buildings

MDPI

Article

Analysis of Pedestrian Behavior for the Optimization of Evacuation Plans in Tall Buildings: Case Study Santiago, Chile

Rodrigo Ternero [1,2], Juan Sepúlveda [1], Miguel Alfaro [1], Guillermo Fuertes [1,3,*], Manuel Vargas [1], Juan Pedro Sepúlveda-Rojas [1] and Lukas Soto-Jancidakis [1]

[1] Industrial Engineering Department, University of Santiago de Chile, Avenida Victor Jara 3769, Santiago 9170124, Chile; rodrigo.ternero@usach.cl (R.T.)
[2] Escuela de Construcción, Universidad de las Américas, Santiago 7500975, Chile
[3] Facultad de Ingeniería, Ciencia y Tecnología, Universidad Bernardo O'Higgins, Avenida Viel 1497, Ruta 5 Sur, Santiago 8370993, Chile
* Correspondence: guillermo.fuertes@usach.cl

Abstract: Countries located in the Pacific Ring of Fire, such as Chile, require robust evacuation plans for tall buildings to manage the ongoing threat of natural disasters. This study presents a methodology for developing evacuation plans by conducting pedestrian movement simulations with agents that have a model of their surroundings. This approach allows us to assess different scenarios and choose the best option based on the specific characteristics of the site. The method combines simulation and data analysis, using the Monte Carlo method to improve emergency evacuations. Initially, Pathfinder software was employed to simulate the evacuation of a tall building. This involved modeling pedestrian movements using a multiagent system. These agents were programmed to behave like real pedestrians and make decisions during evacuation scenarios, providing valuable information. The effectiveness of two evacuation strategies was then evaluated using the simulation data. The proposed methodology was validated using a case study. The simulations showed that the best strategy depends on factors such as the distribution of people, the capacity of the exits, and the time available for evacuation. Finally, the model includes a training process that uses virtual reality technology to improve situational awareness.

Keywords: computer simulation; disaster planning; emergency evacuation; safety management

check for updates

Citation: Ternero, R.; Sepúlveda, J.; Alfaro, M.; Fuertes, G.; Vargas, M.; Sepúlveda-Rojas, J.P.; Soto-Jancidakis, L. Analysis of Pedestrian Behavior for the Optimization of Evacuation Plans in Tall Buildings: Case Study Santiago, Chile. *Buildings* **2023**, *13*, 2907. https://doi.org/10.3390/buildings13122907

Academic Editor: Xavier Romão

Received: 3 October 2023
Revised: 9 November 2023
Accepted: 15 November 2023
Published: 22 November 2023

1. Introduction

Chile is situated within the Pacific Ring of Fire, a region known for its susceptibility to earthquakes, tsunamis, volcanic eruptions, and floods [1]. In the past 60 years, notable events include mega-earthquakes and tsunamis in Valdivia (1960) and Constitucion (2010), the Central Zone earthquake (1985), earthquakes in Arica and Iquique (2014), and the Aysén tsunami (2007), as well as volcanic eruptions in Chaitén (2008) and Cordón Caulle-Pullehue (2011) [2]. These catastrophic events have caused enormous damage to the country's infrastructure and human life.

Chile is taking measures to enhance its preparedness for natural disasters. Nevertheless, the country still faces vulnerability to such events, which underscores the crucial importance of developing robust evacuation plans to mitigate these risks. According to Shin and Moon [3], this aspect is important for both risk management teams and the communities that could be affected. In this context, it is essential to establish methodologies for selecting the appropriate strategy to conduct safe evacuations, thereby ensuring the preservation of life in such eventualities.

Evacuation models are systems that simulate the evacuation of a building or space during emergencies, such as fires or earthquakes. Studies on pedestrian evacuation models primarily focus on four key aspects of the modeling process: psychological factors, the impact of the external environment, pedestrian heterogeneity, and model flexibility [4]. For

Amini et al. [5], formulating evacuation strategies requires anticipating the spontaneous behavior of individuals, small groups, or crowds during such events. In this context, authors such as Lindell and Perry [6] propose the use of post-disaster sociology models. Examples include the Turner/Killian emergent norm theory, which posits the emergence of collective behaviors in large groups of pedestrians, and the panicked agents and decision-making (PADM) theory, which is based on research on people's responses to environmental hazards and disasters. However, due to the complexity of human behavior and the challenges in recreating these situations, there is no single consensus on these topics.

Evacuation is the primary action to mitigate the effects of any disaster. However, as Haghani and Sarvi [7] argue, human behavior may not always align with evacuation guidelines. The failure of some individuals to follow instructions can lead to uncontrollable situations. The behavior of evacuees during a disaster and the methodologies used to assess such behavior are essential elements in the management of any emergency [8].

Contribution, Scope, and Limitations of the Study

This study combines optimization models for pedestrian movement paths, with agent profiles representing cognitive behaviors, to create highly realistic evacuation simulations.

This study is grounded in the Turner/Killian and PADM conceptual models, which incorporate sociological perspectives that address relevant variables for analysis. Within this framework, the stages of the computational development process are identified. Moreover, simulation tools are employed to validate the robustness of these sociological models. Based on these results, informed decisions are made to formulate an optimal strategy for addressing evacuations during natural disaster situations. Additionally, the authors of this study shared their experiences with evacuation experts, which resulted in valuable insights into the behavior of people in the Chilean context.

This study focused on enclosed spaces, which could limit the applicability of the results to other environments. Additionally, it is impossible to replicate all potential situations that may arise. Therefore, while the modeling offers a valuable representation of human behavior during evacuations, it cannot fully represent reality. This is because simulations cannot account for factors such as fear, panic, or uncertainty, among others. Nevertheless, these findings can still be valuable for enhancing evacuation plans and reducing the risk of injury or loss of life.

The rest of this paper is organized as follows: Section 2 presents a literature review to identify methods used in modeling human behavior during evacuations and to gain insight into the current state of the field. Section 3 presents the methodology used in this study, offering a detailed description of each step comprising the model. Section 4 provides the results of the case study. Section 5 discusses the results. Finally, Section 6 outlines the research conclusions.

2. Research Background on the Modeling of Human Behavior in Evacuations

Decision making and the implementation of evacuation plans are crucial during crisis situations. The simulation of events through computer systems is a valuable tool for assessing various strategies and options. The integration of mathematical tools with decision matrices can be used to characterize people's cognitive phases and create agent profiles representing a wide range of types of individuals [9]. This convergence of approaches provides a way to analyze and forecast how different segments of the population might respond to disasters, facilitating more accurate and adaptive planning.

According to Lorusso et al. [10], the modeling and simulation of agent profiles can be used to draw conclusions about human behavior, at both the individual and collective levels, during evacuation processes. This information can be used to generate management plans that aid in making more informed decisions in natural disaster situations.

2.1. Dynamics of the Movement of People

For Tamang and Sun [11], the study of movement dynamics in evacuations involves analyzing how people behave and move during emergency evacuations. In general, it has been observed that most individuals move in an organized and efficient manner in such situations. However, factors such as age, disability, and familiarity with the environment can influence people's ability to evacuate safely and quickly [12].

Studies of evacuation motion dynamics have been instrumental in developing mathematical models and simulations to improve the planning and design of both public and private spaces. These models can simulate various scenarios and assess the effectiveness of different evacuation strategies. Research on motion dynamics during evacuations has been conducted in a variety of settings, including buildings [13], subway transportation systems [14], aerial environments [15], marine environments [16], stadiums [17], and public spaces [18]. In each of these environments, specific factors have been identified that influence people's movement dynamics.

Authors such as Soltanzadeh et al. [19] propose models to analyze movement behavior in buildings, considering factors such as the layout of emergency exits, building height, and elevator capacity, which can affect evacuation speed and efficiency. Additionally, the role of communication processes in influencing decision making during evacuations has been investigated [20].

For Shiwakoti et al. [21], the implementation of public address systems and early warning systems has the potential to provide critical information to individuals about the emergency and guide them to designated exits. Table 1 summarizes the main models used for evacuation simulation in tall buildings.

Table 1. Main models for the simulation of motion dynamics in evacuation situations.

