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Optimizing Evacuation Efficiency in Buildings: A BIM-Based Automated Approach to Sustainable Design

Cherry Rose Godes [1], Shanelle Aira Rodrigazo [1], Junhwi Cho [1], Yooseob Song [2] and Jaeheum Yeon [1,*]

[1] Department of Regional Infrastructure Engineering, Kangwon National University, Chuncheon 24341, Gangwon, Republic of Korea; cherryg@kangwon.ac.kr (C.R.G.); rodrigazo.shanelleaira@kangwon.ac.kr (S.A.R.); xnxlwnsgnl@kangwon.ac.kr (J.C.)
[2] Department of Civil and Environmental Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, USA; ys0029@uah.edu
* Correspondence: jyeon@kangwon.ac.kr

Abstract: This study addresses the challenge of optimizing fire evacuation efficiency in complex buildings by investigating the impact of automating corridor dimension adjustments on reducing evacuation congestion. A Building Information Modeling (BIM)-based approach using Autodesk Revit 2024, Dynamo version 2.17, and Thunderhead Pathfinder 2023 simulations was employed to test this hypothesis. The results show that automated adjustments in hallways have a significant positive impact on evacuation efficiency in the majority of building floor corridor segments. These findings highlight the potential for dynamic design modifications to enhance building safety and sustainability. Future research will focus on refining this approach for diverse building layouts and occupant behaviors.

Keywords: BIM; dynamo; fire safety; evacuation; simulation

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1. Introduction

Ensuring the safety and efficiency of building evacuations during emergencies is a critical concern in modern architecture and urban planning. As buildings become more complex and densely populated, the risks associated with inadequate evacuation strategies have also risen. Structures with high occupancy, such as office towers, schools, and residential complexes, present unique challenges that necessitate careful evaluation of safety measures [1].

In building design, fire safety standards are fundamental to ensure occupant protection in case of fire [2]. These standards encompass a wide range of regulations, from building materials to emergency systems. International standards, such as those developed by the International Organization for Standardization (ISO) [3] and the National Fire Protection Association (NFPA) [4], provide a global benchmark. Local adaptations are frequently incorporated into national building codes. Important provisions for fire safety encompass requirements for exits, signage, emergency lighting, and occupant load capacities [5].

The persistent threat of building fires accentuates the importance of effective evacuation planning. Although there has been a decrease in fatalities, building fires continue to cause significant harm. According to the data from 2009, fires in the United States resulted in 2980 fatalities and 13,900 injuries [6,7]. Recent data from the U.S. Fire Administration highlight the ongoing risk associated with non-residential building fires in 2022. The estimates for these non-residential building fires report 129,500 incidents, with 140 fatalities, 1300 injuries, and $3.74 billion in property damage [8]. These statistics emphasize the critical need for proactive fire safety measures.

Modern architecturally conceived building designs often emphasize aesthetic and functional aspects, sometimes at the expense of safety considerations [9]. However, as building codes evolve and the risks associated with high-density occupancy become more

apparent, the need to integrate safety-focused design principles early in the planning process has gained prominence. Among these principles, optimizing corridor width stands out as a critical factor that must be addressed together with other design elements, such as door width, exit placement, and stairwell configuration, to achieve effective evacuation. The interdependence of these factors necessitates a comprehensive approach to safety in building design.

The width of corridors plays a crucial role in determining how efficiently people can evacuate during emergencies, especially in buildings with high occupancy and complex layouts [10]. Research indicates that corridor width is a critical factor in evacuation efficiency [11], as it directly reduces congestion and improves pedestrian movement. While the benefits of widening corridors may diminish beyond a certain point, optimizing building design—including layout and corridor width—remains essential for effective evacuations. Snopková et al. [12] suggest that wider corridors not only alleviate congestion but also significantly influence route selection during evacuations, with individuals showing a preference for wider and shorter paths with visible exits, thereby enhancing overall evacuation effectiveness and safety. The relationship between safety parameters and modern building design is crucial, especially given the complexity and scale of structures [13]. Hence, optimizing corridor dimensions is essential for enhancing safety and adhering to established principles in architectural and engineering design.

Implementing such measures early in the design process not only reduces risks but also significantly decreases the expenses associated with modifying building designs later during construction or operation [7,14]. Early integration of fire safety strategies allows for cost-effective adjustments to building models, ultimately leading to a safer built environment. Given the limitations of static design methods, a dynamic, data-driven approach is required to address the complexities inherent in modern buildings. Building Information Modeling (BIM) offers a robust platform for this purpose, enabling the integration of architectural design with advanced simulation tools such as Thunderhead Pathfinder. These tools allow for the precise modeling of human movement during emergencies, facilitating real-time optimization of building evacuation plans. The integration of BIM with simulation data enables the identification of potential bottlenecks and the subsequent adjustment of corridor dimensions, thereby improving overall evacuation efficiency.

The study aims to investigate the potential use of congestion data obtained from evacuation simulations in order to automate adjustments to corridor width. Specifically, this automation process involves the use of Dynamo scripting within Autodesk Revit, allowing for iterative calculations of corridor dimensions based on evacuation data from Pathfinder simulations. By dynamically updating corridor widths in response to density and flow metrics, this approach optimizes evacuation efficiency across multiple floor segments. The objective is to improve the efficiency of evacuations. The study presents a framework that utilizes BIM and real-time simulations to optimize design and enhance safety in complex, high-occupancy buildings, overcoming the constraints of conventional design methods. The study shows that utilizing a BIM-based approach to dynamically optimize corridor widths can lead to substantial improvements in evacuation efficiency. By reducing congestion and enhancing pedestrian flow, design modifications such as widening corridors have been shown to have a significant impact on flow dynamics across multiple floors. These findings highlight the importance of continuously refining building design and implementing targeted interventions to address congestion in critical areas and enhance overall safety during evacuations.

2. Literature Review

2.1. Corridor Width in Evacuation Efficiency

Congestion is a critical factor impacting evacuation time and safety. Research by Adrian et al. [15] highlights the impact of corridor width on density and queuing behavior, suggesting a transition point between 1.2 m and 2.3 m. Similarly, Nassar [16] emphasizes the importance of correlating corridor design with occupant flow, presenting a queuing model

to evaluate occupant density and validate design variables. Furthermore, Zhang et al. [17] further elaborate on the impact of corridor width on evacuation efficiency, showing that different queuing methods and widths influence evacuation efficiency differently, with critical widths for evenly divided queues affecting efficiency levels. These findings underscore the importance of hallway width, not only as a parameter but as a pivotal design element that directly mitigates congestion, enhances pedestrian flow, and reduces evacuation times. As an example, in a high-rise teaching building, adjusting the width of the corridors was a component of a multi-factor optimization that resulted in a significant improvement in total evacuation time, with an increase of up to 29.5% [18].

An essential aspect of designing hallways effectively is to understand the correlation between physical space and the number of occupants. This relationship has been carefully studied by Stojanovic and Vujovic [19]. Their study on occupant density offers valuable insights for determining the most suitable occupancy limits in different building environments. Similarly, research on occupant load density in exhibition halls [20] emphasizes the necessity of adjusting maximum occupant load densities based on specific building functions, which further supports the argument that corridor width must be carefully tailored to the intended use and occupancy of the space. These factors emphasize the significance of hallway dimensions in an evacuation route, as they often serve as the primary shared space. While parameters such as door width and exit placement are important, they cannot completely offset the impact of insufficient corridor dimensions.

While existing building codes offer general guidance on hallway dimensions, they may not sufficiently address the complexities of specific building types or potential congestion hotspots. This gap highlights the need for more meticulous design strategies that prioritize hallway width in conjunction with other elements such as stairwell configuration and exit placement.

Evacuation simulation tools have emerged as valuable assets in assessing building performance under fire conditions. By modeling occupant movement, fire growth, and smoke spread, these tools can identify potential bottlenecks and evaluate the effectiveness of different hallway designs. Simulation enables designers to test various layout configurations, optimize exit placement, and quantify evacuation times.

The application of evacuation simulation has yielded significant improvements in hallway design across various building types, including hospitals [21], educational institutions [18], office buildings [22], and public spaces [23]. By identifying congestion points and evaluating design alternatives, simulation has optimized evacuation routes and enhanced overall building safety. In particular, multi-story university research facilities, with their complex layouts and high occupancy, can benefit greatly from the application of simulation to improve evacuation efficiency.

