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# Performance-Based Evacuation Optimization for Teaching Building with Heterogeneous Populations: Simulation and Numerical Studies

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**Abstract:** Building evacuation safety has been one of the focal points of researchers, and there is a wealth of research findings for certain places (e.g., buildings with a high population density) or for particular research subjects (e.g., the physically challenged ethnic group). However, current publications are relatively rare in analyzing the features of physically impaired individuals in crowded places and their impact on the effectiveness of the whole evacuation process, including non-disabled people. Additionally, only such studies tend to concentrate on the behavioral characteristics of disabled people, which lack exploring and comparing evacuation optimization strategies and evaluation of comprehensive evacuation performance. This paper proposed a computer simulation-based method that combined horizontally phased evacuation and vertically phased evacuation, supplemented with the use of handicapped ramps and a reasonable arrangement of class locations, to achieve the optimal evacuation performance of a teaching building with special consideration of the heterogeneous population. And then, a simulated building model was constructed to test and compare the effectiveness and applicability of these approaches through 33 evacuation scenario studies. The results found that (1) component design can improve evacuation effectiveness, with the arrangement of ramps and the location of stair doors successfully reducing evacuation time by 12% and 6.6%, respectively; (2) a combination of two ramps and separate handicap access can decrease evacuation time by 18%; (3) the horizontal-phased evacuation approach drops evacuation time by 7.1%, but the vertical-phased evacuation strategy is not very efficient. When the two are successfully combined, evacuation time is further reduced to 9.2%; and (4) based on the above measures, the evacuation time can be finally shortened by 19% if the veteran teachers are concentrated in the classrooms on the lower floors. These obtained conclusions will provide significant reference and methodological support for the safe evacuation of other similar buildings with heterogeneous populations.

**Keywords:** evacuation optimization; heterogeneous populations; performance-based



**Citation:** Yang, L.; Zhou, B.; Wu, T. Performance-Based Evacuation Optimization for Teaching Building with Heterogeneous Populations: Simulation and Numerical Studies. *Fire* **2023**, *6*, 273. https://doi.org/10.3390/fire6070273

Academic Editor: Lizhong Yang

Received: 1 June 2023
Revised: 4 July 2023
Accepted: 6 July 2023
Published: 13 July 2023



## 1. Introduction

### 1.1. Background

Fire is a disaster caused by uncontrolled combustion in time or space. Fire not only destroys material property, causing disruption of social order and ecological balance, but directly or indirectly endangers human lives. Over the past 20 years, the average National Fire Death Rate in the United States has reached 12.1 per million population per year [1]. In China, a total of 825,000 fires were reported in 2022, with 2053 deaths, 2122 injuries, and direct property damage of RMB 7.16 billion [2].

On university campuses, teaching buildings are collective living spaces where students study and where they spend most of their time (4.5 h on average) [3]. In addition, university teaching buildings are characterized by a relatively high density of people indoors, usually consisting of 50–180 students sharing classes in one room in China. In addition to able-bodied and young people, there are some physically handicapped and elderly people in the teaching building. According to the survey [4,5], 0.145% of students are disabled, and 0.446% of college students have sports injuries that affect their normal walking ability for a period of time. Moreover, with the aging of society, older teachers and researchers have become a non-negligible category of the population using teaching buildings. However, it is observed that many teaching buildings do not provide appropriate supporting facilities for these vulnerable people to help them evacuate smoothly in times of emergency because of their relatively old construction age.

Researchers have long been concerned with the safety evacuation performance of teaching buildings [3,6,7]. Despite a sizable amount of research, the diversity of various evacuation populations has received scant consideration. Even when studies have been conducted, they have mainly concentrated on the behavioral characteristics of those who have physical limitations. Few studies have concentrated on how persons with physical disabilities interfere with people without disabilities as they evacuate crowded places like buildings in universities and how this impacts the evacuation's overall effectiveness. There are not many studies examining and contrasting high-risk population evacuation optimization strategies in teaching buildings either.

In this study, we thoroughly took into account the physiological traits of heterogeneous populations in university teaching buildings and how they interacted during the evacuation process, notably how physically challenged persons interfered with normal people. Based on this, an integrated evacuation optimization strategy was developed, which combined vertical-phased evacuation, horizontal-phased evacuation, improvements to the architectural design (such as the addition of accessible ramps), and class location settings for older faculty members to ultimately achieve the highest level of evacuation efficiency through numerical simulation.

### *1.2. Literature Review*

The most important issue in the field of building safety evacuation research is the source of the values, and there are two main types of simulation methods: real-world emergency escape tests [8,9] and computer-based evacuation simulations [10,11]. Since evacuation drill is more reliable and the results are more realistic, some scholars have used this approach in studying the evacuation of teaching buildings [12]. The principal limitation of the experimented method is that escapees' behaviors are quite complex and may be different even in the same scenario [13]. Moreover, it may cause additional losses, even personal injury. This is why computer simulations have received increasing attention in recent years. In a simulation approach, the evacuation process and the physical behavior of pedestrians are mathematically modeled [14], and occupants with different physical parameters can be simulated by the models. At any time during the simulation, the pedestrian flow and the movement data of every simulated occupant can be collected for analysis, and so, constraints of time and space are lifted.

Due to their own characteristics, campus buildings have been one of the main subjects of research into the safe evacuation of buildings, such as dormitories [15], libraries [16], teaching buildings [6], and so on. The research perspectives of present studies include mainly evacuation behavior [17], standard procedure for safety evacuation [18], egress choice [19], and campus evacuation plan [20]. In addition, a staircase is an important emergency evacuation component and has been the focus of research in this area, containing pedestrian merging behavior [21,22], the impact of stair design on evacuation times, including stair tread depth [23], riser height, stair slope [24], etc.

On the basis of these findings, several studies have also considered the evacuation of heterogeneous populations [25,26]. For the normal population, the main concern is the differences due to age, gender, movement speed, physical size, etc. A broader perspective has been adopted by M. Manley (2011) [27], who applied an agent-based simulation method incorporating heterogeneous populations. In the same vein, [28] Yameng Chen (2020) studied the impact of the distribution of the elderly with different physical conditions in evacuation, and Jeongin Koo represents new evacuation strategies for a heterogeneous population in high-rise building environments [29].

A summary of the references above is shown in Table 1 below.

**Table 1.** A summary of the references above.

| Author | Scenarios | Research Objects | Research Methods |
| --- | --- | --- | --- |
| [9] R.D. Peacock et al., 2012 | High-rise building | Fire evacuation | Drill |
| [13] Max Kinateder et al., 2020 | - | | |
| [18] Suwen Jiang et al., 2021 | Dormitory | | |
| [15] JIANG Zhong-an et al., 2011 | Dormitory | | Simulation |
| [17] SHANG Rong-xue et al., 2013 | Campus | Human behavior | Simulation |
| [10] Peizhong Yang et al., 2013 | Subway station | Emergency evacuation | Simulation |
| [16] Mufeng Xiao et al., 2021 | Library | | |
| [19] Wenjun Lei et al., 2012 | Dormitory | | |
| [20] Shan Gao et al., 2023 | Campus | | |
| [28] Yameng Chen et al., 2020 | High-rise nursing home | Evacuation strategies (Vertically phased evacuation) | Simulation |
| [14] V. K. R. Kodur et al., 2020 | High-rise building | Evacuation strategies | Simulation |
| [25] Adriana Braun et al., 2005 | - | Heterogeneous population | Simulation |
| [26] Xiaoshan Pan et al., 2007 | - | | |
| [27] M. Manley et al., 2011 | Airport | | |
| [29] Jeongin Koo et al., 2013 | High-rise building | | |

### *1.3. Aim of This Work*

The evacuation performance of a building is influenced by the characteristics of its components and the emergency response strategy. These factors can be optimized to achieve efficient evacuation. However, evacuating people with physical limitations can be challenging for both the individuals and the other normal building occupants. Previous studies have focused on the specific behavioral patterns of single populations rather than the overall evacuation performance resulting from the interplay between heterogeneous populations. Additionally, previous research has only evaluated the effectiveness of a certain evacuation phase or a single evacuation optimization measure. Therefore, building performance optimization cannot be thoroughly analyzed because different aspects of design and management strategies are not integrated into the optimization process. To address this issue, we investigated the composition of the population using a particular university teaching building and analyzed the characteristics of all building components that influence evacuation performance. Based on this analysis, we recommend a more comprehensive and eclectic approach to optimization.

The following are the precise goals of this work: (1) We anticipate doing a thorough investigation of the factors influencing the teaching building's evacuation performance based on the projected user population composition and individual building components. (2) It is aimed to find the best optimal solution for the teaching building to increase evacuation performance through a thorough analysis and combination of design and management solutions. (3) Compared to the baseline, the maximum possible improvement of evacuation performance is expected to be obtained. (4) In addition, the methodology suggested in this work is to be adaptable to other similar buildings. The remainder of this paper is arranged as follows. In the Section 2, the overall framework of optimized strategy based on pathfinder simulation is introduced in detail. In the Section 3, a teaching building is chosen as a case study for analysis, and the results are discussed. The last section summarizes this work.

