options. Finally, 3D-BIM will serve as the environment to visualize these results.

51.5 Conclusions and Future Work

This paper proposed a comprehensive BIM-based simulation design that combines FDS and ABM to improve building fire safety management. By analyzing the simulation results shown in the case study, we verified the reliabilities of (1) simulating the fire growth by FDS tool; (2) involving the characteristics of the building properties, fire conditions, and human behaviors into the Agent-based evacuation design; (3) using a linear regression model to optimize the building design. In the end, 3D BIM served 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 simulation.

Besides, this study leaves room to improve the simulation design: (1) it is recommended to test the effect of different ignition locations on the fire growth rate since the ignition location of a fire is hard to predict in real life; (2) 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; (3) multi-story building structures should be studied to conduct more complex fire evacuation planning; (4) 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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