2.2. Current Studies on Fire Evacuation

A cornerstone of contemporary fire safety research is the development and application of evacuation modeling and simulation techniques. These methods have transformed the ability to analyze building performance and occupant behavior during fire conditions. Researchers have employed various simulation platforms and modeling approaches to investigate the impact of building design, occupant density, and emergency systems on evacuation outcomes. While human behavior remains a critical factor in evacuation dynamics, research has also explored the use of agent-based models and data-driven approaches to simulate crowd behavior and predict congestion patterns.

A significant body of research has emphasized the significance of congestion data in informing building design decisions. Studies have investigated the relationship between hallway width, length, and occupant density on congestion levels. Researchers have utilized simulation tools to generate congestion maps and identify critical areas for design intervention. By correlating congestion data with evacuation time, studies have demonstrated the impact of design modifications on improving evacuation efficiency.

While progress has been made in understanding the role of congestion in fire evacuation, several research gaps persist. There is a need for further investigation into the development of standardized metrics for measuring congestion levels and assessing the effectiveness of design interventions. Additionally, exploring the application of advanced data analysis techniques, such as machine learning, to identify optimal hallway configurations based on congestion patterns is a promising area of research.

2.3. Optimization Techniques in Building Design

Optimization techniques have gained prominence in building design to achieve performance objectives such as energy efficiency, structural integrity, and occupant comfort. In the context of fire safety, optimization methods can be employed to identify optimal building configurations that minimize evacuation time and maximize safety. Techniques like genetic algorithms, particle swarm optimization, and simulated annealing have been applied to optimize building layout, exit placement, and emergency system design.

Integrating optimization techniques with simulation tools, such as Thunderhead Pathfinder, enables a holistic approach to building design. By coupling simulation-generated data with optimization algorithms, it is possible to iteratively improve building performance. This integration allows for the exploration of a vast design space and the identification of optimal solutions that meet specific design criteria.

For enhancing fire evacuation efficiency, optimization techniques can be applied to determine optimal hallway dimensions. By defining objective functions that prioritize factors like evacuation time, congestion levels, and accessibility, optimization algorithms can generate multiple design alternatives. These alternatives can then be evaluated using simulation tools to select the most effective hallway configuration.

2.4. Simulation Tools in Evacuation Planning

Evacuation planning benefits greatly from the use of specialized simulation tools, which offer valuable insights by accurately modeling real-world scenarios and optimizing safety strategies. Tools such as Thunderhead Pathfinder focus on pedestrian dynamics and congestion analysis, offering precise measurements of evacuation times and identifying potential bottlenecks. Additionally, the integration of Building Information Modeling (BIM) tools such as Dynamo with simulation software allows for the creation of dynamic building models. However, it is important to note that the functionalities of these tools may vary from those of dedicated evacuation simulators. These tools work in tandem to improve the planning and management of safe evacuation routes by utilizing their unique capabilities.

Comparison of Simulation Tools

A range of simulation tools is available for evacuation planning, each with its own strengths and limitations. Factors to consider when selecting a simulation tool include:

- Modeling capabilities: Pedestrian behavior, fire growth, smoke spread, and environmental conditions.
- Level of detail: Microscopic or macroscopic modeling approaches.
- Integration with BIM: Compatibility with building information models.
- User interface: Ease of use and accessibility.
- Validation and verification: Rigorous testing and validation processes.

Simulation tools play a crucial role in the optimization process by providing data on evacuation performance [24]. By iteratively modifying building designs and running simulations, designers can identify optimal solutions that minimize evacuation time and maximize safety. The integration of simulation tools with optimization algorithms enables efficient exploration of the design space and identification of effective design alternatives.

2.5. Research Gap

Existing research on fire evacuation has made significant strides in understanding occupant behavior, building design, and simulation modeling. However, gaps persist,

particularly in the application of optimization techniques to automate design improvements based on congestion data. This study aims to address these limitations by developing a workflow that integrates simulation and optimization to enhance hallway design in multi-story research facilities. By focusing on congestion as a primary metric, this research seeks to contribute to the development of data-driven design approaches that prioritize occupant safety and efficient evacuation.

3. Methodology

The methodology is divided into five main phases: preparation, simulation, automation, iterative optimization workflow, and analysis. Each phase is designed to ensure a structured and replicable approach to optimizing building evacuation processes. To provide a comprehensive understanding of the research workflow, Figure 1 outlines the workflow stages from building model preparation to simulation and automation. The programming aspect is implemented primarily through Dynamo scripting within Autodesk Revit, which automates corridor adjustments based on simulation data from Pathfinder.

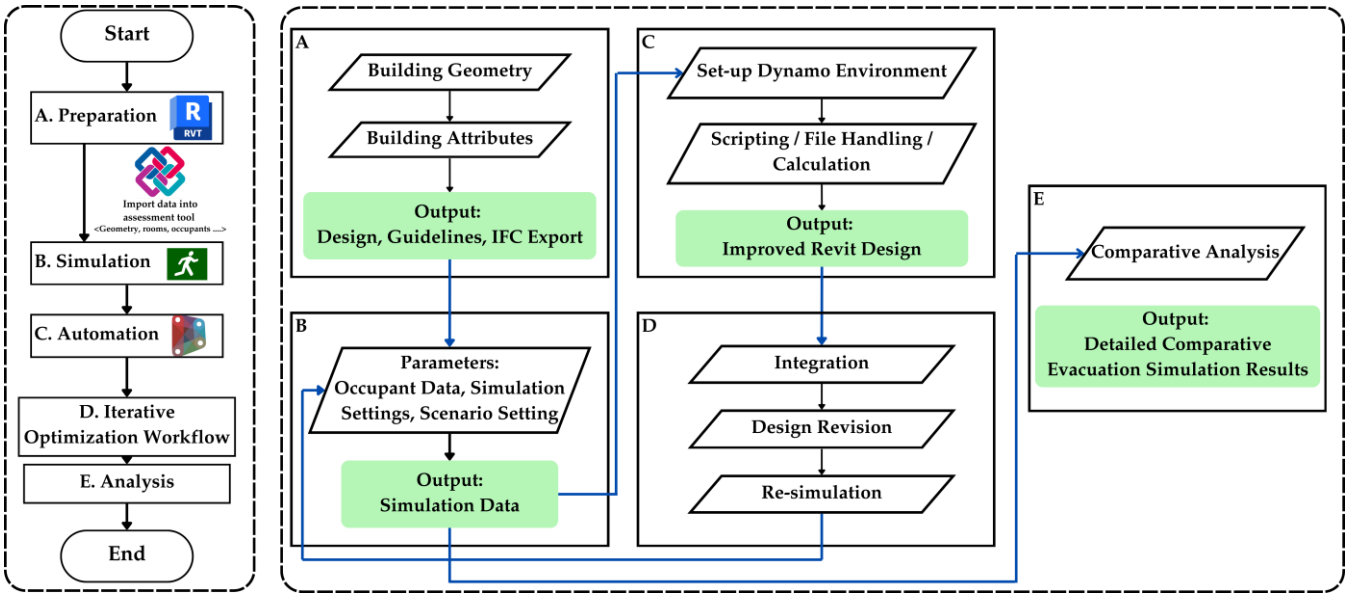


Figure 1. Study workflow.

This flowchart serves as a visual guide, outlining the sequence of activities and their interconnections. It begins with the preparation phase, where building data are imported into the assessment tools, followed by the simulation phase, which involves setting up and running evacuation simulations using Thunderhead Pathfinder. The automation phase utilizes Dynamo scripting for automating design modifications based on simulation data. The iterative optimization workflow integrates the simulation data back into the design process, enabling continuous improvement through re-simulation and design revision. Finally, the analysis phase involves a detailed comparative analysis of the simulation results to derive actionable insights.

The outer dashed-line box on the left side of Figure 1 represents an overview of the entire study workflow, from start to end. The larger dashed-line box beside it, containing phases A-E, provides a detailed breakdown of each major step, representing specific tasks and outputs within each phase. This dual structure clarifies the study's methodology by showing both the overall process and the intricate details of each phase.