## 2. Methodology

### *2.1. Study Building Specification*

According to Figure 1, the research object of this paper is a 6-story teaching building located in a university in Wuhan, China. A schematic drawing of the teaching building is shown in Figure 2. Its dimensions are 192 m long, 18 m broad, and 22.8 m high. There are 18 classrooms on each floor between the second and sixth floors, and there are 9 classes on the ground floor. There are 99 classes in total, each holding 72 pupils, for a total of 7,128 students and 99 teachers. There are 7227 evacuees when the entire building is occupied. The structure is 23 m tall. There are 6 exits, 4 staircases, and 4 elevators in the building. The first through fourth staircases in Figure 2 are, respectively, 3.9, 2.8, 2.1, and 3.4 m wide.

Several studies have explored methods to optimize the evacuation design of high-rise buildings. These include the use of elevators as an evacuation tool [30] and models to evaluate the optimal evacuation strategy for high-rise buildings [31]. However, some countries, such as China and the United Kingdom, have laws that require ordinary elevators to be shut down and out of service in the event of a fire. Elevator shafts can create a chimney effect, and evacuees may become trapped in the elevator car in case of electromechanical failure or power failure. Therefore, our study does not consider elevators as a means of personnel evacuation [32].

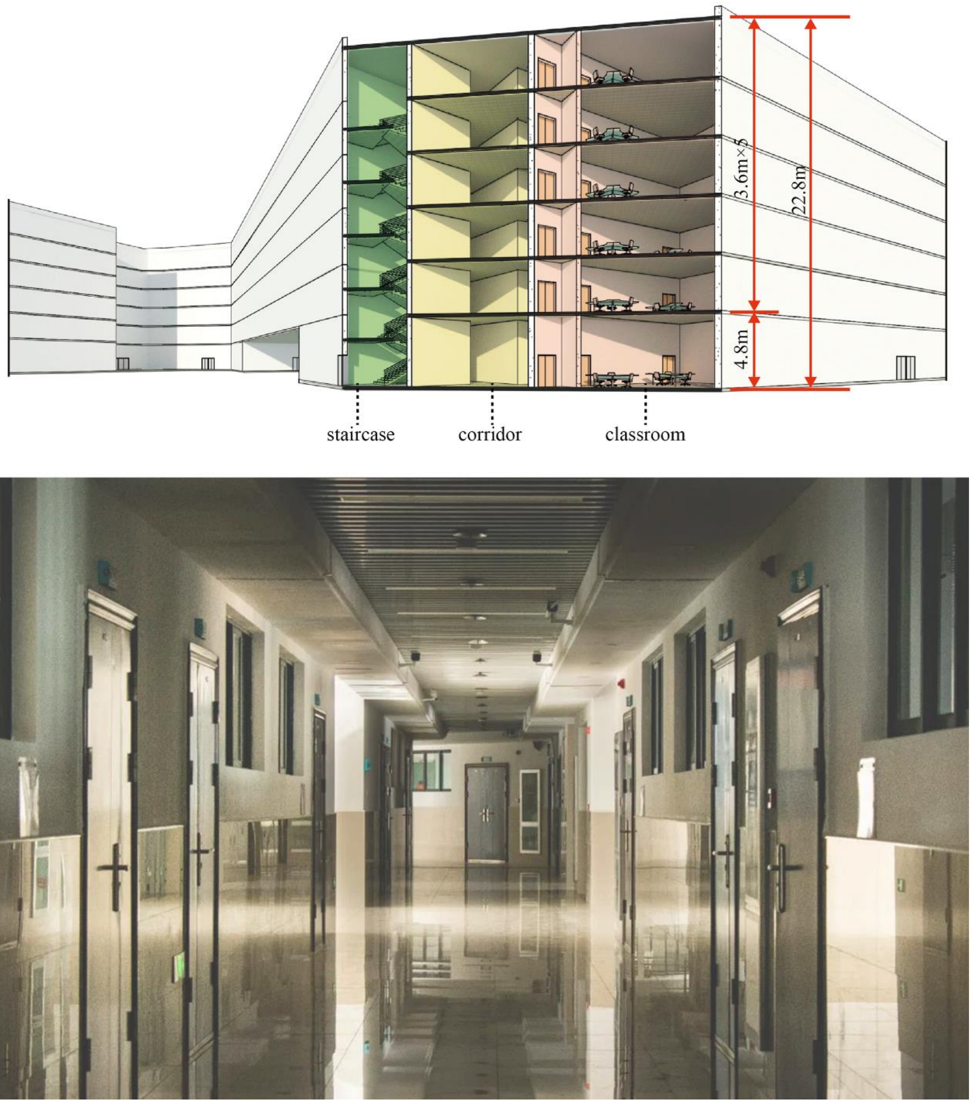



**Figure 1.** Building overview drawing.

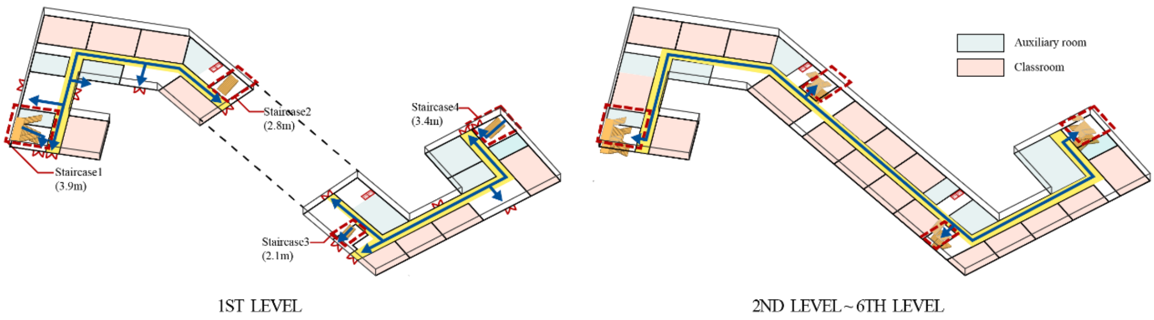



**Figure 2.** The floor layout of the teaching building.

*2.2. Indicators for Evaluations of Egress*

Figure 3 illustrates the different stages of fire development. The initial stage is characterized by a small burning area, low temperature, and a moderate rate of development. During the development stage, the flames gradually become larger, the temperature rises, and the fire begins to spread rapidly. The violent stage is marked by the peak of the burning area and temperature, rapid spreading, and accompanied by roaring, explosions, etc. After the fire is successfully controlled, the temperature gradually decreases until it is extinguished in the extinguishing stage. The way a fire burns and its effect on the ability to safely evacuate a building varies depending on the stage it is in. Therefore, evacuation plans should be developed based on the different fire stages to improve the building's emergency response capability.

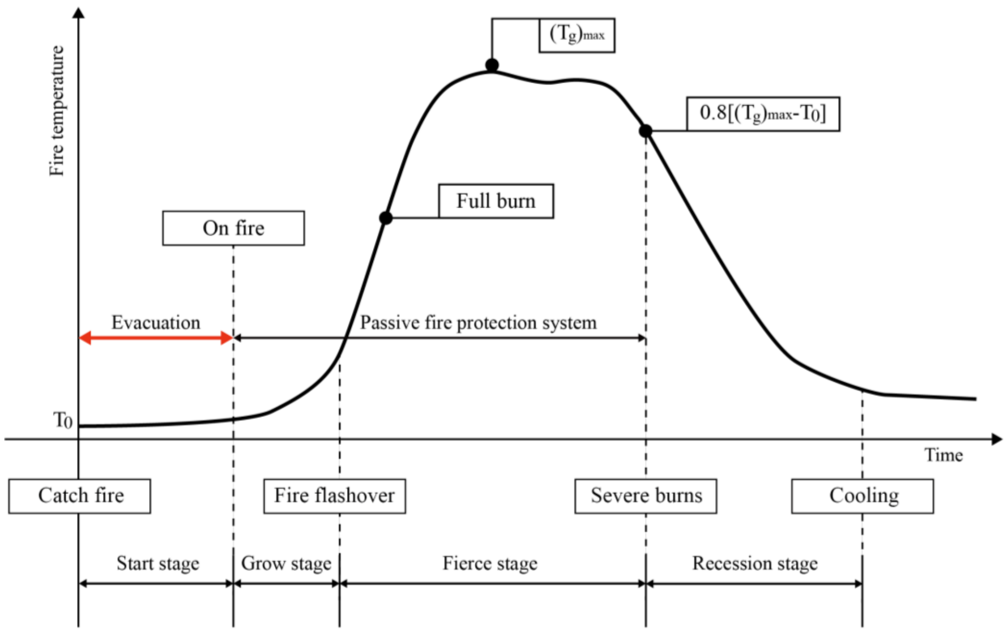



**Figure 3.** Fire development stage.

In addition to the fire resistance of a building, the fire safety performance of a building includes the ability to evacuate in the event of a fire. Protecting human life in the event of a fire is paramount, which requires that all evacuees reach safety before they are affected by the fire. Figure 4 shows two indicators: required safe evacuation time (RSET) and available safe evacuation time (ASET), which are often used to assess the safe evacuation capacity of a building. ASET > RSET is considered safe [33].