Simulation Model	Description
Cellular automata	Method for simulating the movement of people during evacuations. It divides the space into cells, each of which can accommodate one person. The model then simulates the movement of individuals from one cell to another, following specific guidelines [22].
Agent-based modeling	It is supported by the generation of virtual agents. These agents have the capacity to make decisions and adhere to certain behavioral guidelines, thereby emulating the actions of people during evacuations [23].
Discrete-event simulation	Simulation of events that occur during an evacuation, such as the activation of fire alarms or the opening of exit doors. These events are represented in a chronological sequence, allowing for the evaluation of response and evacuation times [24].
Fluid dynamics	Simulation used primarily to analyze the effectiveness of evacuation routes and congestion in public areas. This technique is founded on the application of fluid theory to model the movement of individuals as if they were particles in a fluid [25].
Game theory	It is used to model people's decision-making processes during evacuations. Different evacuation scenarios are simulated, and people's behavior is assessed in relation to different alternatives [26].
Social force model	Simulation of the social dynamics of a group of people during an evacuation. Considers the interaction between individuals and their physical environment. It also represents different social relationships and factors that influence people's behavior during evacuations [27].

It is important to note that each simulation model has its own set of advantages and disadvantages, and their selection depends on the specific objectives of the simulation. Furthermore, in many cases, different models are combined to achieve more accurate results.

2.1.1. Agent-Based Model (ABM)

According to Wooldridge and Jennings [28], an agent is a computer system situated in an environment that can autonomously take actions to achieve its goals. When multiple agents interact in an environment and coordinate their actions and behaviors, they form more integrated systems known as ABM.

For Singh et al. [29], each agent has a unique and independent set of attributes, including physical and mental parameters. These attributes include characteristics such as gender, mobility, age, weight, and other factors that affect the agent's speed and overall evacuation time. When agents collaborate to solve complex problems, they cooperate and coordinate their actions to reach a comprehensive solution [30]. The essential aspect of agent-based crowd models is the set of attributes and the definition of interactions between the various agents.

For Railsback and Grimm [31], ABM models are well suited for exploring alternative scenarios and representing uncertainty in complex systems. This makes them an effective tool for comparing results and investigating causal relationships between small-scale processes and large-scale patterns in an agile and efficient manner.

ABM is used in a variety of fields, including economics, ecology, political science, psychology, and health. For example, de Assis et al. [23] used ABM to model the dynamics of a market in which multiple agents make decisions about the purchase and sale of electric vehicles in Brazil. Additionally, Burrow et al. [32] used ABM to simulate the behavior of a frog population within an ecosystem. Kasereka et al. [33] used ABM to simulate the spread of diseases within populations, while Poledna et al. [34] used it for economic forecasting. Foramitti [35] argues that ABM is valuable for exploring various scenarios and assessing alternative policies.

2.1.2. ABM as a Social Research Tool

ABM has gained significant popularity as a tool in social research. Wijermans et al. [36] state that ABM is used in social research to model a wide range of phenomena, including information diffusion, opinion formation, collective decision making, and group dynamics. Şahin et al. [37] argue that ABM allows researchers to incorporate the inherent complexity and variability found in social systems. According to Smaldino [38], ABM realistically models social processes and captures the effects of interactions at both macroscopic and microscopic levels. It also facilitates the exploration of how individual decisions and behaviors of agents impact the entire system, addressing the complexity and variability present in social systems [39].

However, ABM models, which rely on assumptions about human behavior, require a significant number of computational resources. Despite this, they offer valuable insights into the complexities inherent in evacuations during emergencies.

2.1.3. Cognitive Analysis of Individuals

Throughout history, humans have consistently sought to understand and explain recurring patterns within societies. These studies, collectively referred to as the field of collective behavior, have given rise to disciplines within social psychology and sociology [40]. Currently, there are two predominant approaches to understanding collective behavior: (1) The model derived from mass psychology posits that collective behavior is anomalous, irrational, emotional, asocial, and pathological. This perspective advocates for the implementation of external intervention strategies aimed at control and prevention [41]. (2) The sociological approach, on the other hand, stems from specific sociological theories and post-disaster sociology. This perspective postulates that collective behavior represents a manifestation of social behavior characterized by normativity, sociability, rationality, cooperation, and prosocial behaviors [42].

Zarboutis and Marmaras [43] used ABM as a cognitive tool for designing effective evacuation plans in complex sociotechnical systems during crisis situations. According to authors such as Turner and Reynolds [44], social psychological factors play a significant role in influencing people's self-organized movements. Many instances of collective behavior in mass evacuations can be explained by the self-categorization theory. Reicher [45] noted that collective behavior becomes possible when individuals share a common psychological and social identity.

2.1.4. Theory of the Emerging Norm (Turner/Killian)

The Turner/Killian emergent norm theory [46] is a sociological theory that explains how norms can emerge in crowds. The theory argues that crowds are not inherently irrational, but that they can develop new norms when there are common interests among the individuals in the crowd. Ding et al. [47] argue that a rigorous and valid study of collective behavior requires the integration of multiple levels of analysis, including intergroup, intragroup, and individual behaviors.

2.1.5. Situational Awareness in Evacuations

According to Zander et al. [48], situational awareness (SA) is used to describe the ability of an individual or system to perceive the critical elements of its environment, understand their significance, and infer future states based on that information. Huang and Xiao [49] also define SA as the understanding of events involving multiple actors and dynamic components, especially in the context of command and control operations.

Endsley [50] presents a three-level SA model: perception (identification of raw data), comprehension (interpretation in context), and inference (projection of future states based on the information). Endsley's model has enjoyed widespread use and study. However, in certain contexts, some studies have suggested that it may be oversimplified, leading to the formulation of alternative approaches that incorporate complementary elements like social dynamics, cognitive load, and the impact of decision support systems [51].

Different methodological advancements have led to the development of techniques and tools for measuring and enhancing SA. Among these methodologies, the situation awareness global assessment technique (SAGAT) stands out. SAGAT uses random queries during simulations to assess SA. Additionally, the SA management model offers strategies for real-time operational optimization [52].

In the context of evacuations, SA plays a crucial role in individual decisions, such as choosing an escape route or determining the safe time to move [53]. The integration of SA into agents within evacuation simulations is known as ABM. These models provide each agent with an internal representation of the environment and the rules for updating and utilizing that representation [54].

An agent's information about their environment can vary based on factors such as visibility, stress, and prior knowledge of the environment. Agents may make decisions based on their situational awareness, such as altering their route when encountering a blocked exit or following others if they are uncertain about the route [55].

Simulations can modify agents' SA to analyze its impact on evacuation dynamics. Agents with high-level SA can evacuate efficiently, while those with low SA may contribute to congestion and slow down the evacuation process [56].

2.1.6. Monte Carlo Method in Evacuations

According to Robert and Casella [57], the Monte Carlo method (MCM) is a computational technique that approximates solutions to complex mathematical and physical problems by conducting many randomized experiments. To execute an MCM simulation, inputs are randomly generated according to the appropriate probability distribution. These inputs are then fed into a system model, which produces an output [58]. This process is repeated many times, and the results are analyzed statistically to yield an approximate solution.

MCM is a versatile method that can be applied to a wide range of problems. While it can be computationally intensive, it is particularly valuable for addressing high-dimensional problems that would be challenging or infeasible to solve using analytical methods [59].

In the context of evacuation simulation, MCM involves creating a computational model of the environment and the individuals within the scenario [60]. Each individual or agent is assigned random attributes, such as movement speed, knowledge of the environment, and behavior under stress [61]. Evacuation is then simulated, with agents moving toward exits based on their attributes and interactions with other agents and the environment. This process is iterated multiple times, incorporating various combinations of attributes and initial conditions, to generate a distribution of potential outcomes.

MCM can be used to explore a broad spectrum of evacuation scenarios and generate statistics on variables such as total evacuation time or the density of people in various locations during an evacuation [11]. These results can be used to improve evacuation plans, enhance building design safety, or train emergency response teams.

However, MCM does not predict human behavior with absolute precision, given the inherent nature and complexity of real emergencies. It is still a valuable tool for understanding potential scenarios and preparing for them.

2.1.7. Virtual Reality in Evacuation Models

Virtual reality (VR) has seen increasing use in evacuation modeling as a tool to enhance planning and preparedness for emergency situations [10]. VR is used to create realistic virtual environments that replicate the building, enabling users to undergo simulated evacuation experiences within a safe and controlled setting. This proves valuable for assessing the efficacy of evacuation strategies, identifying potential issues, and enhancing emergency planning.