3.1. Building Design with Revit

3.1.1. Building Description and Design Selection Criteria

A model of the seven-story university educational research facility, named Convergence Platform, depicted in Figure 2, proposed for Kangwon National University College

of Agriculture and Life Sciences, was initially created in Revit. The building encompasses a total floor area of 13,694 square meters and includes 213 rooms, such as professor offices, laboratories, equipment rooms, convention halls, and smart farms. It is divided into three distinct zones: the research zone (front side), the public zone (middle), and the experiment zone (back side). The building includes four elevators and three staircases connecting all floors, with a prominent 6-meter-wide staircase on the first floor to facilitate efficient vertical circulation. The main entrance features two dual vestibule doors, and there is a separate single-door service entrance to the garage, both located on the first floor. Typical door sizes in the facility are 36 inches for single doors and 71 inches for double doors. The staircases are 1.5 m wide, and hallway widths range from 1.2 to 2.4 m. Professor rooms typically measure 3.3 m by 7.8 m, while laboratories are 6.6 m by 9.0 m. The dimensions of other rooms vary depending on their specific functions and purposes. The floor height in the 3D Revit model was set at 4.0 m, which is consistent with standard design criteria for this type of facility. The floor with the highest number of rooms, totaling 40, is illustrated in Figure 3. The doors are shown in yellow as per the default settings in Pathfinder. The presence of these features indicates that the building offers a practical and demanding setting for examining the effectiveness and safety of evacuation methods.

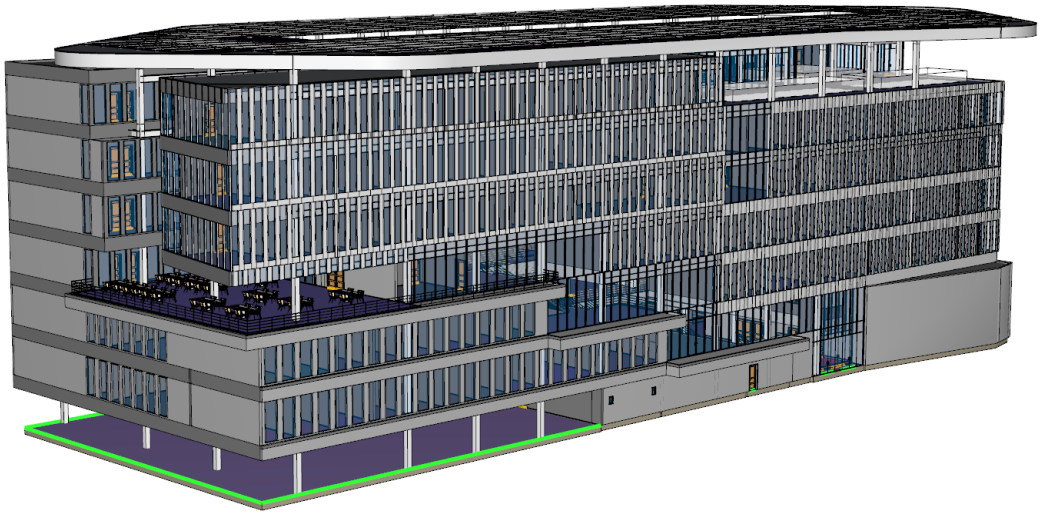


Figure 2. 3D Revit model of the facility. The green areas represent designated exit paths as defined in Pathfinder.

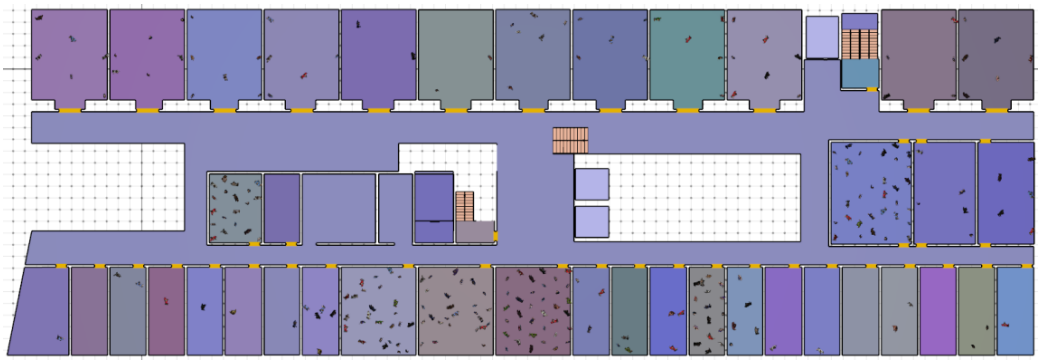


Figure 3. Floor plan of the facility with maximum room count.

3.1.2. Tools and Software

To model the building and simulate evacuation scenarios, three tools and software were used: Revit 2024, Dynamo version 2.17, and Pathfinder 2023.

1. Pathfinder [25] by Thunderhead Engineering was used for evacuation simulations. Pathfinder is known for its advanced modeling of human movement during emer-

gencies, offering detailed metrics such as density, velocity, and person flow rates. Its ability to simulate different emergency scenarios makes it a valuable tool for evaluating evacuation efficiency. However, its limitations include the assumption of uniform behavior among occupants, which may not accurately reflect diverse reactions and occupant interactions observed in real emergencies.

2. Autodesk Revit was utilized for creating detailed building models due to its robust capabilities in architectural design and interoperability with other tools. Revit's features include 3D modeling and parametric design, allowing for automatic updates to the model dimensions when changes are made via Dynamo scripts.
3. Dynamo was employed for scripting and automation. Its integration with Revit allows for intricate design modifications and parametric adjustments, enabling the automation of repetitive tasks and enhancing the efficiency of model updates.

The use of these tools facilitates a thorough approach to building modeling and evacuation simulation, enabling detailed analysis and optimization of evacuation procedures.

3.2. Evacuation Simulation with Pathfinder

3.2.1. Simulation Setup

The initial evacuation simulation setup involved importing the building design from Revit into Pathfinder. The setup included defining the building geometry, attributes, and occupant characteristics within the Pathfinder environment. Parameters such as occupant density, movement speed, and egress paths were meticulously configured to mirror real-life evacuation conditions.

The exported IFC file was imported into Thunderhead Pathfinder to configure and run evacuation simulations. Pathfinder, developed by Thunderhead Engineering, was used to simulate the evacuation of the university research facility. The college that will use the facility has a statistical population of approximately 1300 individuals. However, during the evacuation simulation, the distribution of occupants is considered based on the occupancy rate for each room. The simulation parameters were determined using the occupancy guidelines provided by the Society of Fire Protection Engineers (SFPE) [26] for each room type. The number of occupants in the simulation was determined by these parameters, and they were categorized into three types: guest, office, and student.

The simulation comprises 1854 occupants who were allocated speeds based on their occupant type. Based on the SFPE's occupant load factors, the second floor, which consists of 16 rooms, has the highest occupancy rate of 16.61%. Table 1 presents an overview of the number of people per floor, indicating the percentage of occupants from the student, office, and guest groups, as well as the corresponding speed parameters. The detailed parameters, including occupancy loads, evacuation speeds, and occupant profiles, were input based on guidelines from the SFPE and the National Fire Protection Association (NFPA) to ensure realistic simulations.

Table 1. Occupant load distribution and movement parameters by floor and occupant type.

Floor	Occupant Load	Proportion (%)	Student (%)	Office (%)	Guest (%)
1st	297	16.02	4.04	17.51	78.45
2nd	308	16.61	0.00	28.25	71.75
3rd	240	12.94	4.58	12.08	83.33
4th	293	15.80	0.34	8.53	91.13
5th	218	11.76	1.83	25.23	72.94
6th	259	13.97	2.32	20.46	77.22
7th	239	12.89	10.46	5.86	83.68
	Occupant Count		1480	315	59
Total	1854	100%	79.83%	16.99%	3.182%
	Parameter				
	Minimum Speed (m/s)		1.55	1.08	1.19
	Maximum Speed (m/s)		1.79	1.63	1.419

3.2.2. Data Collection and Processing

Metrics collected during the simulation included occupant density, velocity, and the count of persons per second at various points within the building. These metrics are critical for analyzing evacuation efficiency and identifying potential bottlenecks.

3.2.3. Mathematical Models

The mathematical foundations for the evacuation simulations follow the Society of Fire Protection Engineers (SFPE) guidelines, employing key metrics like occupant density and travel speed. The occupant load L is calculated using the following equation:

$$L = A/F \tag{1}$$

where A is the area and F is the occupant factor. Movement speed S incorporates density D and friction factors F, calculated as follows:

$$S = S_0 - D \times F \tag{2}$$

The flow rate through egress components, which helps identify potential bottlenecks, is calculated using the equation:

$$Flow\ Rate = Density \times Speed \tag{3}$$

where density is the number of occupants per square meter and speed is the average travel speed of the occupants. These mathematical models allow for an accurate representation of the occupant dynamics during an evacuation, yielding insights into areas for design improvement.

3.3. Automation with Dynamo

3.3.1. Setup

The Dynamo scripting environment was set up to automate the iterative design process. This setup involved installing necessary packages, configuring the scripting environment, and ensuring compatibility with both Revit and Pathfinder outputs. The setup process is detailed to allow others to replicate the automation workflow.