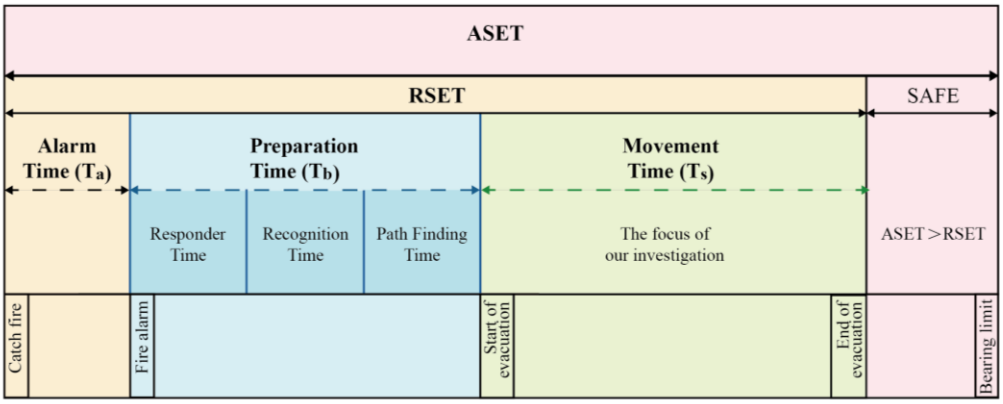



**Figure 4.** Save evacuation.

ASET is the time between the start of a fire and the development of lethal environmental conditions that people cannot tolerate; it is usually fixed [34,35]. The tolerance limit of a person is reached when the person in the room is completely incapacitated due to smoke, heat, or toxic products. The RSET can be calculated using empirical formulas and evacuation software and is the time taken from the start of the fire until each person is evacuated to safety. As shown in Figure 4, Ta is the time it takes for the fire alarm to sound; Tb is the time before action (including reaction time, recognition time, and pathfinding time), the period during which individuals estimate the likelihood of a fire and begin evacuation procedures; and Ts is the time it takes to bring everyone to a safe area. This study focuses on Ts.

As mentioned earlier, although both stairs and elevators are common means of transportation, some countries, including China, do not allow the use of elevators to escape in case of fire [36]. Therefore, this paper only considers the use of stairs or other building elements, such as ramps, for evacuation.

### *2.3. Parameters Setting*

Pathfinder is a human motion-based simulator [37] developed by Thunderhead Engineering, Inc. in the United States that is widely used for fire evacuation simulations. The software uses a three-dimensional geometric spatial model that can be divided into a two-dimensional planar navigation grid consisting of adjacent contiguous irregular triangles [38]. As shown in Figure 5, obstacles are accurately represented as gaps in this navigation grid; pedestrians move through this navigation grid space. A research paper [39] has shown that the Pathfinder model is consistent with experimental observations.

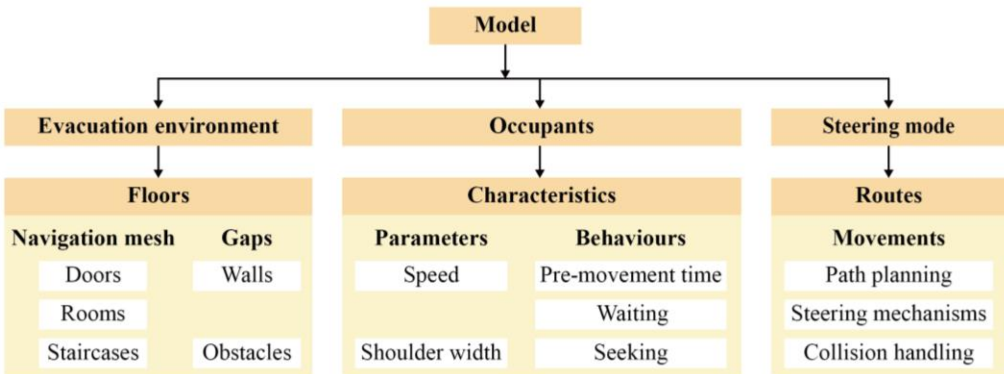



**Figure 5.** Abstract basis of the model construction.

In this study, Pathfinder was used to simulate the timing of individual evacuations. Figure 6 shows a screenshot of the model created in Pathfinder, which simulates crowd evacuation paths and times based on the evacuation environment and personal behavior.

To regulate how people move, Pathfinder's steering model incorporates path planning, guidance systems, and collision handling. If the interval between an individual's path and the nearest point is greater than a predetermined threshold, a new path can be generated to adapt to the new evacuation environment. The steering model is used in this study because it is closer to the emergency evacuation behavior of a crowd. The algorithm of the steering model is given by the following equation [40].

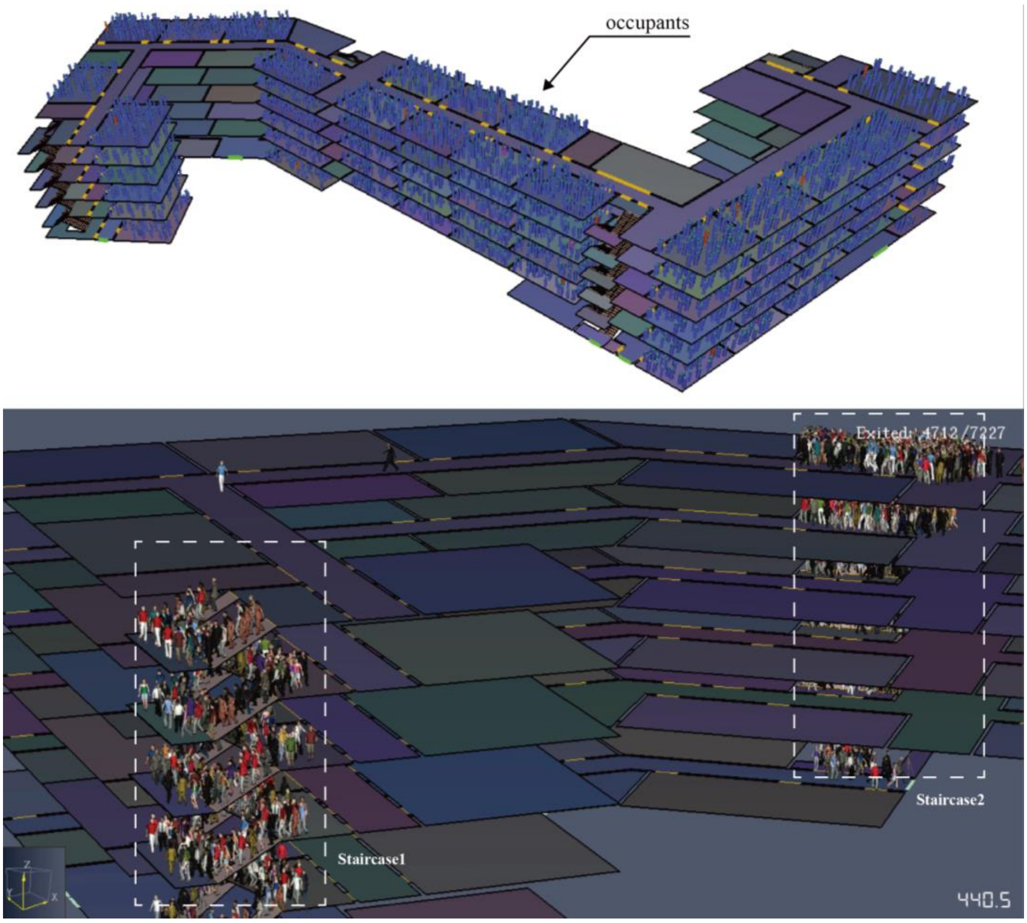



**Figure 6.** Side view of the 6-story teaching building.

(1) Expected acceleration and velocity in the initial condition

Where $v_1$ stands for the anticipated velocity of the initial location, $v_{max}$ for the multi-agent body's highest speed, and $k$ for the surroundings-dependent evacuation impact factor. The maximal acceleration is $a_{max}$, and the acceleration time is $t_a$.

$$v_1 = v_{max} \times \frac{0.85k}{1.19} \tag{1}$$

$$a_{max} = \frac{v_{max}}{t_a} \tag{2}$$

(2) Evacuation direction

Where $C$ stands for direction weight and $\theta$ for the angle that separates the seek curve and the best evacuation curve's velocity direction.

$$C = \frac{\theta}{2\pi} \tag{3}$$

(3) The preferred rate of acceleration and velocity in the evacuation state

$$\left|\vec{v_1}\right| = \begin{cases} 0(d_{max} \leq d_s) \\ v_1(d_{max} > d_s) \end{cases} \quad (4)$$

$$\vec{v_2} = \left|\vec{v_1}\right| \times \vec{d_1} \quad (5)$$

$$\left|\vec{a_1}\right| = \frac{\vec{v_2} - \vec{v_1}}{\left|\vec{v_2} - \vec{v_1}\right|} a_{max} \quad (6)$$

where $\vec{v_1}$ represents the vector velocity of the current direction of motion, $d_{max}$ represents the maximum walking distance in that direction, $d_s$ represents the shortest acceleration distance in that direction, $\vec{v_2}$ represents the vector velocity of the direction of movement with the least weight, $\vec{d_1}$ represents the vector direction in that direction, and $\vec{a_1}$ represents the vector acceleration in that direction.

(4) After the motion position, the vector equation of velocity and position.

$$\vec{v_3} = \vec{v_2} + \vec{a_1}\Delta t \quad (7)$$

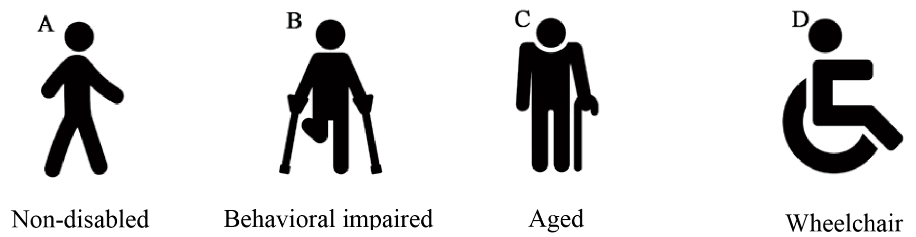
$$\vec{q_2} = \vec{q_1} + \vec{v_2}\Delta t \quad (8)$$

where $\vec{q_1}$ and $\vec{q_2}$ represent the arrival point and current location, respectively, and $\Delta t$ is the interval time, $\vec{v_3}$ represents the vector velocity after the motion.