Furthermore, VR serves as a valuable tool for training individuals in effective evacuation procedures [62]. Users can practice evacuation in a virtual environment, allowing them to experience simulated emergency situations and learn how to respond appropriately.

3. Methodology

3.1. Case Study

This study was conducted in response to the University of Santiago de Chile's requirement to implement an evacuation plan for the new classroom building of the School of Engineering. The plan's design involves modeling three different scenarios. The agents in the simulation represent different types of pedestrians found within the building. The Pathfinder program, with support from MCM, was used to conduct the simulation process and to obtain evacuation times, average values, standard deviations, and pedestrian concentrations. These values facilitated the comparison of the three scenarios and the determination of the optimal evacuation plan for the building. This optimal plan was then replicated in a VR environment to train building occupants on its execution.

In this document, the evacuation simulations consider the frequency of seismic events in Chile and compliance with seismic resistance standards. The Pathfinder program was used for architectural surveys and agent configuration, generating multiple scenarios for evacuation simulation [63]. Additionally, based on the information presented in Section 2 and insights gathered from expert meetings, an evacuation plan is proposed, considering two key elements: zoned user loads and limited elevators. The simulations provided valuable insights for determining the optimal combinations within the building's evacuation plan.

The object of study is the Teaching Innovation Rooms building within the Faculty of Engineering at the University of Santiago de Chile (USACH) [64]. This closed environment provides an ideal setting for evaluating the behavior of groups of people during events that trigger evacuation processes. The architectural dimensions of the building are 28 × 35 × 30 m. The building consists of eight levels, with each floor featuring five classrooms, an auditorium, restrooms, and three elevators. Additionally, it has four staircases, including three lateral staircases and one central staircase (two of which are designated as emergency staircases). The building also has a spacious entrance area that extends to the eighth floor, creating a large central space. As a result, all occupants within the building can have a complete view of the entrance from any floor.

The building is encircled by an exterior structure that defines the central area, creating slight undulations due to wind effects. The building was designed to accommodate an average of 1000 people, distributed across all floors.

Figure 1 shows the methodological framework of this study. This approach is robust and has the potential to serve as a generic methodology that experts can employ in their projects to make substantial contributions to the development of effective evacuation strategies.

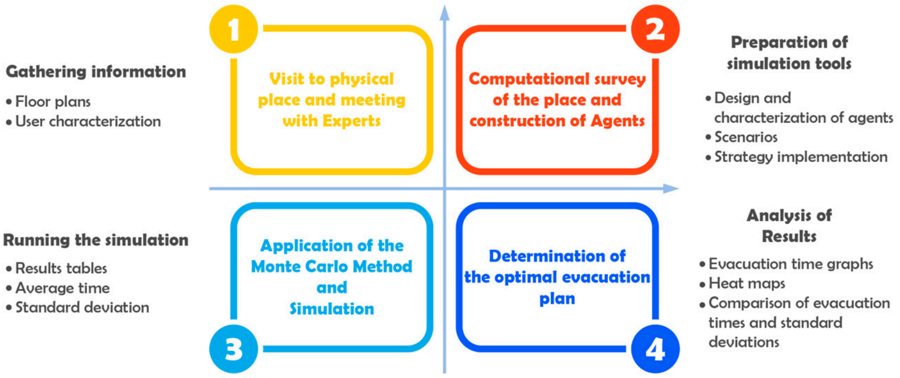


Figure 1. Methodological framework of this study.

3.2. Pathfinder Software

Pathfinder software version 2023.2 is used because it simulates realistic evacuations, reducing the need for multiple drills and lowering the costs of evacuation plan design [65]. The agent's navigation and sensing abilities are based on Reynolds' direction model [66], which has been refined for improved accuracy by Amor et al. [67]. Each agent has a range of attributes, including age, gender, speed, and the time it takes to react or move.

The velocity is determined based on the calculations by Xiong et al. [68] (Equation (1)).

$$\mu_i = \begin{cases} 1.4 & \rho \leq 0.75 \\ 0.0412\rho^2 - 0.59\rho + 1.867 & 0.75 < \rho \leq 4.2 \\ 0.1 & \rho > 4.2 \end{cases} \tag{1}$$

where μ_i represents the user's velocity in m/s, and ρ indicates the user density in user/m^2. According to the Pathfinder program, the maximum velocity that an average pedestrian can reach is 1.19 m/s. Rahouti et al. [69] confirmed these velocities using security cameras during unannounced drill scenarios to obtain an empirical analysis of pedestrian speeds. The results obtained using the Pathfinder program reveal similar values.

The agent's geometric shape is modeled as a cylinder with a diameter equivalent to the distance between a person's shoulders, which averages at 0.6 m, and a height of 1.75 m. Within the simulation, this cylinder is represented as a human figure.

3.3. Architectural Survey

The building plans were provided by USACH through its construction unit. A scale model of the original dimensions of the building was then generated within the Pathfinder program using this information (Figure 2).

The architectural survey is aligned with the physical measurements of the building (Figure 3). Once the physical scenario has been established, the agents are configured for the simulation.

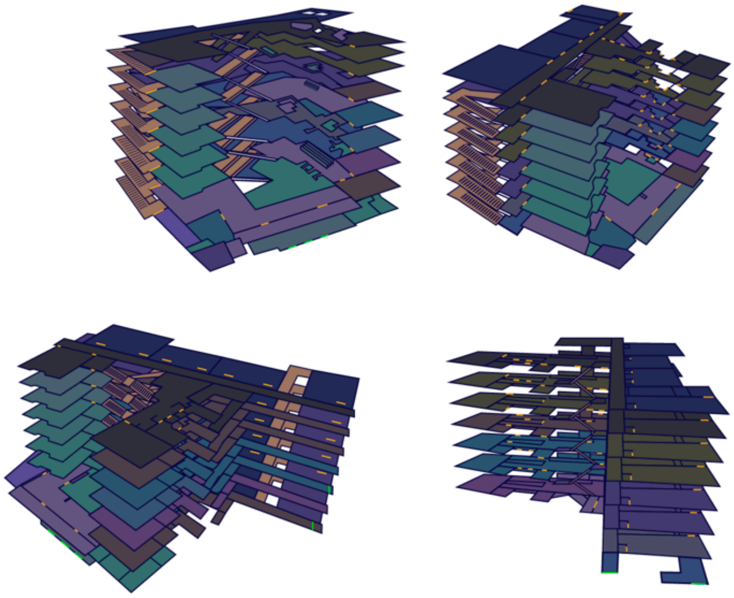


Figure 2. Pathfinder view of different positions of the building.

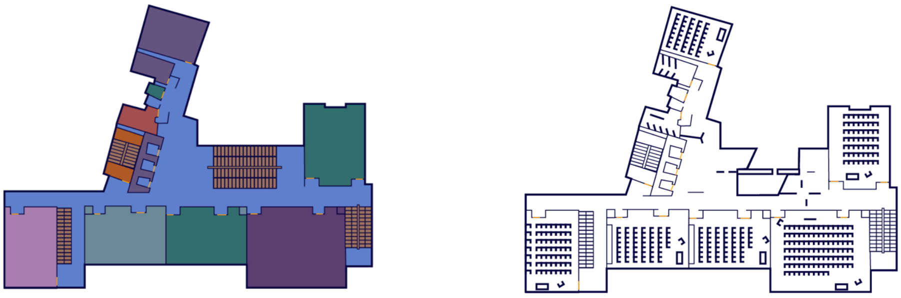


Figure 3. Construction plan of the building with its Pathfinder equivalence.

3.4. Agent Configuration

Three types of agent profiles were configured: (i) robot, (ii) young, and (iii) adult. The values used to define these agents were validated by Thunderhead Engineering, the company that owns the program. All profiles are characterized by their velocity and acceleration, with male agents exhibiting higher acceleration than female agents.

- **Robot**: Used to calculate the minimum travel time from the building to the safe zone. The program's default configuration (100% distribution) is used. This agent uses an optimization algorithm to find the fastest route to the safe zone, without considering realistic factors such as obstacles or other people.
- **Young**: This category encompasses individuals under the age of 50. In Pathfinder, they are further categorized into four subgroups based on their age and gender: males under 30; females under 30; males between 30 and 50; females between 30 and 50.
- **Adult**: This category includes individuals aged 50 and above. Within Pathfinder, they are classified into six subgroups based on their age, gender, and physical condition: men over 50 and women over 50 in good physical condition; men over 50 and women over 50 in average physical condition; men over 50 and women over 50 with reduced physical condition. Individuals with reduced physical condition experience a decrease in acceleration.