3.3.2. Theoretical Background

The theoretical foundation of this study is rooted in pedestrian flow dynamics and queuing theory, both of which are crucial for modeling and optimizing pedestrian movement within building corridors.

Pedestrian flow dynamics, a subfield of traffic flow theory, provides a framework for understanding the movement of individuals in confined spaces [27]. The study utilizes key concepts, including the fundamental diagram of pedestrian flow and the speed–density relationship modeled by Greenshield's equation.

$$v(W) = v_o\left(1 - \frac{d}{d_{max}}\right) \tag{4}$$

where $v(W)$ represents the walking speed as a function of corridor width W, v_o is the free-flow speed, and d_{max} is the maximum pedestrian density. This model illustrates that as density increases, walking speed decreases linearly until it reaches its maximum.

Flow rate $q(W)$, which provides a measure of pedestrian efficiency, is calculated as the product of density, speed, and corridor width.

$$q(W) = d(W) \times v(W) \times W \tag{5}$$

To derive the flow rate as a function of corridor width, the density is defined as the number of occupants per unit area.

$$d(W) = \frac{number\ of\ Occupants}{length \times W} \tag{6}$$

The walking speed $v(W)$ decreases as density increases and is modeled by substituting the density equation into Greenshield's model. The flow rate is then calculated by combining the equations for density and walking speed as follows:

$$q(W) = \frac{number\ of\ Occupants \times v_{sim}\left(1 - \frac{number\ of\ Occupants}{d_{max} \times length \times W}\right)}{length} \tag{7}$$

This equation is essential for determining the optimal corridor width that maximizes pedestrian flow while considering constraints such as density and speed.

In addition to pedestrian flow dynamics, the study incorporates queuing theory, particularly Little's Law, to model pedestrian movement within the corridor. Queuing theory is a mathematical study of waiting lines, or queues, which is applied here to model the flow of occupants during evacuation. Little's Law is defined as follows [28]:

$$L = \lambda W \tag{8}$$

where L is the long-term average number of pedestrians in the corridor, λ is the effective arrival rate, and W is the average time pedestrians spend in the corridor. This relationship is instrumental in linking the number of pedestrians with their arrival rates and travel times, providing a robust framework for understanding and optimizing pedestrian flow.

While these theoretical models offer a solid foundation, they are subject to certain limitations. Many models assume uniform pedestrian behavior and density distribution, which may not fully capture the variability observed in real-world scenarios. Additionally, the speed–density relationship is often simplified as linear, though actual pedestrian behavior may exhibit non-linear characteristics. Furthermore, basic models may not account for dynamic changes in pedestrian flow over time or varying environmental conditions such as obstacles and variations in corridor width.

3.3.3. Dynamo Script

Building on the theoretical framework outlined in Section 3.3.1, this section describes the practical execution of optimizing corridor width using a Dynamo script built into the Autodesk Revit system. Dynamo enables the automation of iterative design adjustments based on the principles of pedestrian flow dynamics and queueing theory. Through this node-based visual programming environment, it facilitates the selection of room elements, input of required values, and adjustment of building geometry directly with the Revit model, as shown in Figure 4. For the script to work effectively, rooms and walls in the Revit model must be properly identified and tagged.

The Dynamo script automates corridor width adjustments by setting specific threshold criteria for acceptable congestion levels, informed by Pathfinder simulation data. When the occupant density in a corridor segment exceeds the predetermined threshold, the script dynamically adjusts the corridor width in increments to alleviate congestion and enhance evacuation flow. The adjustments are capped at a designer-determined maximum width to maintain practicality and regulatory compliance, ensuring the corridor dimensions remain within building and fire safety code standards. This approach optimizes evacuation efficiency while respecting constraints on corridor width.

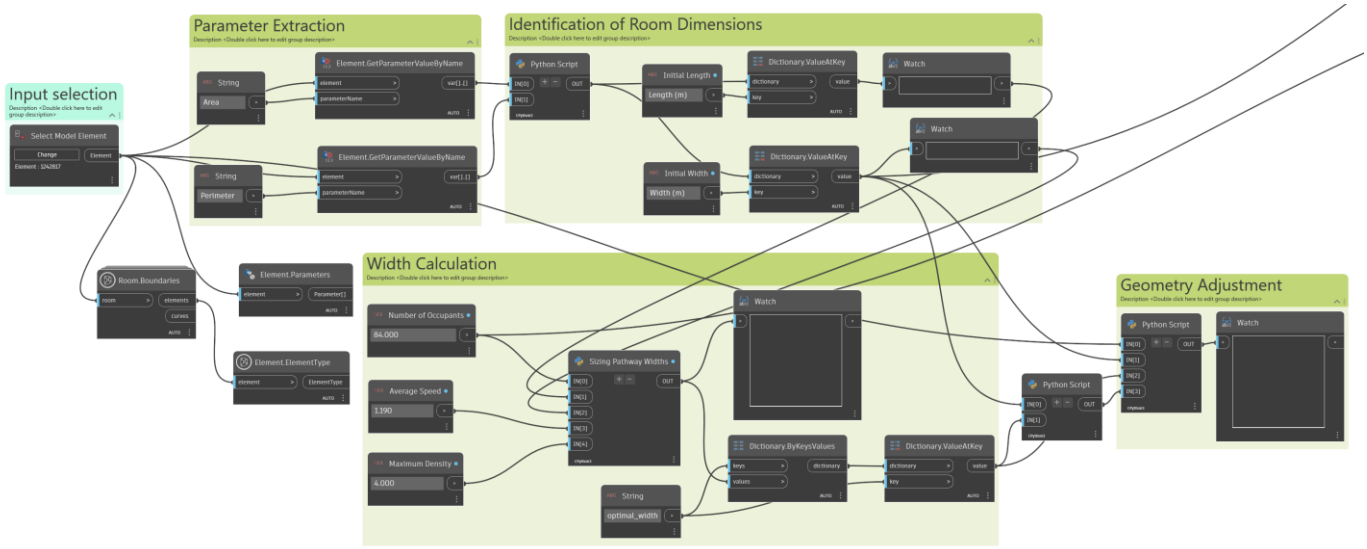


Figure 4. Sample Dynamo script workflow for optimizing corridor widths in building design.

4. Results

4.1. Simulation Results

The evacuation simulation yielded important findings regarding evacuation times, occupant flow rates, and density metrics. During the baseline simulation, Simulation 1, the total evacuation for the occupants of the entire building was 490.5 s. After applying the BIM-based corridor width optimization in Simulation 2, the total evacuation time was 472.9 s, demonstrating a decrease of 17.6 s. This represents an overall improvement of approximately 3.6% in evacuation efficiency.

To understand the factors contributing to these improvements, the study further analyzed the relationship between speed, density, and occupant distribution on stairwells in each simulation. This analysis provides insight into how pedestrian dynamics differed between the baseline and optimized scenarios, especially in terms of movement efficiency at varying density levels.

4.1.1. Speed–Density Relationship

In comparing the speed–density relationships observed in the initial evacuation simulation (Simulation 1) with those from the subsequent simulation (Simulation 2), several consistent patterns and notable differences emerged, as shown in Figure 5. Both simulations demonstrated the expected inverse relationship between pedestrian speed and corridor density. Specifically, as density increased, there was a corresponding decrease in pedestrian speed—a trend consistent across all selected measurement regions.

At lower densities (below 1.0 pers/m^2), both simulations exhibited considerable variability in pedestrian speed, suggesting that in less congested conditions, factors beyond density—such as individual movement behavior or corridor-specific characteristics—may influence pedestrian velocity. A critical density threshold of approximately 1.0 pers/m^2 was identified in both simulations, beyond which a marked decrease in speed was evident, indicating that higher congestion levels significantly impair evacuation efficiency in both scenarios.

However, differences between the two simulations were also apparent. In Simulation 1, speed values were more tightly clustered at higher densities (above 1.5 pers/m^2), with most pedestrians moving at speeds below 0.5 m/s. Conversely, Simulation 2 exhibited less clustering in these high-density conditions, suggesting that pedestrian movement may have been less constrained during the second simulation. Additionally, certain measurement regions in Simulation 2 (e.g., 4th Floor Segment and 5th Floor Segment) maintained higher speeds at comparable densities relative to Simulation 1, potentially indicating improved

corridor conditions or differences in crowd dynamics. The overall dispersion of data in Simulation 2 was broader, particularly at densities exceeding 1.5 pers/m^2, which may reflect a wider range of movement behaviors or varying conditions between the two simulations.