Based on the experimental survey [41,42] and the proportions of older teachers, students with disabilities, and inadvertently injured students mentioned in the previous section, the staffing structure shown in Table 2 was used in this study.

**Table 2.** Population characteristics.

| Agent Type | Population Composition | Occupation Width (m) | Speed (m/s) | |
|---|---|---|---|---|
| | | | Default | Stair |
| Non-disabled | 99.23% | 0.4 | 1.19 | 0.47 |
| Disabled | | | | |
| Behavioral impaired | 0.44% | 0.4 | 0.70 | 0.28 |
| Aged | 0.19% | 0.4 | 0.70 | 0.28 |
| Wheelchair | 0.14% | 0.98 | 0.70 | 0.28 |



### 2.4. Dentification of Scenario Clusters

Table 3 shows several different evacuation strategies, including normal evacuation, phased evacuation (vertical and horizontal-phased evacuation, a combination of both), ramped evacuation, placement options for aging teachers, and composites between these strategies.

**Table 3.** Segmentation and details related to studied scenarios.

| Description | Details of Scenarios | Abbreviation | Scenario Types | Strategy |
|---|---|---|---|---|
| All evacuees were evacuated at once, with aged teachers being dispersed at random. | No improvement | NE | Normal Evacuation | Without Strategy |
| | Open the antechamber's stairway door | CD1 | Component Design | Architectural Strategy (for stairwells) |
| | Extending the stair railings | CD1 | Component Design | Architectural Strategy (for stairwells) |
| All evacuees were evacuated in a vertically phased evacuation, with aged teachers being dispersed at random. | The chosen three levels are evacuated first, followed after a predetermined amount of time by the other floors. | VPE | Phased Evacuation | Management Strategy |
| All evacuees were evacuated in a horizontally phased evacuation, with aged teachers being dispersed at random. | All classes should have designated evacuation stairs, and everyone should be evacuated simultaneously. | HPEA | Phased Evacuation | Management Strategy |
| All evacuees used a combination of vertically and horizontally phased evacuation, with aged teachers being dispersed at random. | Divide the classrooms into two groups using the same stairwell; evacuate the first group first, delaying the evacuation of the second group for a predetermined amount of time. | HPEB | Phased Evacuation | Management Strategy |
| According to the HPEB approach, a ramp is installed to facilitate evacuation of individuals, with aged teachers being dispersed at random. | Install 1 ramp | R1 | Ramp Installation and Phased Evacuation | Architectural and Management Strategy |
| | Install 1 ramp and a separate corridor. | R2 | | |
| | Install 2 ramps | R3 | | |
| | Install 2 ramps and a separate corridor. | R4 | | |
| According to the R4 approach, place aged teachers on a certain floor. | Aged teachers are placed at the lowest level. | ER1 | Emplacement, Ramp Installation, and Phased Evacuation | Architectural and Management Strategy |
| | Aged teachers are placed at the highest level. | ER2 | | |

#### 2.4.1. Normal Evacuation

Figure 7a illustrates a typical evacuation scenario called NE. The number of mobility-impaired people in each classroom is randomly distributed, and there are 72 students and one teacher in each classroom.

In the event of a fire, each person is evacuated at once. The location of the stairway door in the CD1 scenario is different from that in the original model, as shown in Figure 7b. The stairwell evacuation door in the current state opens directly towards the corridor, while in the CD1 scenario, it opens towards the side aisle. The location of the evacuation doors for stairwells 1 and 4 of the building remains unchanged, as they are located at opposite ends of the building, and possible congestion near the stair doors would not hinder evacuees. Stairwells 2 and 3 are both adjacent to an overpass, so we tried to adjust their evacuation doors to open into the overpass rather than the corridor.

In the CD2 scenario, the length of the railing of the resting platform was increased by 30 cm to see if this improvement would improve the evacuation efficiency of the stairs.

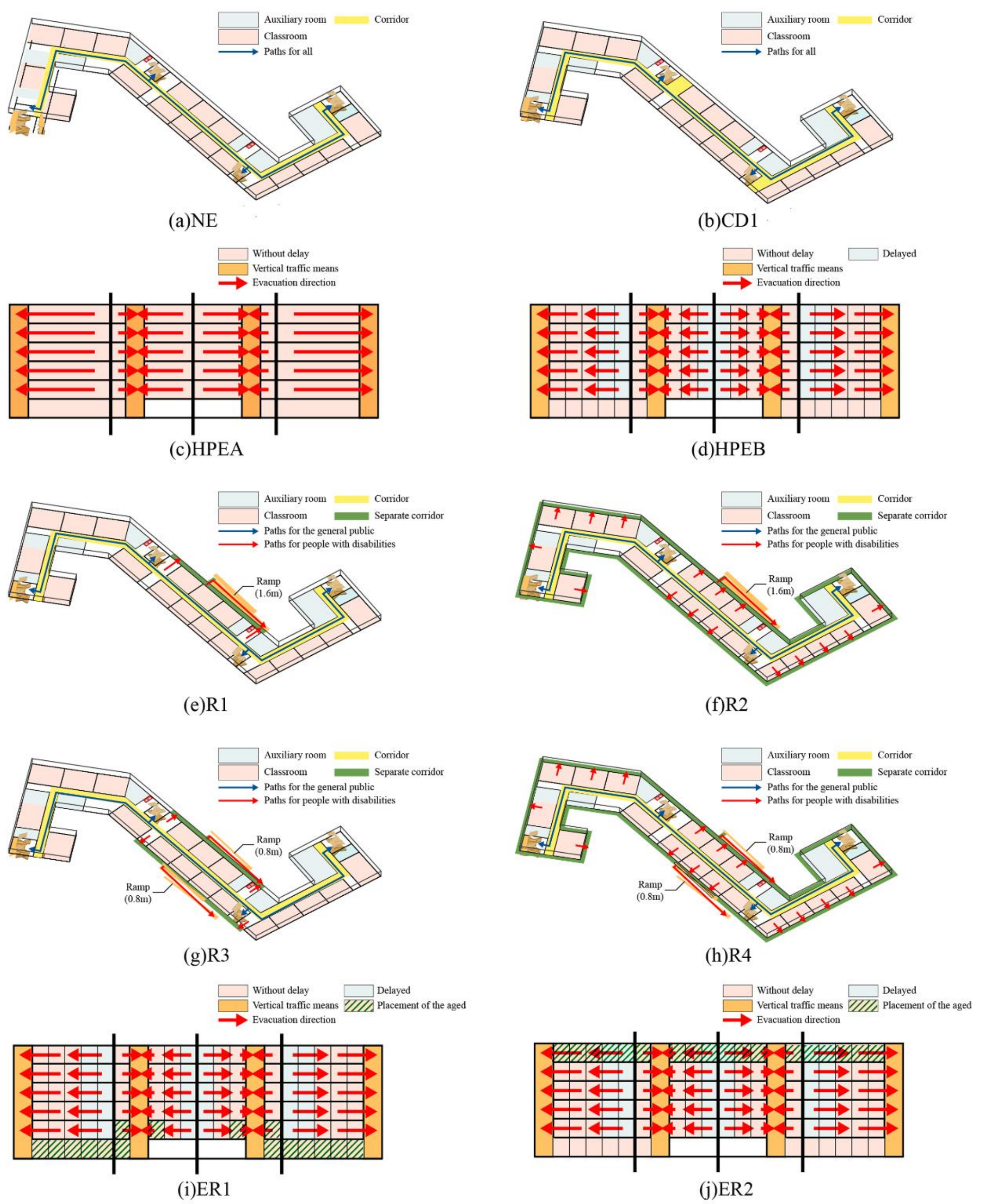



**Figure 7.** Scene diagrams.

#### 2.4.2. Vertically Phased Evacuation

The VPE scenario is a vertically phased evacuation scenario in which we attempt a two-phase evacuation of the academic building. First, we evacuated three of the floors, and after a delay of 50–300 s, we conducted a second evacuation to clear the remaining three floors. We assigned numbers to the floors, starting with 1 for the ground floor, 2 for the second floor, and so on, to compare the advantages and disadvantages of each scenario. For example, scenario name 123 describes the first evacuation from the first, second, and third floors. According to Figure 8, the VPE scenario contains 20 cases (123, 124, 125, 126, 134, 135, 136, 145, 146, 156, 234, 235, 236, 245, 246, 256, 345, 346, 356, and 456). Evacuation time is positively correlated with delay time. We will calculate the fastest evacuation time for each case.