3.5. Scenario Construction

The agents are presented in three proposed evacuation scenarios: (i) without prior knowledge, (ii) with knowledge (evacuation strategy 1), and (iii) with knowledge (evacuation strategy 2).

In each scenario, a distribution of agents representing different situations is configured. This allows for the assessment of the need to optimize evacuation plans to determine the best proposal. The goal is to create realistic scenarios by assigning behavioral characteristics to the groups that mirror real-life conditions and incorporating cognitive variables into the agents.

I. **Without knowledge**: This scenario represents a situation in which building occupants have not received evacuation training and lack situational awareness. Additionally, they predominantly use elevators as the initial means to descend to the second floor. Upon reaching the second floor, they reassess their situation in search of an exit, primarily focusing on the main exit without considering alternative escape routes. The reaction time of each agent varies and follows a logarithmic normal distribution with the following characteristics:
    - Reaction time: agents react at varying time intervals, with the highest probability of reacting at 2 s and the possibility of delayed reactions, up to a maximum of 45 s.
    - Arrival on the second floor in the main lobby: agents descend to the second floor and make their way to the main lobby.
    - Reevaluate the situation: following the same layout as described above, agents reassess their situation in search of an exit.
    - Search for a safe area: primarily, agents seek safety through the main exit.

II. **With knowledge**: It is assumed that individuals are aware of the emergency and have received evacuation training. Consequently, they will only resort to using the elevator in cases of extreme necessity, except for low-speed profiles.

Profiles seek the optimal exit based on their initial positions. They will not reevaluate their situation once they reach the first floor. A strategy will be implemented for the profiles with knowledge, which involves limiting elevator use and allocating percentages of people to different zones within the building.

This will result in the creation of two scenarios with different percentage distributions.

The reaction time of each agent remains like that in case (I) and follows a lognormal distribution with the following characteristics:

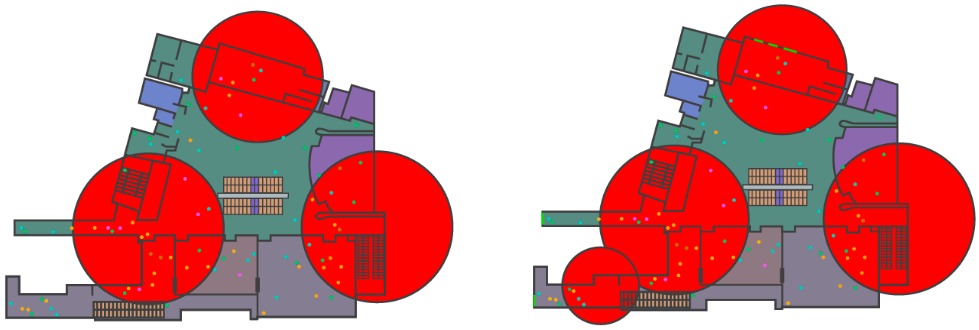
- Arrival on the first floor in the main lobby: agents select either the stairs or elevators based on their physical condition.
- Safe zone search: the agents, equipped with their knowledge of the building and the evacuation plan, select the most appropriate exit to reach the safe zones (Table 2).

Table 2. Distribution of the number of agents by strategy.

Areas	(ii) Strategy 1	(iii) Strategy 2
North	333	166
Center	333	499
South	-	167
Emergency	333	167

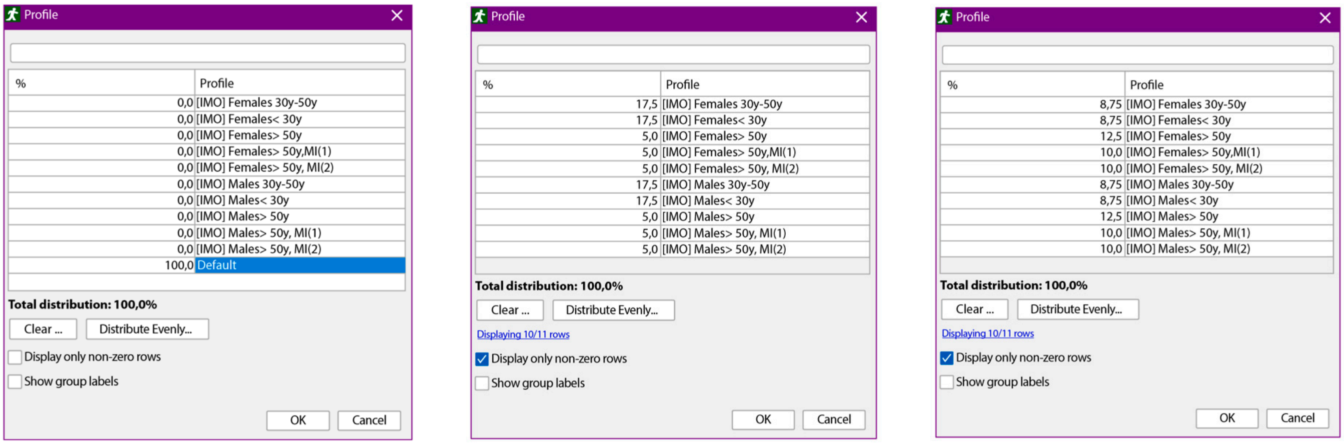
To achieve the distribution of agents as shown in Table 2, movement zones were configured on the first floor (Figure 4).

The simulation was carried out in each scenario with a distribution of 70% evaluated agents and 30% unevaluated agents. This ratio ensures a realistic simulation, as there is not only one type of user in an evacuation situation. Figure 5 shows the distribution of agents used in the different scenarios.



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

Figure 4. Floor view with defined exit zones. (**a**) corresponds to the distribution of the first strategy, and (**b**) shows the zones defined for the second strategy.



%	Profile
0,0	[IMO] Females 30y-50y
0,0	[IMO] Females< 30y
0,0	[IMO] Females> 50y
0,0	[IMO] Females> 50y,MI(1)
0,0	[IMO] Females> 50y, MI(2)
0,0	[IMO] Males 30y-50y
0,0	[IMO] Males< 30y
0,0	[IMO] Males> 50y
0,0	[IMO] Males> 50y, MI(1)
0,0	[IMO] Males> 50y, MI(2)
100,0	Default

Total distribution: 100,0%

☐ Display only non-zero rows
☐ Show group labels

(**a**)

%	Profile
17,5	[IMO] Females 30y-50y
17,5	[IMO] Females< 30y
5,0	[IMO] Females> 50y
5,0	[IMO] Females> 50y,MI(1)
5,0	[IMO] Females> 50y, MI(2)
17,5	[IMO] Males 30y-50y
17,5	[IMO] Males< 30y
5,0	[IMO] Males> 50y
5,0	[IMO] Males> 50y, MI(1)
5,0	[IMO] Males> 50y, MI(2)

Total distribution: 100,0%

Displaying 10/11 rows

☑ Display only non-zero rows
☐ Show group labels

(**b**)

%	Profile
8,75	[IMO] Females 30y-50y
8,75	[IMO] Females< 30y
12,5	[IMO] Females> 50y
10,0	[IMO] Females> 50y,MI(1)
10,0	[IMO] Females> 50y, MI(2)
8,75	[IMO] Males 30y-50y
8,75	[IMO] Males< 30y
12,5	[IMO] Males> 50y
10,0	[IMO] Males> 50y, MI(1)
10,0	[IMO] Males> 50y, MI(2)

Total distribution: 100,0%

Displaying 10/11 rows

☑ Display only non-zero rows
☐ Show group labels

(**c**)

Figure 5. Distribution of percentage of agents by scenario. (**a**) Robots and (**b**) Adult and (**c**) young.