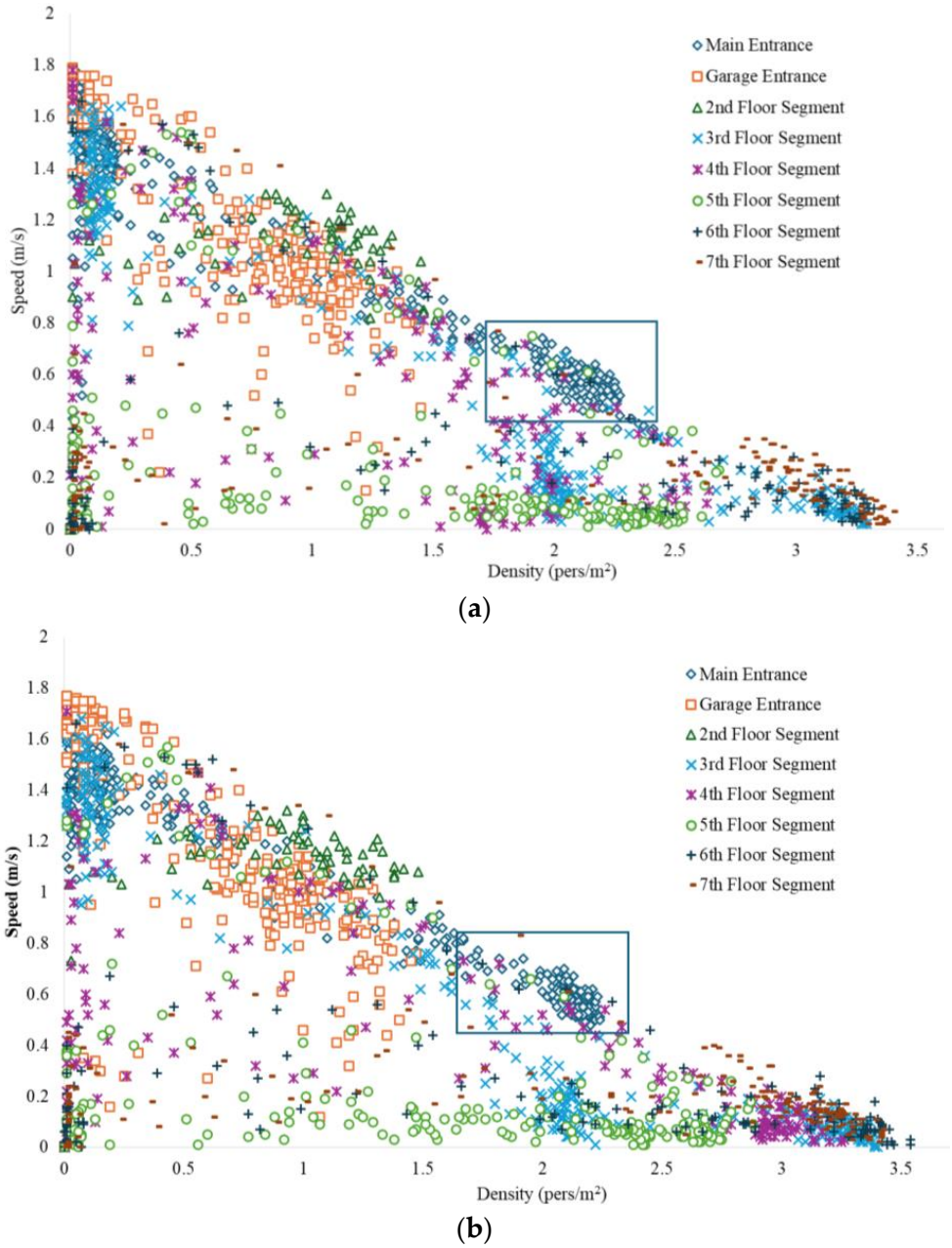
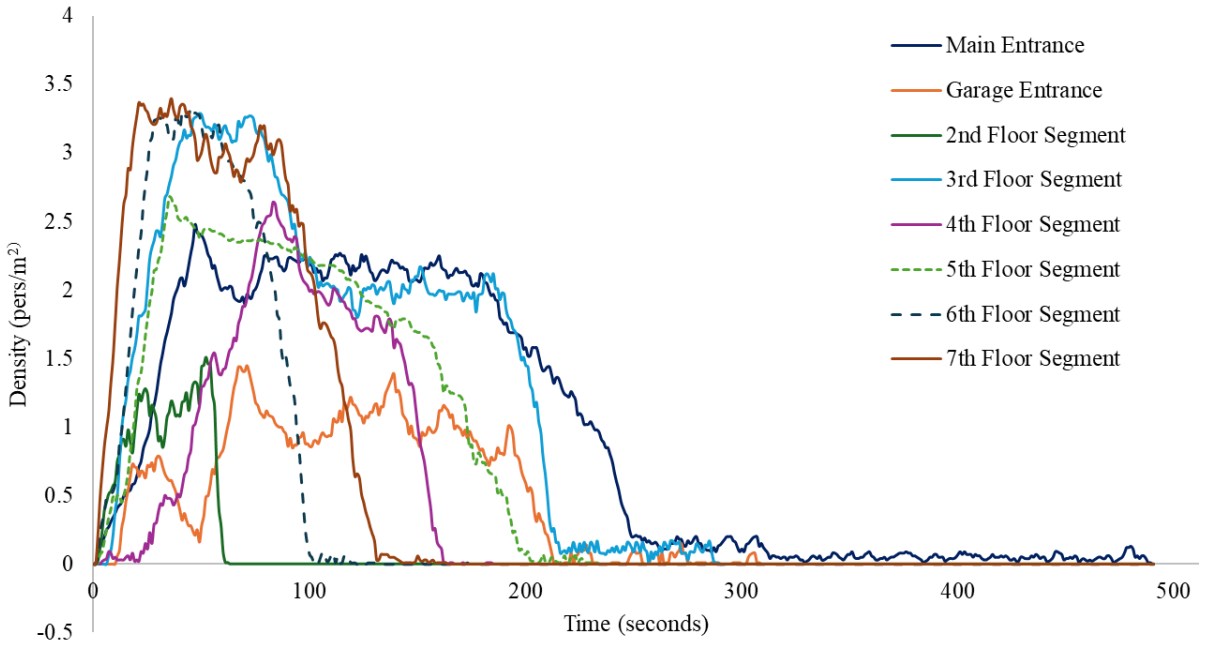


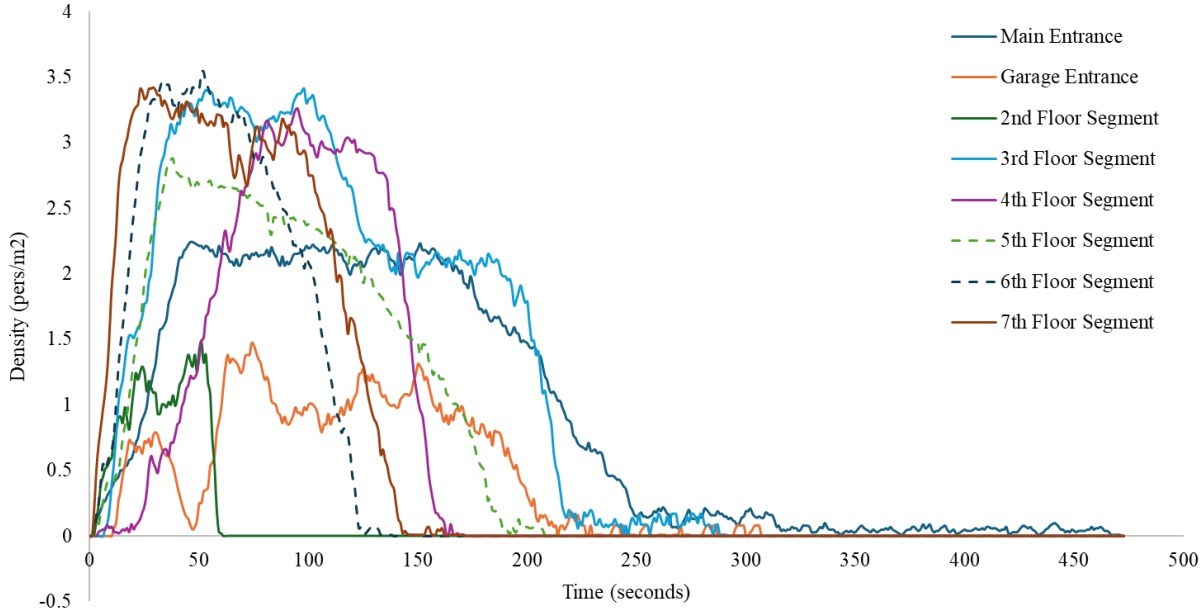
Figure 5. Speed vs. density for the measured regions for (**a**) Simulation 1 (top) and (**b**) Simulation 2 (bottom). The blue square highlights a cluster of data points representing the main entrance at higher densities, where a notable reduction in pedestrian speed is observed.