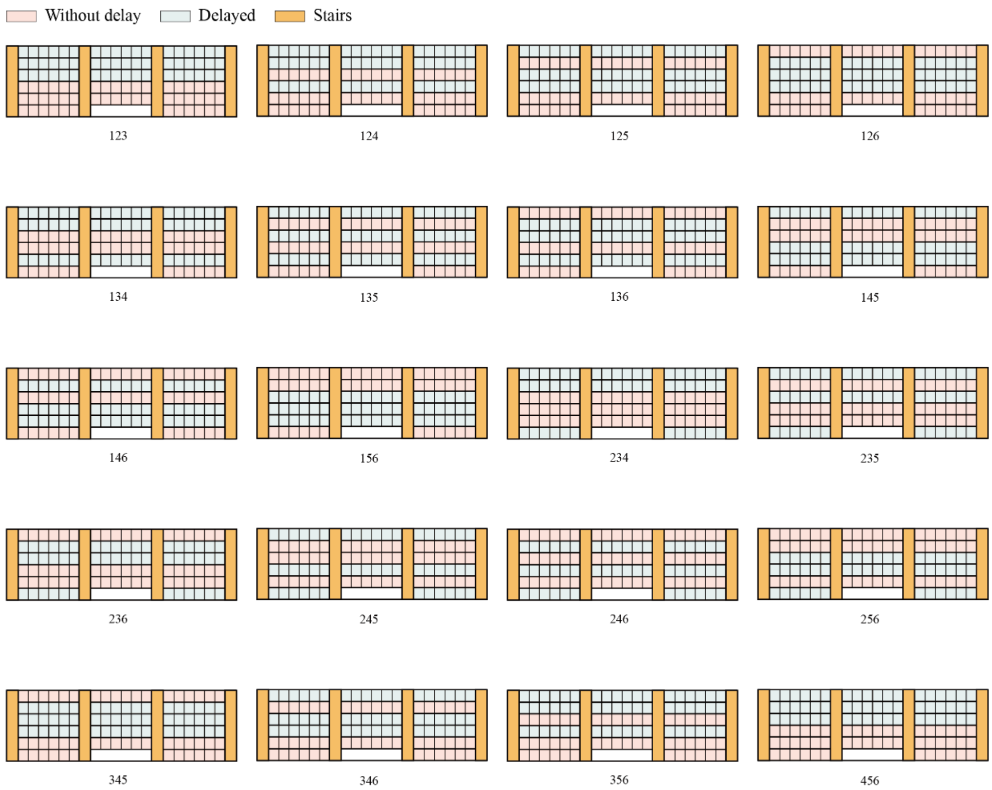



**Figure 8.** Section of the building from vertically phased evacuation scenarios.

### 2.4.3. Horizontally Phased Evacuation

According to the HPEA scheme, each classroom on each floor should have its own corresponding evacuation staircase, as shown in Figure 7c. This maximizes the equal number of evacuees per unit width (d) of each stairway and ensures that everyone leaves at the same time. The 90 rooms that use the staircase are distributed equally across the six staircases, where *Wi* is the width of each staircase and *W* is the total width of all stairs [40]:

$$W = W_1 + W_2 + W_3 + W_4 \tag{9}$$

$$d = 90 \times \frac{W_i}{W} \tag{10}$$

The calculations are as follows: stairway 1 evacuated 28 rooms, stairway 2 evacuated 21 rooms, stairway 3 evacuated 16 rooms, and stairway 4 evacuated 25 rooms.

### 2.4.4. Combination of Vertically and Horizontally Phased Evacuation

As shown in Figure 7d, the HPEB scenario combines a horizontal-phased evacuation with a vertical-phased evacuation. In this scenario, all classrooms using the same staircase are divided into two groups, with the first group participating in the first evacuation and the second group starting the evacuation after a delay of 50–300 s. The fastest evacuation time was recorded.

### 2.4.5. Setting up Ramps for the Building

Next, we will try to determine the number of ramps and the combination of their configuration with the accessible route, as shown in Figure 7e–h, with a total ramp width of 1.6 m. To achieve efficient evacuation, we add these solution strategies to the phased evacuation measures already used in the HPEB scenario. In total, there are four scenarios, R1, R2, R3, and R4. In R1, there is a 1.6 m wide ramp on one side of the building, and people with disabilities and the general public share the same corridor. In the R2 scenario, there is a 1.6-m-wide ramp on the same side of the building, but people with disabilities enter the ramp through a separate corridor. In the R3 scenario, there are two 0.8-m-wide ramps on both sides of the building, and people with disabilities and the general public share the same corridor. In the R4 scenario, there are two 0.8-m-wide ramps on either side of the building, but people with disabilities enter the ramp through a separate corridor.

#### 2.4.6. Placement of Aged Teachers

There are two possible evacuation scenarios in this plan: ER1 and ER2. They are both based on the R4 scenario mentioned earlier. Since there are only nine classrooms on the first level, the ER1 scenario configures the older teachers on the lower level, as shown in Figure 7i, and adds five teachers on the second level. The ER2 scenario places the older teachers on the sixth level, as shown in Figure 7j.

### *2.5. Framework*

The research framework of this paper is shown in Figure 9.

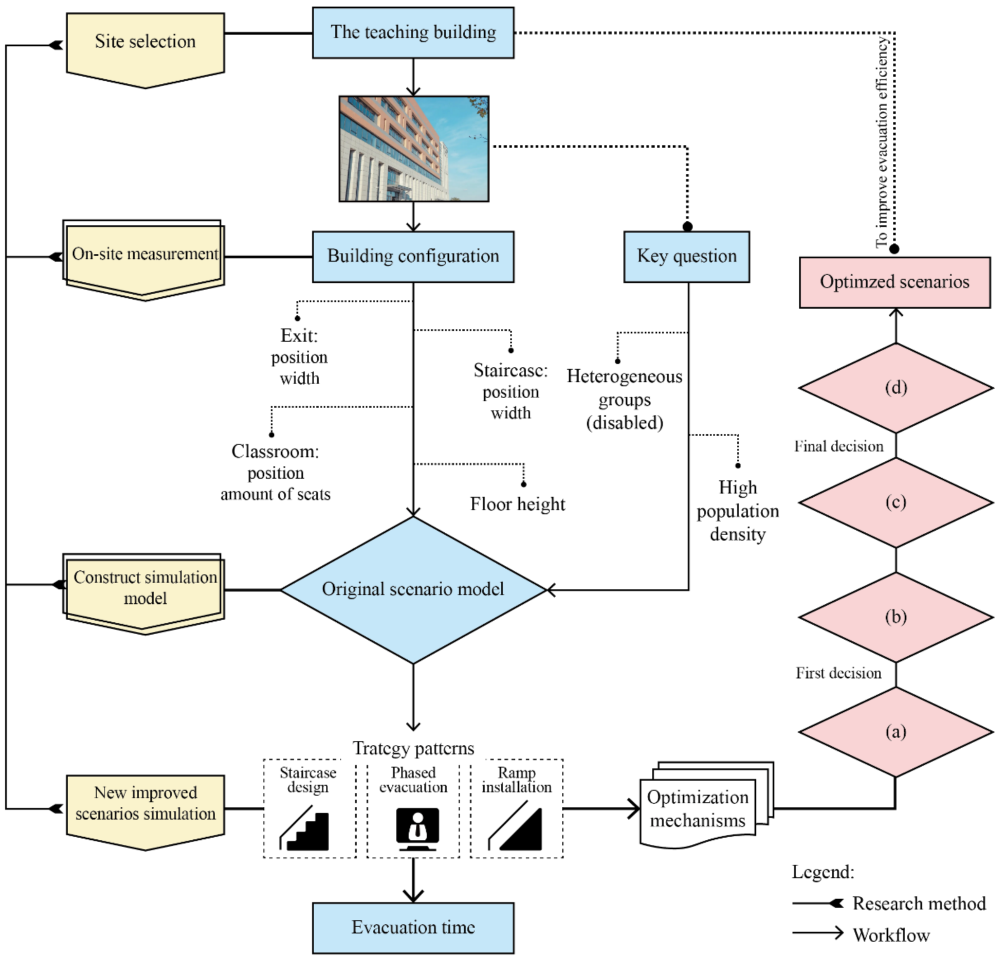



**Figure 9.** The research method and workflow of the simulation. (**a**) Staircase design; (**b**) Phased evacuation; (**c**) Ramp installation; (**d**) Emplacement.

Because stairs are the only vertical means of transportation between floors and the last step in the planar evacuation of each floor of the building, we first modified the stairs to investigate how improvements in the building components of the stairwell affected evacuation times. We then attempted a phased evacuation management approach: (1) a vertical-phased evacuation; (2) a horizontal-phased evacuation; and (3) using both vertical and horizontal-phased evacuation. Those with limited mobility (disabled students, injured students, and elderly teachers) are at high risk during evacuation. In the context of the specific situation, we considered a ramp for these groups and set the elderly teacher lecture classroom at the bottom of the building. As shown in Figure 10, we evaluated and analyzed the results of each scenario measure, selected the most successful strategy among them, and overlaid the best dispositions in each step to finally arrive at the optimal evacuation combination approach.