3.6. Use of the Monte Carlo Method

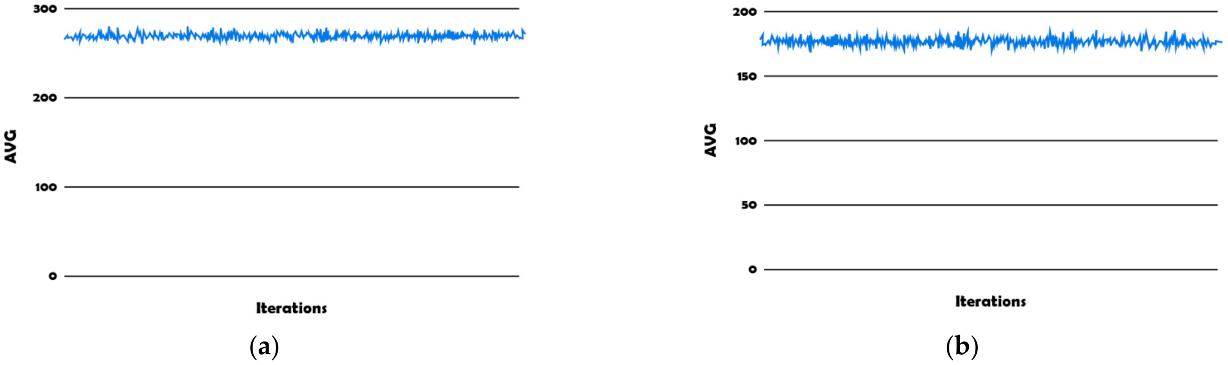
To achieve consistent results in terms of average times, the Monte Carlo method (MCM) was used. MCM allowed for the random relocation of agents within the physical environment. As a result, 500 repetitions of the simulations were conducted. This approach eliminates the possibility of interpreting the study solely based on individual behaviors.

The procedure was successfully validated, as demonstrated by the minimal variation in the mean evacuation time values across multiple repetitions. Figure 6 shows the average evacuation times for 500 repetitions with randomized agent positions.

Figure 6 shows that the dispersion and mean values of the times are nearly identical for robot and young agents. This process was executed using commands in the Windows CMD terminal. The codes were run in CMD to initiate the simulations, create the MCM data tables, and compute the meantime values for each scenario, along with their respective standard deviations (Table 3).

Table 3. Average times and standard deviations for each scenario.

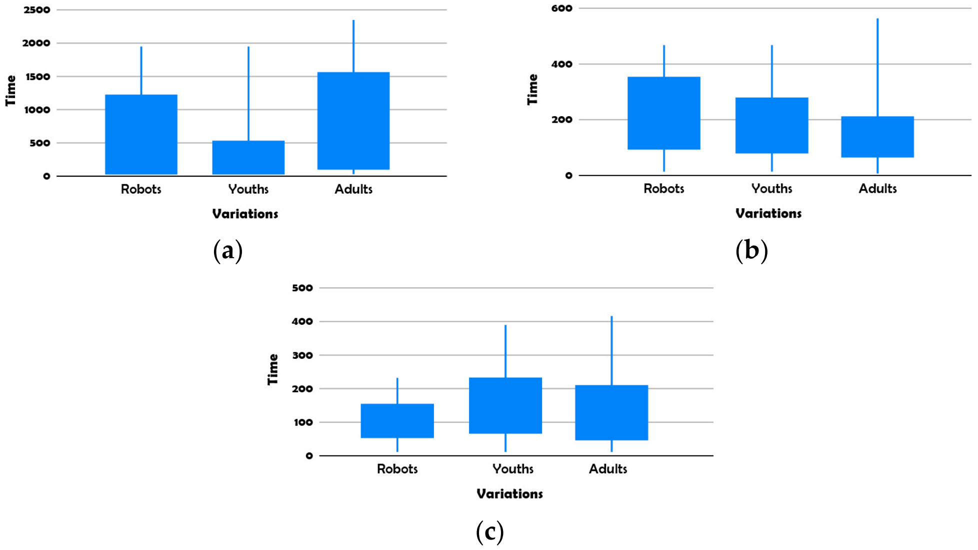
	Without Knowledge		**With Knowledge Strategy 1**		**With Knowledge Strategy 2**	
	$\bar{x}$ (s)	**σ (s)**	**$\bar{x}$ (s)**	**σ (s)**	**$\bar{x}$ (s)**	**σ (s)**
Robot	617.13	591.62	135.54	71.66	108.79	50.40
Young	263.70	243.20	176.94	100.68	146.10	75.05
Adult	818.44	719.35	219.21	125.99	160.70	82.96



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

Figure 6. Results showing the variation in average times for (**a**) robots and (**b**) young.

Figure 7 shows the box plots that allow visualization of the performance of each scenario. The unit of time is seconds.



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

Figure 7. Box plots: (**a**) without knowledge, (**b**) with knowledge of strategy 1, and (**c**) with knowledge of strategy 2.

The results presented in Table 3 and Figure 7 indicate that the average evacuation time values decrease as various strategies are implemented. This supports the assertion that people's movement is unpredictable when they lack knowledge of the environment and an evacuation plan. Furthermore, evacuation times can be significantly improved by a strategy that minimizes congestion, as reflected in Figure 7b,c, which show reductions in average times and standard deviations.

The value achieved by the robot agent in strategy 2 serves as a benchmark for the best possible evacuation time. While real people may not be able to reach that value, they can come close to it. This underscores that strategy 2 with young individuals is the most effective in terms of evacuation.

4. Results

4.1. Time Analysis

In this section, the methodology of the study involved using the tables of values generated with the Pathfinder program to conduct a statistical analysis of the correlations among several variables, including the number of remaining individuals, velocity, agent types, and time.

The analysis revealed that the number of remaining individuals was the primary variable of interest in the second-degree function. The other variables received considerably less weight.

Multiple regression for time: X1 = profile of agents, X2 = velocity of agents, and X3 = agents not yet out of the building.

Equation (2) defines the evacuation time model.

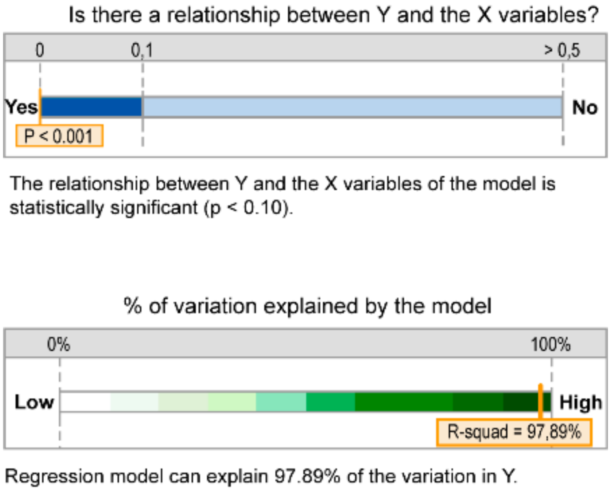
$$Time = -0.02508X3^2 + 48.88X3 - 23803 \tag{2}$$

Figure 8 shows that evacuation time is primarily determined by the number of users remaining in the building. In this model, the variables of agent type and velocity have negligible influence on the evacuation time.

A statistical analysis of the data was conducted using the Minitab tool. Multiple regression analysis identified the critical variables that influence evacuation time. The results indicated that individual velocity and agent type were not the most significant factors. Instead, the number of agents remaining in the building during evacuation emerged as the key variable. This finding underscores the importance of considering collective dynamics and group interactions in evacuation situations, rather than concentrating solely on individual factors.

Figure 8b shows an adjusted line that illustrates the relationship between time and the number of remaining agents. The curve identifies a set of points at which the agents' positions remain constant, despite the passage of time. This portion of the curve represents the residual time required for the agents to initiate the evacuation of the building. Understanding this time is crucial for comprehending the evacuation process.

The statistical analysis supports the need to examine two curves to effectively analyze different evacuation scenarios: (1) evacuation time (total duration required for all agents to exit the building) and (2) number of people leaving (count of agents vacating the building at a specific time). This statistical analysis provides insights into the factors influencing evacuation effectiveness and underscores the importance of population-based approaches for enhancing safety in emergency situations. Figure 9 displays the evacuation time curves for each scenario and agent.