These findings suggest that while the general trend of decreased speed with increased density was consistent, the second simulation showed evidence of improved movement efficiency under similar conditions. This warrants further investigation to elucidate the factors contributing to these differences, such as potential improvements in corridor design or variations in occupant behavior.

The comparative analysis of the two evacuation simulations in Figure 6 reveals distinct patterns in occupant density over time across various measurement regions. In the first simulation, a rapid surge in density was observed across all regions within the initial 50 to 100 s, with peak densities reaching approximately 3 to 3.5 pers/m^2, particularly at the higher floors like the 6th Floor Segment and 7th Floor Segment. These peaks indicate significant congestion and potential bottlenecks early in the evacuation process. The subsequent decline in density was gradual, with certain areas, notably the 3rd Floor Segment and 7th Floor Segment, maintaining higher densities for an extended period, suggesting delays in these regions.



(**a**)



(**b**)

Figure 6. Density over time in the measured regions for (**a**) Simulation 1 and (**b**) Simulation 2.

In contrast, the second simulation displayed a more varied yet slightly delayed peak density across regions, with a generally more even distribution. Although the main entrance and lower floors still experienced higher densities, the overall evacuation flow appeared more efficiently managed, as evidenced by a more uniform dissipation of crowds across regions. The reduced sustained congestion in areas like 5th Floor Segment further supports the notion of improved flow during the second simulation, possibly due to better exit utilization or enhanced routing strategies.

This comparison indicates that the second simulation yielded a more efficient evacuation process, though certain areas still acted as bottlenecks. The findings underscore the importance of ongoing refinement in evacuation procedures, as iterative adjustments can lead to significant improvements in safety and efficiency. However, targeted interventions may still be necessary to address persistent congestion in critical areas, highlighting the need for continued analysis and optimization. Figure 7 shows a sample corridor width difference between Simulation 1 and Simulation 2.

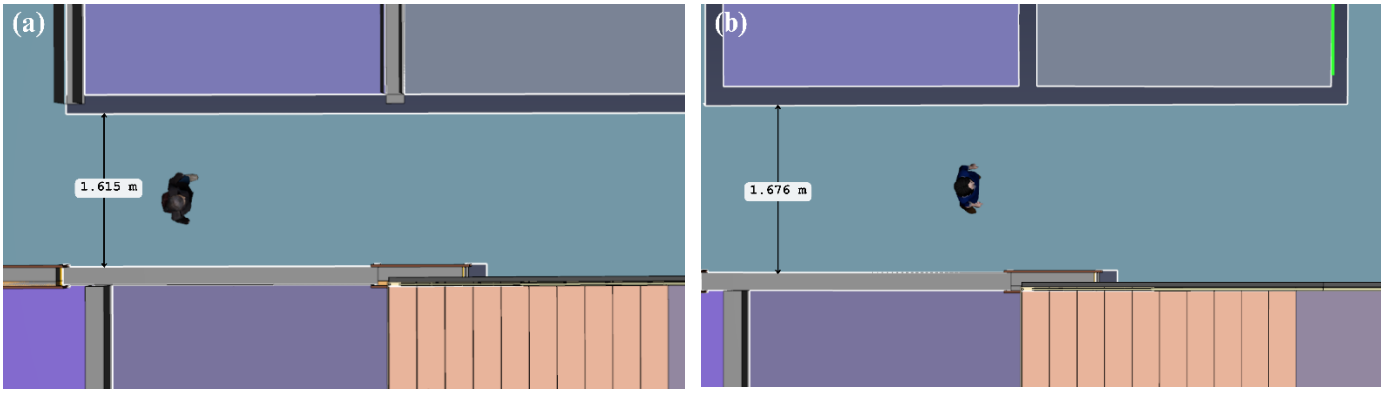


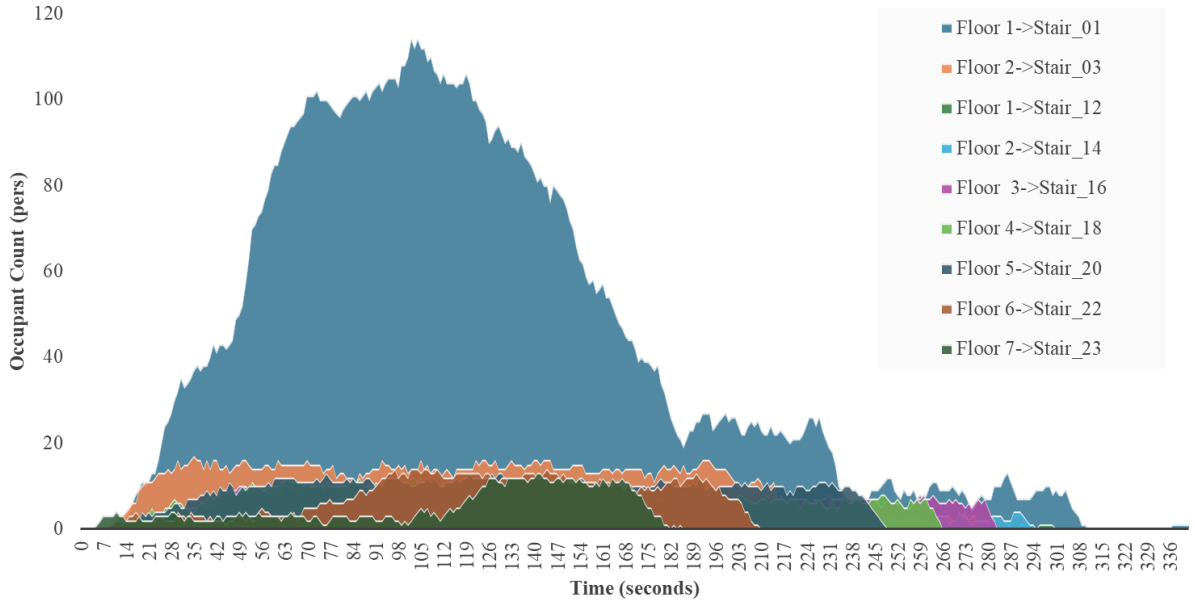
Figure 7. Sample comparison of corridor width on the 2nd Floor. (**a**) Before optimization in Simulation 1, showing a width of 1.615 m, and (**b**) after optimization in Simulation 2, showing an increased width of 1.676 m.

4.1.2. Occupant Distribution on Stairwells

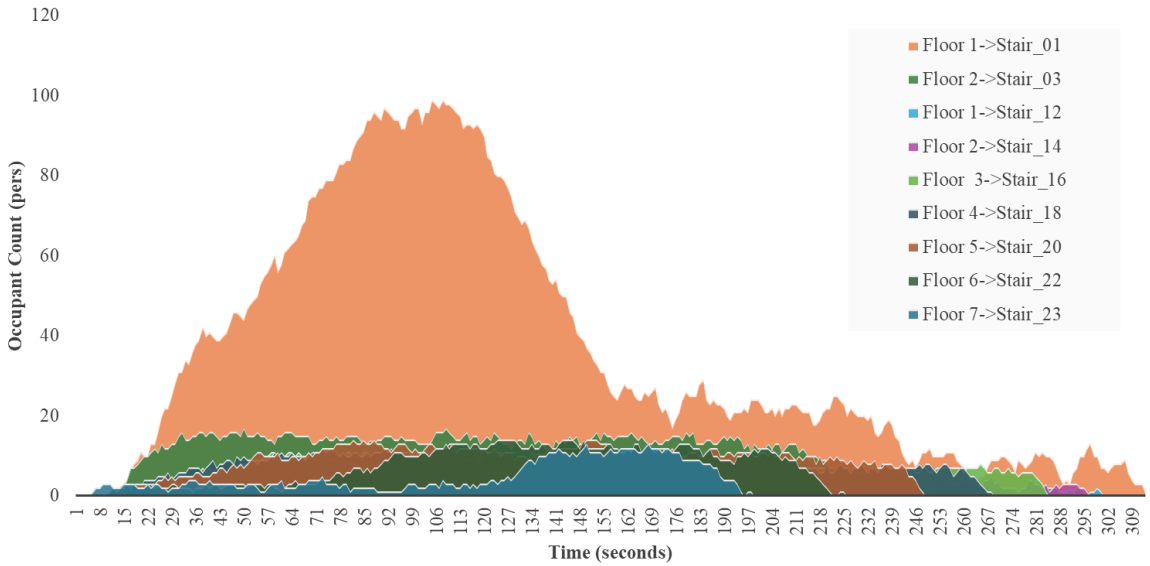
The occupant count on each stairwell for each floor, as seen in the baseline simulation (Figure 8a) and Simulation 2 (Figure 8b), highlights key differences in how occupants moved through the stairwells near the optimized corridors during evacuation. In Simulation 1, stairwell 1 near the main entrance shows a steep initial rise in occupant count within the first 50–100 s, reaching peak densities quickly, where occupant count reaches up to 114. This sharp increase suggests that congestion built up rapidly, potentially slowing movement as occupants converged on stairwell exits.