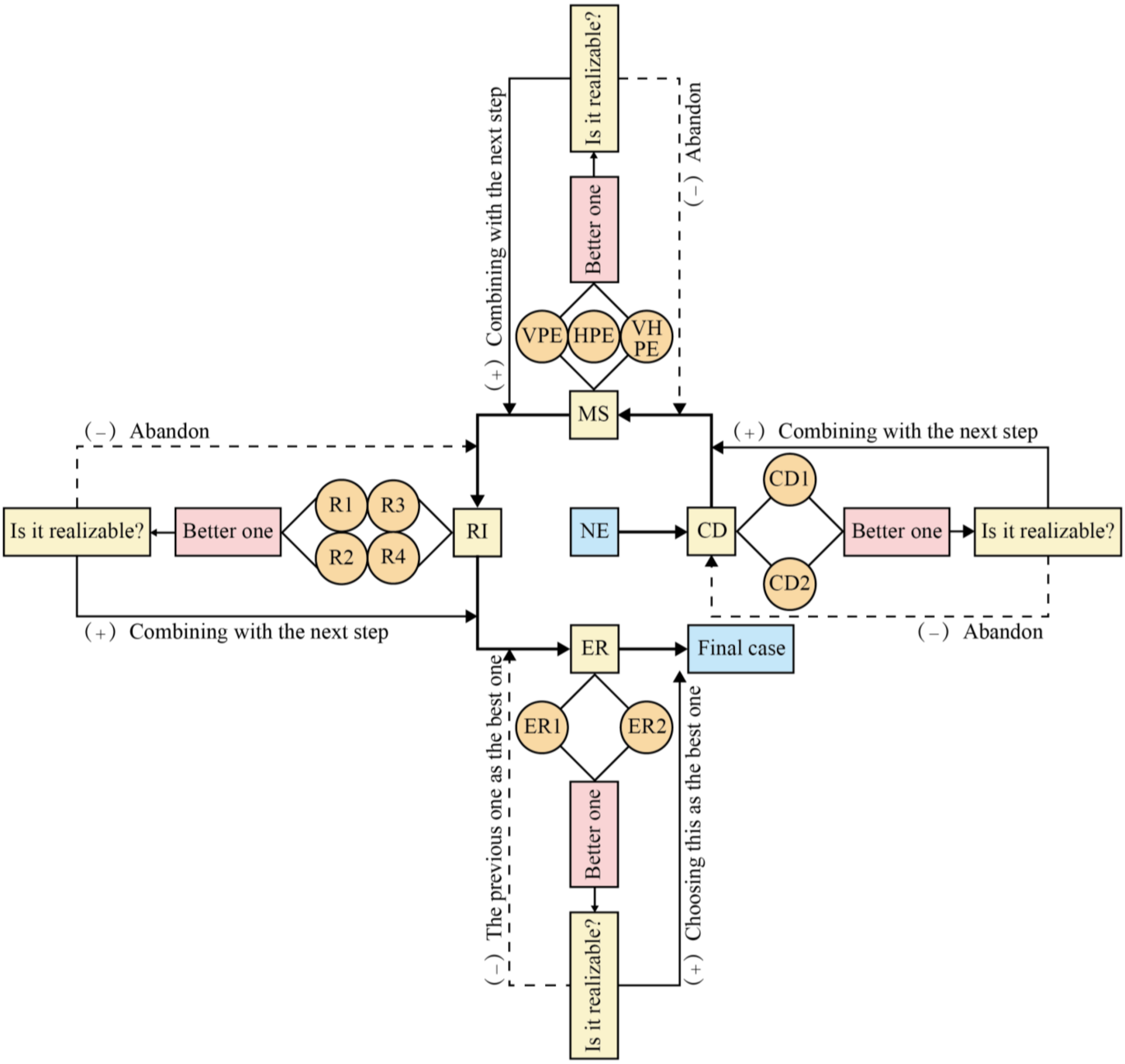



**Figure 10.** Classified analysis of scenario clusters.

## 3. Results and Discussions

### *3.1. Initial Evacuation Plan*

Figure 11 shows an evacuation time of 784s for the original scenario. In the event of a fire, all evacuees will be the first to rush out of their rooms and leave the building. According to Figure 6, stairway 2 is extremely well used with a large crowd gathering, and stairway 1 has a low flow of people.

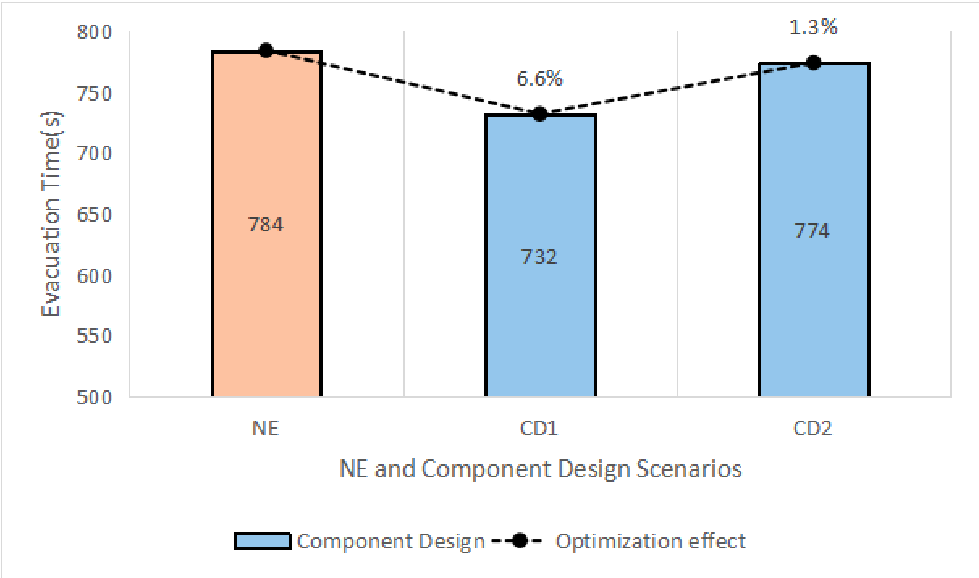
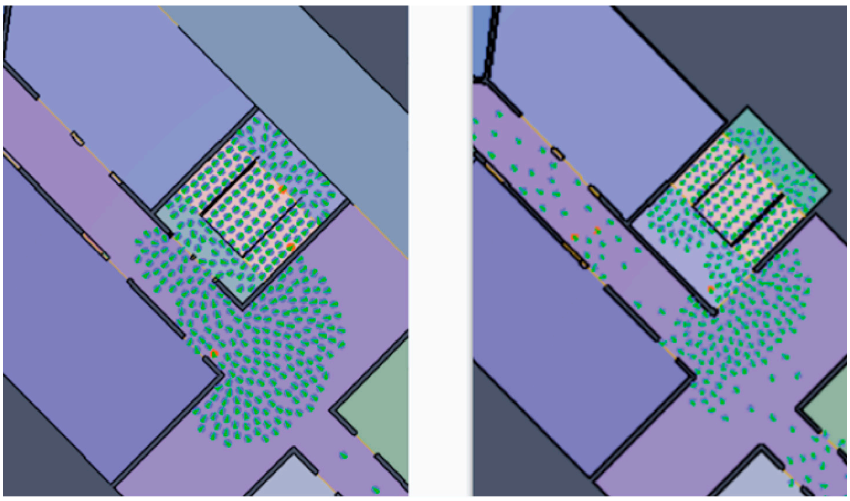



**Figure 11.** The evacuation times of NE, CD1, and CD2 scenarios.

### *3.2. Improving Structural Elements*

#### 3.2.1. Open the Antechamber's Stairway Door

The CD1 scenario reduces the evacuation time by 6.6%, as seen in Figure 11. Figure 12 allows for a comparison of the actions of individuals in the five-level corridor under the NE and CD1 scenarios. In the NE scenario, it is crowded in the hallway in front of the door so that people can use staircase 2, which prevents those who wish to switch the evacuation stairs from passing. However, in the CD1 scenario, opening the stair door toward the antechamber enables the antechamber to accommodate a large number of people as opposed to taking up space in the corridor. As a result, people can search for steps with lower evacuation pressure through the hallway, resulting in a more balanced utilization of each stairway.



(**a**) (**b**)

**Figure 12.** The evacuation scene of staircase 2 on the fifth floor. (**a**) NE, (**b**) CD1.

#### 3.2.2. Extending the Stair Railings

The CD2 scenario reduces the evacuation time by 1.3%, as seen in Figure 11. People tend to walk on the inner side of the steps [43], and the expansion of the railing forces them to move deeper into the resting platform. As a result, more space on the resting platform is occupied. Numerous studies have shown that the stair design (slope, door position on the platform) significantly affects the amount of time it takes to evacuate [24,44]. And this is clearly seen in Figure 12.

Nevertheless, the improved utility of staircases as a vertical evacuation tool is not obvious in this teaching building because it is not a high-rise structure but rather because the planar area of each floor is large, resulting in larger planar evacuation loads, so we consider other evacuation strategies.

### *3.3. Vertically Phased Evacuation*

Figure 13 shows that only 25% of the vertical-phased evacuation scenarios reduce the overall evacuation time. The fastest scenario, 236, drops the evacuation time by 2.8%, while the least effective scenario, 456, increases it by 7.9%. This situation is mainly due to the building plan's evacuation characteristics. The teaching building's floor plan is elongated, and the stairwell is unevenly distributed. Under the "proximity" principle, people mostly use staircase 2 to evacuate, and staircases 1 and 3 have low utilization rates. The higher the utilization rate of staircase 2, the more concentrated the flow of people and the longer the overall evacuation time. Figure 14 compares the utilization rate of the corridor directly opposite staircase 2 in scenario 236 and NE.