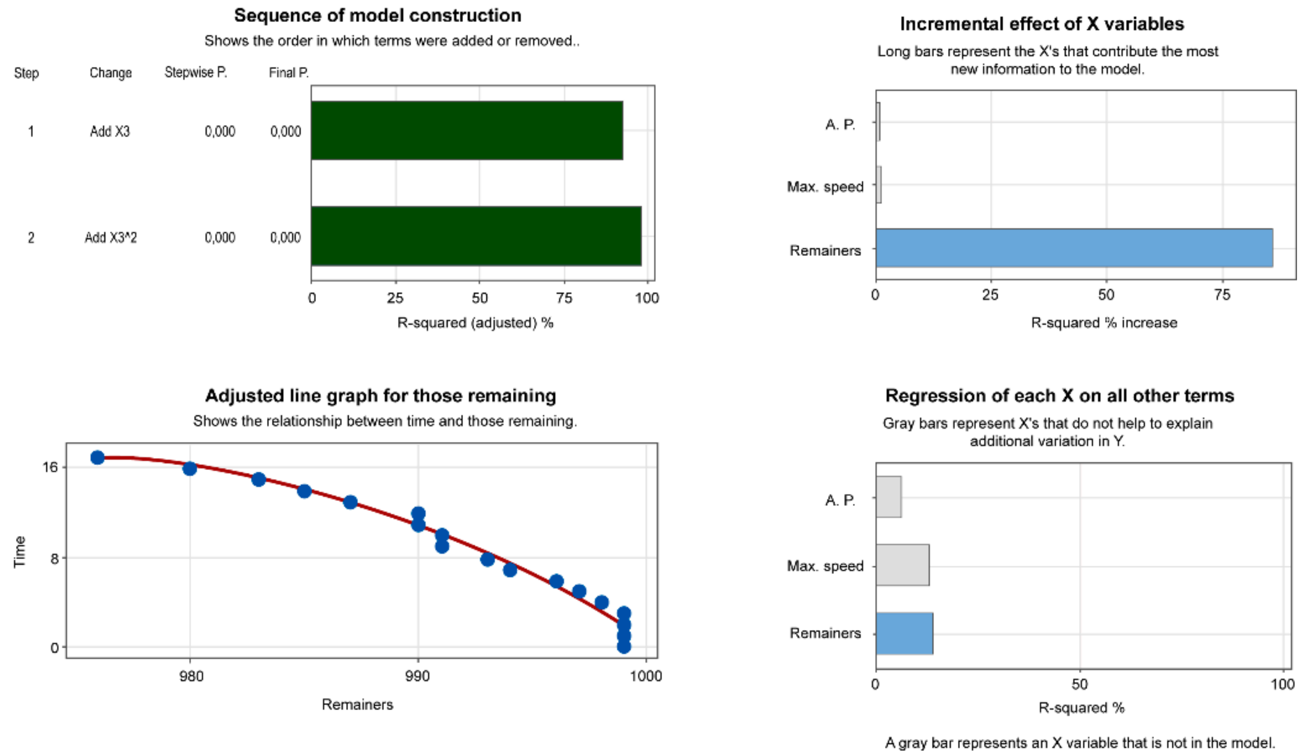


The relationship between Y and the X variables of the model is statistically significant (p < 0.10).

Regression model can explain 97.89% of the variation in Y.

(**a**)

Figure 8. *Cont.*



(**b**)

Figure 8. Multiple regression plot for the time function. (**a**) Multicriteria indices; (**b**) statistical report combining the various variables to determine the contribution of each one to the model.

Figure 9 shows that strategy 2 achieves the best evacuation times.

4.2. Heat Map Analysis

The heat maps provide insights into congestion at various evacuation points. These charts highlight specific areas that are experiencing a bottleneck of people, which is important for understanding and mitigating the risks associated with evacuations. They are color-coded, with red indicating the most congested points where the risk of injury or fatality is significantly higher. By identifying and addressing these congestion points, the efficiency of evacuation procedures can be improved.

Figure 10 displays the heat maps for the different scenarios, providing a comprehensive three-dimensional visualization of the entire building structure for each agent and proposed scenario. Despite the differences in evacuation times, the heat map graphically indicates critical points of pedestrian congestion. With this information, it is possible to generate comparisons between the three scenarios.

Figure 10 shows that strategy 2 represents the optimized solution for the evacuation plan, with no observable pedestrian congestion points.

4.3. Training Process for Improved Situational Awareness

This study uses Pathfinder software to create a detailed and precise representation of the building. The program allows for the development of a 3D model of the environment that can be explored from multiple perspectives, providing a complete 360° view. This 3D representation is essential for occupants to become familiar with the building's structure and layout, including evacuation routes, emergency exits, and other important safety features.

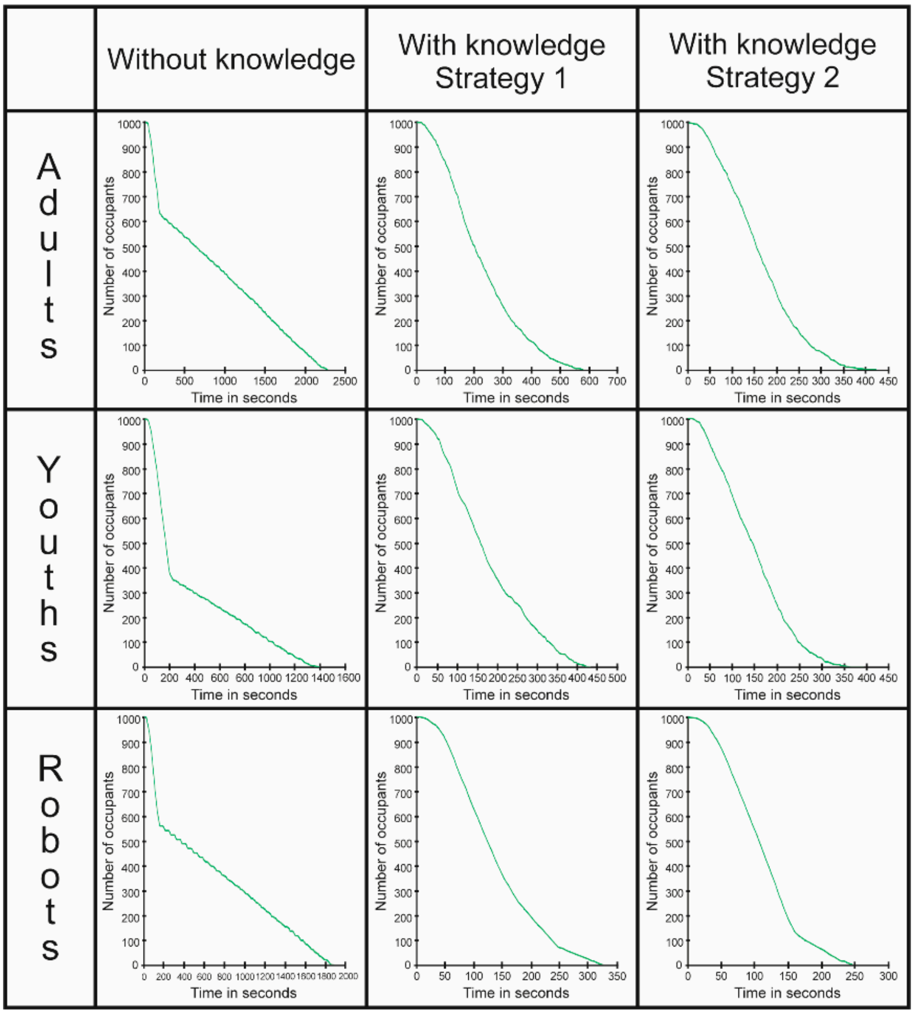


Figure 9. Evacuation time curves for each scenario.

To improve training processes, virtual reality (VR) technology is introduced. The 3D model created with Pathfinder is transferred to a VR device, allowing occupants to immerse themselves interactively and realistically in the building's virtual environment. This allows occupants to learn about the building's structure and layout, including evacuation routes, emergency exits, and other critical safety aspects.

VR training processes allow occupants to simulate evacuation situations in a safe and controlled manner. They can familiarize themselves with evacuation routes, practice various emergency scenarios, and boost their confidence in their ability to respond effectively.

The goal of this training is to improve the situational awareness of building users. By virtually experiencing the environment and emergency situations, users can gain a deeper and more realistic understanding of the actions required in the event of an emergency and learn how to evacuate safely and efficiently. The VR equipment used is the Meta Quest 2 and the Lenovo ThinkStation™ p620 server, made in China, in Taizhou City.

The platform used in this study was developed to facilitate repeated training sessions, ensuring that users attain an optimal level of situational awareness. The goal is for users to align with the profile of a knowledgeable agent, particularly in line with strategy 2. This means that users are not only aware of their environment, but they can also act effectively within it, relying on predefined strategies and acquired knowledge. Repetition and immersion are essential to achieving this goal.