In Simulation 2 (Figure 8b), however, the peak occupant count on stairwells is lower at 99, indicating a more manageable flow. The smoother curves in Figure 8b indicate a more even distribution of occupants over time. This trend suggests that the adjusted corridor widths in Simulation 2 allowed for a steadier dispersal of occupants onto stairwells, lessening the build-ups seen in Simulation 1 (Figure 8a). Notably, the descent in occupant count on stairwells is more gradual in Simulation 2, reflecting a more controlled evacuation flow that reduced bottlenecks and improved exit rates as shown in the speed–density relationship section.

These findings underscore the effectiveness of the BIM-based corridor optimizations in Simulation 2, which facilitated better flow management on stairwells across floors. By reducing the intensity of congestion on stairwells, particularly on lower floors, the adjustments contributed to a more efficient evacuation process, minimizing delays and potential safety risks associated with high-density stairwell usage.



(**a**)



(**b**)

Figure 8. Occupant density over time across the measured stair regions for (**a**) Simulation 1 and (**b**) Simulation 2.

4.2. Two-Way T-Test

The paired two-way *t*-test was employed to statistically evaluate the impact of corridor width adjustments on occupant density across multiple floors. This test was chosen for its ability to compare mean density differences between two simulations, providing insight into whether the observed changes in density were statistically significant and thus likely due to the design modifications rather than random variation. By using a *p*-value threshold of <0.0001, the study aimed to ensure a high confidence level in the results, supporting the replicability and robustness of the automated corridor adjustments.

The paired two-way *t*-test results provide insight into how the wider corridor segment on the second floor impacted density across different floors. The analysis shows that the second simulation, which included the wider corridor on the second floor, generally resulted in higher mean densities across the 2nd, 3rd, 4th, 6th, and 7th floor segments. Specifically, the mean density difference for the 2nd-floor segment was 0.7913 (95% CI:

0.5895, 0.9973; $p < 0.0001$), indicating a substantial effect size (Cohen's d = 0.8), likely due to the wider corridor influencing flow dynamics. Similarly, significant increases were observed on the 3rd, 4th, 6th, and 7th floors, with mean differences of 0.100443, 0.16772, 0.13276, and 0.07187, respectively, all with p-values <0.0001. In contrast, the 5th-floor segment, where the mean difference of 0.00587 was not statistically significant ($p = 0.8419$), suggests that the corridor widening did not have a measurable impact at that level. These findings, as summarized in Table 2, suggest that the wider corridor on the second floor had a cascading effect on congestion, influencing density on multiple floors above it.

Table 2. Paired differences in corridor density across floor segments between two simulations.

Paired Differences							
Pair	**Mean**	**Std. Error**	**95% Confidence Interval of the Difference**		**t**	**df**	**Sig. (2-Tailed)**
			Lower	**Upper**			
2nd Floor Segment	0.7913	0.10486	0.589527	0.99733	7.546223	491	1
3rd Floor Segment	0.100443	0.01166	0.08152	0.12734	8.957637	491	1
4th Floor Segment	0.16772	0.01526	0.13773	0.19771	10.98888	491	1
5th Floor Segment	0.00587	0.00586	−0.0056	0.01738	1.003146	491	0.8419
6th Floor Segment	0.13276	0.01571	0.10189	0.16364	8.449061	491	1
7th Floor Segment	0.07187	0.00918	0.05384	0.0899	7.833196	491	1

4.3. Wilcoxon Signed-Rank Test for Corridor Density

The Wilcoxon signed-rank test was conducted to compare corridor density measurements across various floor segments between the first and second simulations. The results, as summarized in Table 3, indicate a consistent increase in mean density across all floor segments in the second simulation. For instance, in the 2F Corridor, the mean density rose from 0.1152 in the first simulation to 0.9065 in the second. This trend of increased density is observed across other floors as well.

Table 3. Wilcoxon signed-rank test for corridor density in two simulations.

Area	**N**	**Mean**	**Std. Deviation**	**Minimum**	**Maximum**	**Percentiles**		
						25th	**50th (Median)**	**75th**
2F Corridor	1st Sim	492	0.1152033	0.33699	0	1.51	0	0
	2nd Sim	492	0.9065041	2.6590732	0	12	0	0
3F Corridor	1st Sim	492	0.9269919	1.1542022	0	3.29	0	0.09
	2nd Sim	492	1.0314228	1.2792416	0	3.41	0	0.09
4F Corridor	1st Sim	492	0.4242886	0.7696809	0	2.64	0	0
	2nd Sim	492	0.5921022	1.0818957	0	3.26	0	0
5F Corridor	1st Sim	492	0.6913821	0.9635327	0	2.68	0	0
	2nd Sim	492	0.6972561	1.0195524	0	2.88	0	0
6F Corridor	1st Sim	492	0.4520528	1.0100749	0	3.32	0	0
	2nd Sim	492	0.5848171	1.1430544	0	3.54	0	0
7F Corridor	1st Sim	492	0.6307528	1.1711373	0	3.4	0	0
	2nd Sim	492	0.7089228	1.2289773	0	3.42	0	0

The standard deviation, representing the variability in density, also increased in most floor segments from the first to the second simulation. This suggests not only a higher average density but also greater variation in density across different areas within the corridor segments in the second simulation.

Despite the increase in mean density, the median density for most floor segments remained at 0 in both simulations, except for the 3F Corridor, where the median was 0.09 in both simulations. This indicates that a substantial portion of the corridor segments had low-density values. Additionally, the increase in the 75th percentile values across simulations supports the observation of higher densities in the second simulation.

The maximum density observed also increased across all floor segments, with a particularly notable increase in the 2F Corridor, where the maximum density rose from 1.51 in the first simulation to 12 in the second. This significant increase suggests that certain areas within these corridors experienced markedly higher congestion during the second simulation.

The results from the Wilcoxon signed-rank test likely indicate that these differences in density between the two simulations are statistically significant, implying that the modifications implemented in the second simulation, such as adjustments to corridor width, led to increased congestion. These findings underscore the importance of evaluating pedestrian flow dynamics carefully when making such modifications to manage congestion effectively.

5. Discussion

The primary objective of this study was to identify potential bottlenecks within evacuation routes and optimize them for faster and safer egress using a BIM-based approach. Through detailed simulations and analyses, the study aimed to enhance fire evacuation efficiency in existing building designs by automating the optimization of hallway dimensions and leveraging simulation data to identify and mitigate congestion points. The results of this study provide significant insights into the effectiveness of this approach, with the potential to contribute to the development of safer building designs with improved evacuation efficiency.

The study's BIM-based approach, which integrated Autodesk Revit for modeling and Thunderhead Pathfinder for dynamic simulation, proved effective in optimizing evacuation routes across most of the building's floor segments. The use of Dynamo scripting for automated adjustments to hallway dimensions allowed for rapid, iterative optimizations based on real-time simulation data. This process was crucial in identifying and mitigating congestion points, leading to significant improvements in evacuation efficiency on five of the six floor segments analyzed.

The observed reduction in total evacuation time, decreasing from 490.5 s to 472.9 s, underscores the effectiveness of the BIM-based optimization approach in achieving measurable improvements in evacuation efficiency. Although the improvement represents a modest 3.6% decrease, it demonstrates how even incremental corridor adjustments can yield a meaningful impact on overall egress times, especially in high-occupancy, multi-story buildings. This reduction is particularly important in emergency scenarios where every second contributes to occupant safety and evacuation success. By optimizing congestion points through automated corridor width adjustments, the BIM-based framework provides a scalable solution adaptable across different building types and occupant densities.