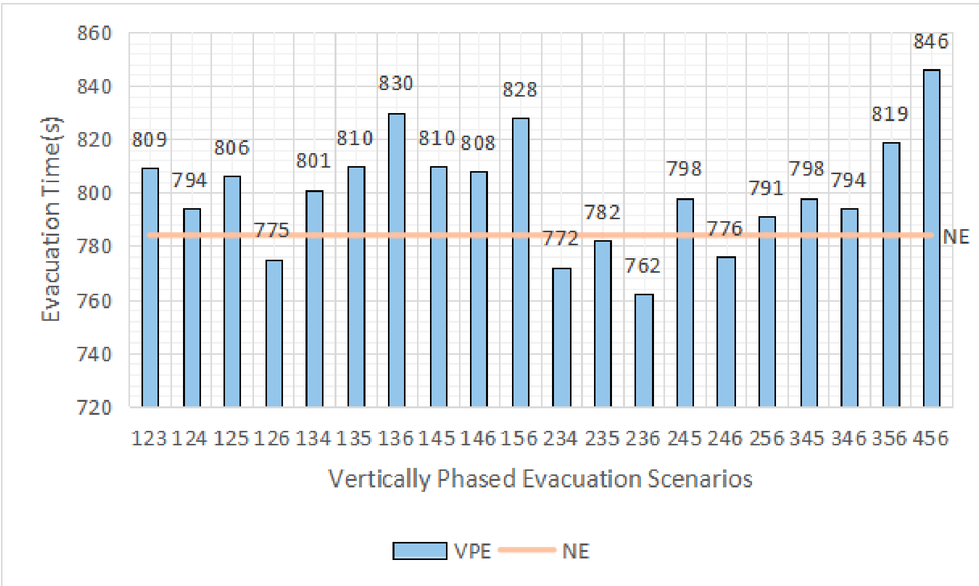
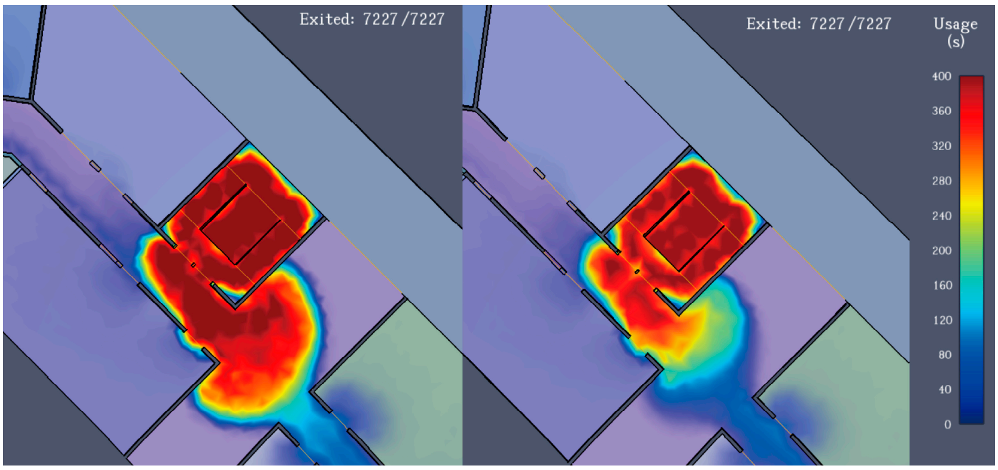



**Figure 13.** The evacuation time in vertically phased evacuation scenarios.



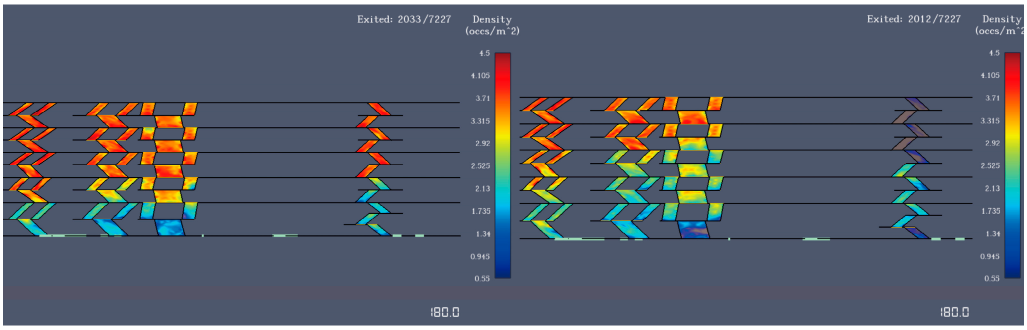

(**a**) NE (**b**) 236

**Figure 14.** The accumulated usage in the staircase 2 on the fifth floor. (**a**) NE, (**b**) 236.

The utilization rate of the corridor in front of staircase 2 in scenario 236 is lower. It is evident that scenario 236's evacuation efficiency is higher due to controlling the number of people using staircase 2. The majority of current studies suggest that vertical-phased evacuation is effective. However, our study's results differ from these findings due to two reasons. Firstly, while previous studies have focused on homogeneous populations, our study considered mixed populations, including physically disabled individuals and elderly teachers. These groups delay the evacuation efficiency of the normal population and counteract the results of the phased evacuation [45]. Additionally, their simulation results showed [29] that using a vertical-phased evacuation scheme in heterogeneous populations would instead increase the evacuation time. Secondly, if the staircases are unevenly distributed in the floor plan, the vertical-phased evacuation plan exacerbates this imbalance, and its adverse effects may offset or even outweigh the advantages of reducing the staircase density. Therefore, in cases where staircases are unevenly distributed at each level, a suitable horizontal-phased evacuation may be more effective.

### 3.4. Horizontally Phased Evacuation

Figure 15 displays the duration of the NE, VPE (236), HPEA, and HPEB evacuations. According to the findings, HPEA and HPEB have faster evacuation times than vertically phased evacuation, decreasing their respective evacuation times by 7.1% and 9.2%, respectively. In teaching buildings with high evacuation loads, planar zoning evacuation is more effective than vertical zoning and can reduce the overall evacuation time. Planar-zoned evacuation can be achieved through fire training for students and faculty [46].




(**a**) HPEA (**b**) HPEB

**Figure 15.** The density of people in staircases.

### 3.5. Combination of Vertically and Horizontally Phased Evacuation

Figure 16 shows that the evacuation time for the scenario HPEB is less than HPEA. This indicates that using both vertical and horizontal zoning is better than using only horizontal-phased evacuation. Figure 15 compares the density of people in the stairwell at 180 s for scenarios HPEA and HPEB. The density of people in the stairwell on each floor is more uniform and has lower values for scenario HPEB. This finding suggests that maintaining a constant population density along the length of the stairs maximizes evacuation efficiency. Although the population density in stairwells between the fifth and sixth floors is higher than that in stairwells on lower floors, this effect has little impact on evacuation performance [47].

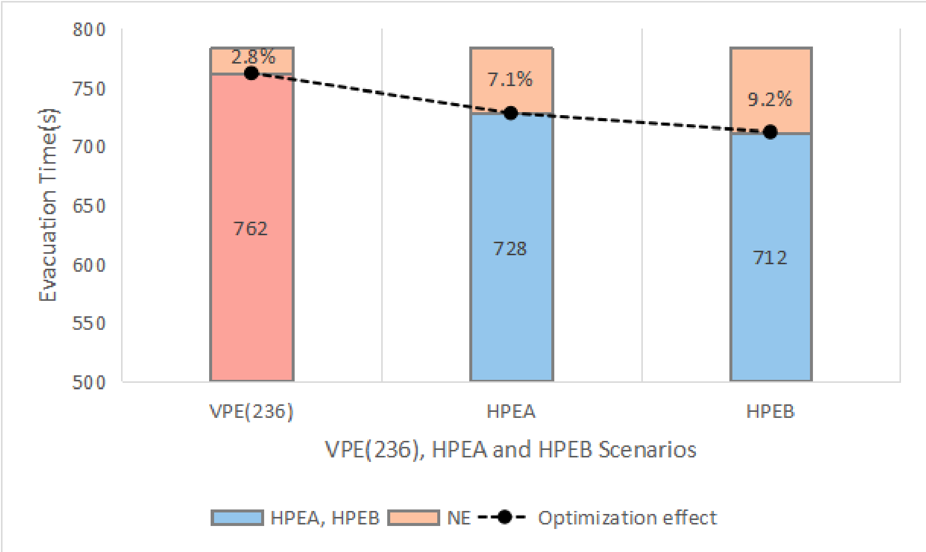



**Figure 16.** The evacuation times of NE, VPE(236), HPEA, and HPEB scenarios.

### *3.6. Ramp Installation*

Figure 17 illustrates that installing ramps on buildings is a way to significantly reduce evacuation times. The evacuation time is reduced by 12%, 13%, 15%, and 18% in the R1, R2, R3, and R4 scenarios, respectively, with the R4 scenario showing the best results. Compared to one ramp, the addition of two ramps allows people with limited mobility to access the ramp from classrooms on both sides of the corridor in close proximity. Thus, the main evacuation flow of normal people does not affect the direction of movement of people with mobility impairments, as there are separate corridors for them to use. Also, these physically challenged individuals will not be an obstacle to the evacuation of normal people [48].