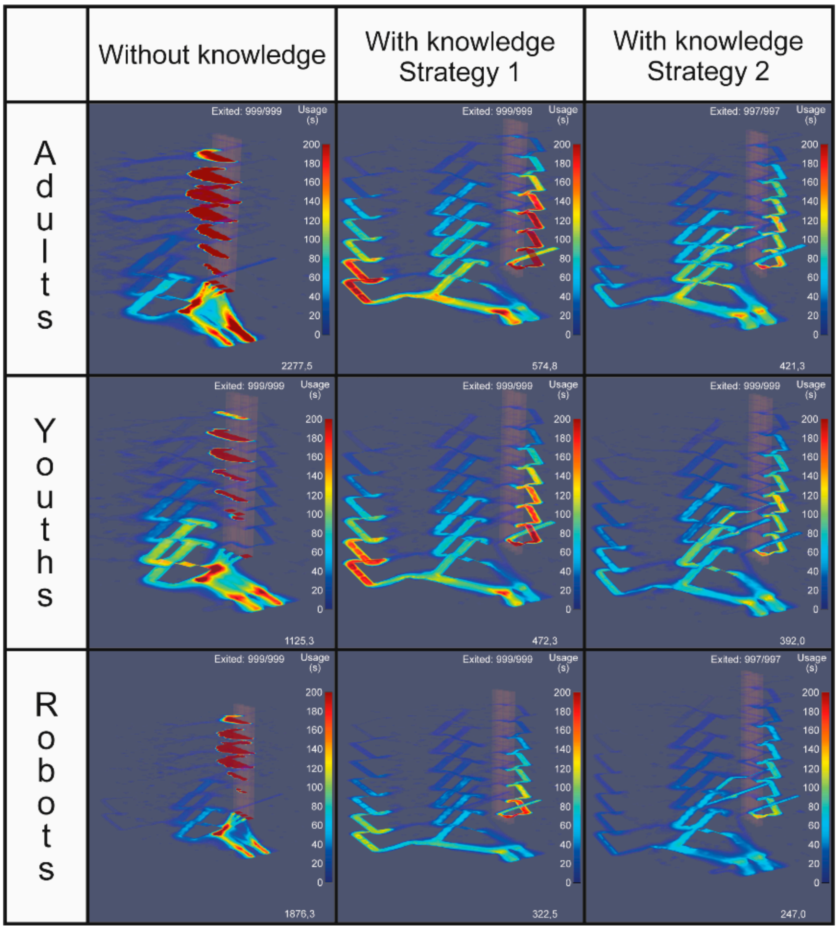


Figure 10. Heat maps for the different scenarios.

As the training process advances, evacuation time can be estimated using Equation (3). The authors of this study propose this equation to determine the optimal evacuation time through training.

$$T_{evacuation} = \%_{users-wok} T_{wok} + \%_{users-wt2} T_{wt2} \tag{3}$$

where

$T_{evacuation}$ = total evacuation time.
$\%_{users-wok}$ = percentage of users without knowledge.
T_{wok} = evacuation time of users without knowledge.
$\%_{users-wt2}$ = percentage of users with knowledge and who know strategy 2.
T_{wt2} = evacuation time of users with knowledge and who know strategy 2.

The total evacuation time is determined by summing the evacuation times of trained and untrained users. The goal is to transform all building users into knowledgeable agents that align with the profile of strategy 2. This will ensure the effective adoption and implementation of the strategy proposed in this paper, approaching the optimal evacuation time for strategy 2.

To validate the proposed approach, a series of experimental evacuation simulations is necessary. This allows for a comparison between the theoretical data obtained from all simulations and real-world results.

Figure 11 shows the comprehensive methodology for optimizing and implementing training. These seven processes enable the development of an effective evacuation plan in real-life scenarios.

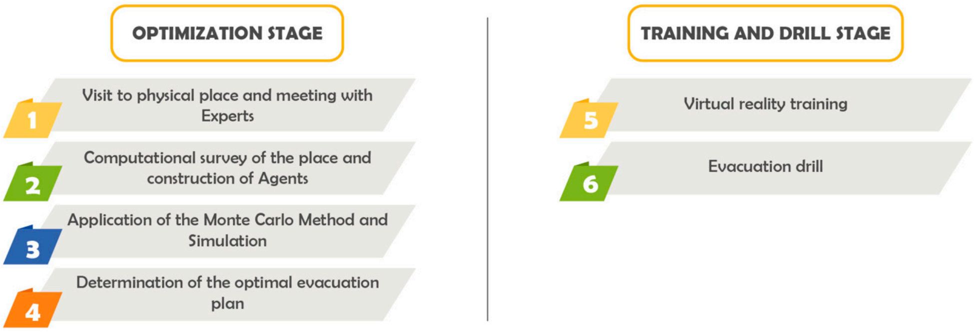


Figure 11. Comprehensive methodological proposal for modeling and simulation of evacuations in tall buildings.

A supporting video provides a visualization of the simulation of youth profile evacuations using strategy 2 within the Pathfinder program [70]. Additionally, a second video offers a 360° view of the evacuation, with the latter being integrated into a VR lens to enhance the training process [71].

5. Discussion

The methodology of this study suggests the use of simulation tools that can replicate real-world situations. To achieve this, the agents must be configured properly. Determining pedestrian velocity is essential. For this case study, empirical velocities were used in the Pathfinder program, with minimum and maximum velocities ranging from 0.37 to 1.85 m/s and different accelerations for different agent profiles. Authors such as Rafi et al. [72] provide empirical velocity values that fall within the range used in this work. However, the empirical values in [69] backed by [72] correspond to lower pedestrian flow densities than those in the simulations in this study.

A statistical analysis of the variables in Figure 8 was performed to assess and visualize their importance in the analysis of the problem. As a result, only the variable (those remaining) was used, which is reflected in the evacuation times.

MCM was used to analyze three scenarios: (i) without knowledge, (ii) with knowledge of strategy 1, and (iii) with knowledge of strategy 2. Strategy 2 showed a significant reduction in the standard deviation, indicating that it is more consistent and reliable than strategy 1. Standard deviation is an important metric for evaluating evacuation strategies, as a lower standard deviation indicates a more consistent and reliable strategy. MCM is a powerful tool for evaluating and improving evacuation strategies.

Evacuation time curves represent the duration it takes for pedestrians to exit the building. When analyzing the shape of these curves, it is evident that smoother curves, with fewer abrupt variations in their trend, indicate a more efficient evacuation strategy. This is because smoother evacuation time curves allow people to move more fluidly, reducing congestion and, consequently, evacuation time. These findings find support in the empirical research conducted by Zhang et al. [73], who studied evacuation in different types of stairways and obtained evacuation time curves similar to those in this study.

Similarly, pedestrian behavior is confirmed using heat maps where it is observed that, when simulating each evacuation strategy, there is a reduction in congestion areas. This is reflected in the decrease in the areas highlighted in red on the heat map. In addition, the heat maps show that the main flow of pedestrians is concentrated mainly in corridors, stairways, and halls. This mainly influences the initial phase of evacuation. The information provided by the time curves and heat maps confirms that they are useful tools that contribute to the search for an optimal evacuation plan.

This analysis also revealed that optimizing the evacuation plan alone does not guarantee its success. To maximize effectiveness, it is essential to complement the evacuation plan with an appropriate training program. This program should aim to improve the situational awareness of users, so that they are not only aware of their environment but can also make informed decisions within it. Through the proposed training, users become agents who not only have knowledge of strategy 2, but also understand and apply it. The combination of a well-designed evacuation plan with training that reinforces situational awareness is essential to ensure an effective response in emergency situations.

6. Conclusions

This study presents a method to develop an evacuation strategy adapted to the Teaching Innovation Rooms building of the Faculty of Engineering-USACH. This method is a valuable tool for emergency planning, as it allows for the evaluation of various scenarios and the selection of optimal options based on the specific environment.

The methodology integrates simulation tools and data analysis, using the Monte Carlo method. Evacuation simulations were conducted using Pathfinder software. Multiagent systems were used to model and predict human behavior during evacuations. These simulations can effectively identify bottlenecks, high-risk areas, and other potential issues that may not be readily apparent through a static site assessment. The agents in the simulation were carefully designed to replicate real-world characteristics of human movement within the building.