In addition to enhancing corridor flow, the BIM-based optimizations contributed to a more controlled distribution of occupants on stairwells, as seen in Simulation 2. The reduction in peak occupant counts on stairwells by 13.16%, from 114 in Simulation 1 to 99 in Simulation 2, reflects a significant improvement in managing congestion at critical points during the evacuation. This improvement suggests that the refined corridor widths facilitated a steadier dispersal onto stairwells, mitigating bottlenecks and supporting a more continuous flow across floors. This finding aligns with the improvements observed in the speed–density relationships, confirming that targeted corridor adjustments can play a key role in alleviating high-density zones and improving overall evacuation efficiency.

The paired *t*-tests and Wilcoxon signed-rank tests revealed significant improvements in crowd density management on the 2nd, 3rd, 4th, 6th, and 7th floors. The high *t*-ratios and confidence intervals that excluded zero in these segments indicate that the observed

changes were likely due to the direct impact of the BIM-based framework rather than random variation.

While the BIM-based approach demonstrated clear success on most floors, the 5th floor presented unique challenges that the framework did not fully overcome. The statistical analysis for the 5th-floor segment yielded a t-ratio of 1.003 with a 95% confidence interval ranging from −0.0056 to 0.01738 and a p-value of 0.3163. These results suggest that the observed differences on this floor were not statistically significant, pointing to potential bottlenecks that the framework failed to optimize.

A likely explanation for this is the specific architectural and occupant distribution characteristics of the 5th floor. Unlike other floors, the 5th floor may have experienced higher congestion due to the confluence of occupants from the less populated 6th and 7th floors, particularly in the measurement region. With fewer occupants on these upper floors, the evacuees likely converged on the 5th floor, exacerbating congestion in areas where the hallway dimensions had not been optimized to handle such a load. Additionally, while the 4th floor had a similar number of occupants, it featured an additional staircase, which likely alleviated congestion that the 5th floor could not mitigate with its fewer exits.

These findings indicate that while the automated optimization process effectively improved evacuation efficiency on other floors, it may need further refinement to address specific challenges, such as those posed by the 5th floor's unique conditions. The flow rate increases linearly with bottleneck width, and the behavior of the occupants in the corridor significantly affects time headways and their distribution [29]. As Shende et al. [30] highlight, optimizing feedback flow rates for pedestrian evacuation can improve performance by converging the system to an optimal congestion state and maintaining consistently high input and exit discharges throughout the network. This suggests that further adjustments to corridor dimensions or pedestrian flow management strategies may be necessary for the 5th floor. Understanding these bottlenecks is critical for enhancing the framework's adaptability and ensuring consistent performance across different building environments.

Another insight from this study is the significant impact of small corridor width adjustments on evacuation flow, as evidenced by the observed improvements with a 6.1 cm increase in corridor width. Although seemingly minor, such adjustments can cumulatively reduce occupant density, alleviate bottlenecks to a degree, and enhance flow efficiency, as shown in Figures 5–7. This occurs in particular in high-density areas where each additional centimeter of width allows more occupants to move freely. This effect is most pronounced in high-traffic zones, where even slight increases facilitate smoother occupant movement, leading to a meaningful decrease in evacuation time.

Studies have consistently shown that wider corridors facilitate smoother movement and reduce the likelihood of congestion. For instance, Tice et al. [31] observed that wider corridors allow for more glance deviation, which can lead to increased attention and faster movement among pedestrians. This also aligns with the observations by Tavana et al. [32] in their experiments on funnel-shaped bottlenecks, where they found that wider exits significantly improved evacuation times in high-density scenarios. Additionally, the psychological comfort associated with wider spaces may also contribute to reduced anxiety and faster decision-making during evacuations, further enhancing flow.

Research by Huo et al. [33] supports this notion, indicating that wider corridors not only improve physical movement but also contribute to a sense of safety and comfort among evacuees. This psychological comfort is crucial in emergency situations, where panic can exacerbate congestion and bottlenecks. Furthermore, Vanumu et al. [34] indicate that specific flow rates do not depend solely on facility width but rather on the overall design and configuration of the space. Omar et al. [35] further emphasize that even minor enhancements in fire safety measures can lead to better outcomes during evacuations, reinforcing the idea that small changes can yield significant benefits in fire safety management. This is particularly relevant in high-density environments where the risk of congestion and delayed evacuations is heightened.

These findings emphasize that small design modifications can yield substantial performance improvements in densely populated evacuation scenarios, underscoring the need for precise corridor width adjustments in critical areas.

Implications for Building Design and Safety and Limitations

The results of this study have significant implications for the field of building design and safety, particularly in the context of fire evacuation planning. The BIM-based approach demonstrated in this study offers a robust and scalable method for automating and optimizing static architectural factors—specifically, segments of a building corridor width—that impact evacuation efficiency. By focusing on the spatial configuration of evacuation routes, the framework provides a practical tool for reducing congestion and improving flow in emergency scenarios.

The framework's utilization of data-driven adjustments to corridor dimensions offers building designers and safety planners a practical tool for improving egress efficiency, allowing modifications to be tested virtually before physical implementation. This capability supports more effective evacuation planning in complex, multi-story buildings, where congestion and flow rates vary significantly by floor. The approach can also be applied in diverse building types, from educational institutions to commercial spaces, by adapting corridor dimensions to occupancy levels and layout configurations.

While the study effectively addresses architectural factors, it does not incorporate fire dynamics, which involves real-time modeling of fire behavior and the spread of smoke, heat, and toxic gases. These dynamic factors can critically influence evacuation by impairing visibility, increasing temperature, and reducing air quality, all of which directly impact occupant safety. The decision to exclude fire dynamics was made to focus on structural adjustments that optimize congestion and flow within evacuation routes. However, future research could integrate fire dynamics—such as smoke layer descent, toxic gas spread, and heat build-up—to provide a more comprehensive understanding of fire safety, especially in multi-story buildings where fire behavior may vary by floor.

While the primary objective of this study was to enhance evacuation dynamics and safety outcomes through corridor width optimization, certain factors that can impact evacuation conditions were not considered in detail. For example, while the floor height in the model was set at 4.0 m—consistent with standard design criteria—the study acknowledges that floor height can influence smoke layer descent time, which in turn can affect occupant safety. Additionally, factors such as people's reaction times during a fire, their choice of escape routes, and their interactions with others were beyond the scope of this research. While these behavioral elements can significantly affect evacuation efficiency, the study focused on structural adjustments to improve flow within evacuation routes. Future research could incorporate these factors to enable a more comprehensive understanding of fire safety and evacuation dynamics in multi-story buildings.

Additionally, while the study prioritized safety improvements, it did not conduct a detailed economic feasibility analysis. Cost assessments were beyond the study's scope, which emphasized enhancing safety performance as a critical first step. Future research could integrate cost analysis to balance performance gains with budgetary considerations, enabling a comprehensive framework that considers both safety and economic feasibility.

Finally, the variability in the framework's effectiveness, particularly on the 5th-floor segment, highlights the importance of context-specific evaluations. Building designers and safety planners must consider the unique characteristics of each floor, including occupant distribution, architectural features, and existing egress options, when applying this framework. As the flow rate increases linearly with bottleneck width and is significantly influenced by pedestrian behavior [29], these factors must be carefully considered in optimizing evacuation strategies. Tailoring the optimization process to these variables is essential for achieving the desired improvements in evacuation efficiency.

6. Conclusions

This study demonstrated the potential of a BIM-based approach to optimize fire evacuation efficiency in existing building designs. By automating the adjustment of hallway dimensions and leveraging simulation data to identify and mitigate congestion points, the framework significantly improved evacuation efficiency on most floors. These results highlight the practical benefits of integrating advanced simulation tools like Autodesk Revit and Thunderhead Pathfinder into the design process, offering a scalable solution for enhancing building safety.

The key findings are:

- Improved Evacuation Routes: The automated framework led to significant improvements in evacuation routes on most floors, highlighting its effectiveness in reducing congestion.
- Scalability and Practicality: The integration of BIM and simulation tools provides a scalable and practical approach to enhancing fire safety in building designs.

However, the study revealed limitations, particularly on the 5th floor, where the framework did not achieve statistically significant improvements. This suggests that the framework's effectiveness may vary depending on specific architectural features, such as stair configurations and occupant distribution patterns. These findings underscore the importance of context-specific adaptations and highlight the need for further refinement of the framework.

Future research should focus on addressing these limitations by exploring how the framework can be tailored to different building layouts and occupant behaviors. Additionally, the integration of adaptive simulation techniques, potentially enhanced by machine learning, could further improve the framework's robustness and applicability. Testing the framework in real-world scenarios is crucial to validate its effectiveness and ensure its practical utility in diverse architectural contexts.

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