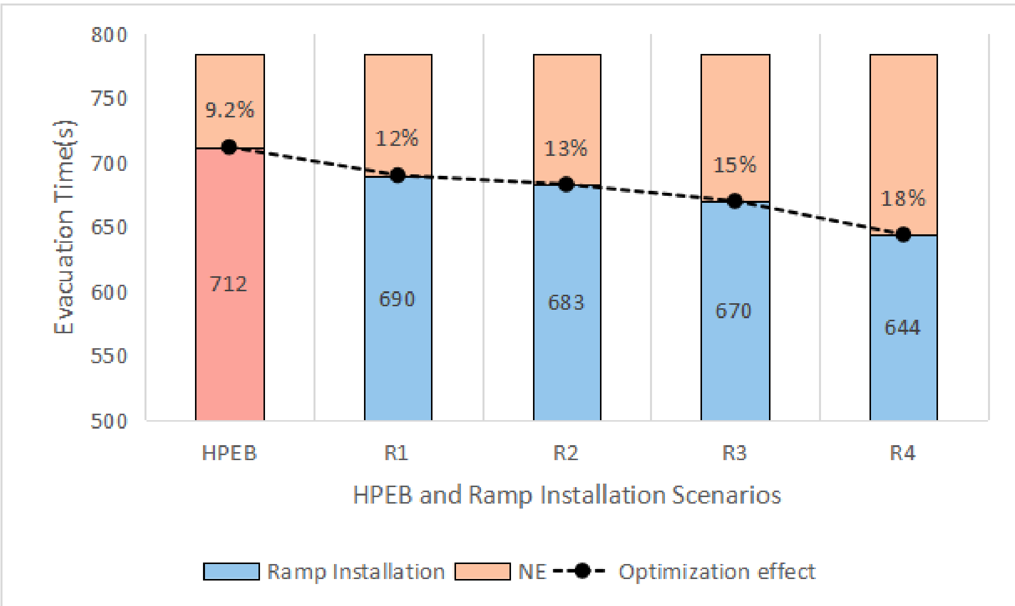



**Figure 17.** The evacuation times of NE, HPEB, R1, R2, R3, and R4 scenarios.

### *3.7. Placement of Aged Teachers*

According to Figure 18, the evacuation time of scenario ER1 is reduced by 19%, even though the difference with scenario R4 is not significant. In addition, although the evacuation time for scenario ER2 is cut down by 13.5%, there is no advantage over scenario R4. Placing older teachers on lower floors increases evacuation efficiency [28], which is due to the fact that older teachers on the ground floor do not use the ramp and avoid their interference with normal people. The low percentage of older teachers with mobility problems in this simulation may be the reason why the ER1 strategy is not as effective. Though older teachers can leave the building earlier and reduce the load on the ramp, students with mobility impairments are still located on higher floors, and they are the main determinants of ramp evacuation effectiveness.

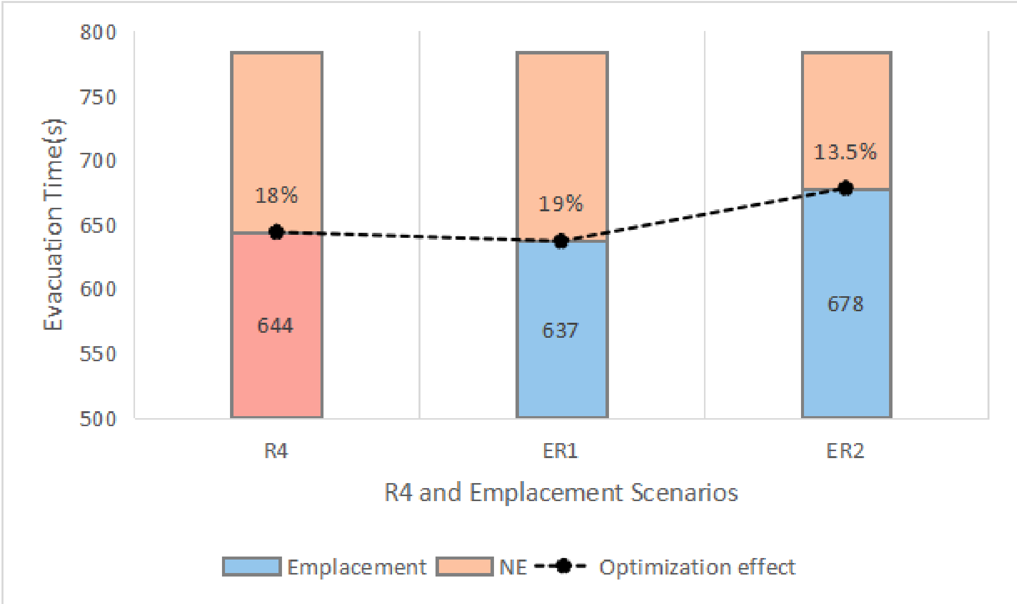



**Figure 18.** The evacuation times of NE, R4, ER1, and ER2 scenarios.

### *3.8. A Comprehensive Comparison with Other Studies*

Jeongin Koo and colleagues tested an evacuation plan in which the total time of the evacuation was cut by 21.5% [29]. This method only allows physically challenged persons to evacuate using elevators, even though it performs somewhat better than the strategy in this study (evacuation efficiency is around 2% higher). The floor height has a big impact on how long passengers must wait in an emergency and how many people must wait. Furthermore, it would be unreasonable to expect physically disabled persons to wait an endless amount of time for an elevator, given the numerous unknowns involved [49]. Additionally, according to the rules of a number of countries [50], not all educational facilities are high-rise structures, and it is impossible that they all have elevators with dependable electrical controls, power supplies, and fire and smoke protection. As a result, utilizing elevators to evacuate is not the best option in the actual world [51]; instead, our scenario is more reasonable and practicable.

The evacuation time was decreased by around 28% because of the plan put forth by Mahdi Rismanian et al. [32]. The key steps that were ultimately carried out in their study case—a residential building-included installing special evacuation ramps for those with disabilities—making it safe for them to move around within the bottom five floors of the building. This improved evacuation capability was primarily attained in light of the building's features. Residential buildings have significantly fewer occupants per square foot than teaching buildings, making evacuation easier. Also, the residential building has a higher percentage of impaired residents than the educational building, allowing the added efficiency of ramps noticeable. Furthermore, from a practical point of view, residential buildings can place all physically disabled people on the bottom five floors, but in teaching buildings, it is only plausible for physically disabled people to be distributed randomly on each floor, which complicates our optimization strategy. As a result, the final comprehensive optimization strategy, which cannot be generalized, is greatly influenced by the planar evacuation characteristics of various building types, the arrangement and distribution characteristics of the building occupants, etc.

## 4. Conclusions

Safety evacuations are critical in university teaching buildings where students spend most of their time. The evacuation performance of a building is determined by the composition of its building components, which can be optimized during the design phase. However, the physiological conditions of those who utilize buildings, such as students, instructors, researchers, etc., vary greatly. Those who are physically challenged and those who are elderly pose a barrier to the general populace in addition to the difficulties they would confront in evacuating themselves. This work incorporates several improvement methods, such as design and management options, to obtain optimization solutions for the study building (i.e., a university academic building). Numerical analysis of simulation software Pathfinder was used to compare 33 optimization strategies, including vertical or horizontal-phased evacuation, additional ramps, and better lecture positions for elderly professors to assess the potential enhancement of evacuation performance. The results of the research demonstrate that the appropriate integration of the aforementioned optimization methods has a positive effect on the building's performance during an evacuation. The following are the key findings of the study:

(1) The placement of stair doors and the addition of ramps can reduce evacuation time by 12% and 6.6%, respectively. The length of the balustrade has little effect. This suggests that designers may consider combining stairs with the anteroom in the architectural design process.

(2) A horizontally staged evacuation plan can shorten the process by 7.1%. If the evacuation steps are not distributed uniformly, the vertical-phased evacuation approach may not be successful. However, the evacuation time can be further decreased by 9.2% if horizontal and vertical-phased evacuation procedures are appropriately coupled. This indicates that solutions for increasing building evacuation effectiveness, such as horizontal-phased evacuation or vertical-phased evacuation, are very stochastic. These two have a tight connection with how stairwells are distributed within the building and how the building's floor plans are laid out, respectively. Additionally, because there are impaired people present, the gain in evacuation efficiency following the combination of the two is still marginal.

(3) Mobility delays in public walkways for people with physical disabilities have a significant obstructive effect. Combining components can provide a better solution. For instance, using two ramps and providing those with impairments with their own access can cut down evacuation times by 18%. The development of ramps for people with disabilities is a practical step based on the application of a staged evacuation strategy. It is important to consider how persons with disabilities will be evacuated vertically as well as how they will reach the ramp, which means the distribution of ramps and accompanying special access is important.

(4) Placing elderly educators on lower floors might drop the time needed for evacuation. The number of levels in the building is positively connected with the magnitude of this measure's influence.

The combination technique presented in this paper can be applied to other comparable buildings. However, additional research is still needed to overcome the limitations of this study. Numerical simulations model complex systems and processes that are challenging to understand experimentally. Although Pathfinder is the most widely used software for evacuation simulation, the simulation findings are only approximate and prone to statistical errors when the Pathfinder software's built-in models cope with uncertainty. Furthermore, the simulation results may also be impacted by measurement errors of the existing structure, and further validation and correction of the values by experiments, observations, etc., are also required.

**Author Contributions:** Conceptualization, B.Z. and L.Y.; Methodology, B.Z. and L.Y.; Writing—original draft preparation, L.Y.; Visualization, L.Y.; Project administration, B.Z.; Software, L.Y.; Supervision, T.W. and B.Z.; Writing—review and editing, L.Y. and B.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the University–Industry Cooperation Collaborative Education Program of Ministry of Education, China (No. 202102213045); Graduate Student Quality Engineering Program of Wuhan University of Science and Technology (No. Yjg202107); and Research projects for teaching of Wuhan University of Science and Technology (No. 2022Z023).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data will be made available on request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| | |
|---|---|
| CD | Component Design of staircases |
| VHPE | Vertically and Horizontally Phased Evacuation |
| MS | Management Strategy |
| RI | Ramp Installation |
| ER | Emplacement of aged teachers and Ramp installation |

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