This study evaluates two distinct evacuation strategies based on the simulation data. The variables considered include emergency exit usage, recommended user capacities for evacuation routes, and elevator capabilities as they relate to agent types. Although the robot agent had the most efficient evacuation times, these results are not achievable by humans. Therefore, strategy 2, implemented with young people, is the best evacuation plan, as there was no pedestrian congestion. All pedestrians should be trained to follow strategy 2. Furthermore, it was determined that pedestrian speed and agent types are not important factors; instead, the number of people left in the building during evacuation is the most important factor.

Due to the constant threat of seismic events in Chile, it is essential to have optimal evacuation strategies supported by simulation tools. These tools offer several advantages. They can be used to virtually optimize and evaluate evacuation plans before they are implemented in the real world, and to adjust evacuation plans based on the results of previous analyses. This can help to avoid unnecessary costs and conduct simulations to compare theoretical data with real-world results. This can help to identify any necessary corrections and improve the overall efficiency of the evacuation process. Having an evacuation plan is not enough if people are not properly trained. Training is essential to familiarize people with the plan and ensure that they can respond correctly in an emergency.

VR is a recommended training tool because it provides an immersive experience that replicates the feeling of being physically present on-site. This allows people to practice evacuation scenarios in a safe and controlled virtual environment. By undergoing virtual evacuation experiences, people can become familiar with exit routes, identify potential obstacles, and improve their decision-making skills under pressure.

Signage and dynamic sensors are essential tools for improving situational awareness and enabling a more effective understanding of and response to emergency situations. These tools can help people to find their way around a building or facility in an emergency; identify the safest routes to evacuate; avoid potential hazards; and stay informed about the situation.

The development of an evacuation plan is a complex process that requires a thorough understanding of the infrastructure and particularities of the site. It is also important to involve an emergency management expert who can identify potential risks and critical areas and propose appropriate solutions and strategies.

An effective evacuation plan must be supported by robust information, professional expertise, advanced technology, and practical training. It is also important to test the plan in real-world conditions to ensure that it is effective.

As future work, it is proposed to use VR to conduct preemptive testing of sensors in emergency environments. This will improve strategies with active guidance systems. In addition, the use of simulation data to train artificial intelligence models that can assist in real-time decision making is proposed. Expanding the scope of this application to catastrophic events is very important. Lastly, we suggest incorporating additional variables, such as topography and environmental conditions, to obtain a better understanding of situations.

Author Contributions: Conceptualization, L.S.-J. and J.S.; methodology, R.T. and G.F.; validation, M.A. and J.P.S.-R.; formal analysis, M.V. and M.A.; investigation, R.T., J.S. and M.A.; writing—original draft preparation, R.T. and M.V.; writing—review and editing, J.P.S.-R. and L.S.-J.; project administration, R.T. and G.F.; funding acquisition, J.S., G.F. and M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by DICYT (Scientific and Technological Research Bureau) of the University of Santiago of Chile (USACH) and the Department of Industrial Engineering. DICYT project: Optimization of coverage and location of water reservoirs to extinction forest fires, code 062217AM.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Pal, S.C.; Saha, A.; Chowdhuri, I.; Ruidas, D.; Chakrabortty, R.; Roy, P.; Shit, M. Earthquake Hotspot and Coldspot: Where, Why and How? *Geosyst. Geoenviron.* **2023**, *2*, 100130. [CrossRef]
2. Molina-Camacho, F.; Constanzo-Belmar, J.; Inostroza-Matus, C. Desastres Naturales y Territorialidad: El Caso de Los Lafkenche de Saavedra. *Rev. Geogr. Norte Gd.* **2018**, *2018*, 189–209. [CrossRef]
3. Shin, Y.; Moon, I. Robust Building Evacuation Planning in a Dynamic Network Flow Model under Collapsible Nodes and Arcs. *Socioecon. Plann Sci.* **2023**, *86*, 101455. [CrossRef]
4. Xu, Z.; Bai, Q.; Shao, Y.; Hu, A.; Dong, Z. A Review on Passenger Emergency Evacuation from Multimodal Transportation Hubs. *J. Traffic Transp. Eng.* **2022**, *9*, 591–607. [CrossRef]
5. Amini, M.; Sanderson, D.R.; Cox, D.T.; Barbosa, A.R.; Rosenheim, N. Methodology to Incorporate Seismic Damage and Debris to Evaluate Strategies to Reduce Life Safety Risk for Multi-Hazard Earthquake and Tsunami. *Nat. Hazards* **2023**, 1–36. [CrossRef]
6. Lindell, M.K.; Perry, R.W. The Protective Action Decision Model: Theoretical Modifications and Additional Evidence. *Risk Anal.* **2012**, *32*, 616–632. [CrossRef]
7. Haghani, M.; Sarvi, M. Crowd Behaviour and Motion: Empirical Methods. *Transp. Res. Part. B Methodol.* **2018**, *107*, 253–294. [CrossRef]
8. Bakhshian, E.; Martinez-Pastor, B. Evaluating Human Behaviour during a Disaster Evacuation Process: A Literature Review. *J. Traffic Transp. Eng.* **2023**, *10*, 485–507. [CrossRef]
9. Tinaburri, A. Principles for Monte Carlo Agent-Based Evacuation Simulations Including Occupants Who Need Assistance. *RSET RiSET. Fire Saf. J.* **2022**, *127*, 103510. [CrossRef]
10. Lorusso, P.; De Iuliis, M.; Marasco, S.; Domaneschi, M.; Cimellaro, G.P.; Villa, V. Fire Emergency Evacuation from a School Building Using an Evolutionary Virtual Reality Platform. *Buildings* **2022**, *12*, 223. [CrossRef]
11. Tamang, N.; Sun, Y. Application of the Dynamic Monte Carlo Method to Pedestrian Evacuation Dynamics. *Appl. Math. Comput.* **2023**, *445*, 127876. [CrossRef]
12. Rostami, R.; Alaghmandan, M. Performance-Based Design in Emergency Evacuation: From Maneuver to Simulation in School Design. *J. Build. Eng.* **2021**, *33*, 101598. [CrossRef]
13. Cisek, M.; Kapalka, M. Evacuation Route Assessment Model for Optimization of Evacuation in Buildings with Active Dynamic Signage System. *Transp. Res. Procedia* **2014**, *2*, 541–549. [CrossRef]
14. Yang, X.; Zhang, R.; Li, Y.; Pan, F. Passenger Evacuation Path Planning in Subway Station under Multiple Fires Based on Multiobjective Robust Optimization. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 21915–21931. [CrossRef]
15. Gibbs, S.G.; Herstein, J.J.; Le, A.B.; Beam, E.L.; Cieslak, T.J.; Lawler, J.V.; Santarpia, J.L.; Stentz, T.L.; Kopocis-Herstein, K.R.; Achutan, C.; et al. Review of Literature for Air Medical Evacuation High-Level Containment Transport. *Air Med. J.* **2019**, *38*, 359–365. [CrossRef] [PubMed]
16. Chen, M.; Wu, K.; Zhang, H.; Han, D.; Guo, M. A Ship Evacuation Model Considering the Interaction between Pedestrians Based on Cellular Automata. *Ocean. Eng.* **2023**, *281*, 114644. [CrossRef]
17. Haghani, M.; Sarvi, M.; Shahhoseini, Z. Evacuation Behaviour of Crowds under High and Low Levels of Urgency: Experiments of Reaction Time, Exit Choice and Exit-Choice Adaptation. *Saf. Sci.* **2020**, *126*, 104679. [CrossRef]

18. Najmanová, H.; Ronchi, E. Experimental Data about the Evacuation of Preschool Children from Nursery Schools, Part II: Movement Characteristics and Behaviour. *Fire Saf. J.* **2023**, *139*, 103797. [CrossRef]
19. Soltanzadeh, A.; Alaghmandan, M.; Soltanzadeh, H. Performance Evaluation of Refuge Floors in Combination with Egress Components in High-Rise Buildings. *J. Build. Eng.* **2018**, *19*, 519–529. [CrossRef]
20. Sadri, A.M.; Ukkusuri, S.V.; Ahmed, M.A. Review of Social Influence in Crisis Communications and Evacuation Decision-Making. *Transp. Res. Interdiscip. Perspect.* **2021**, *9*, 100325. [CrossRef]
21. Shiwakoti, N.; Wang, H.; Jiang, H.; Wang, L. A 'Role-Rule' Model to Examine Passengers' Likely Behaviour and Their Perceived Ability to Evacuate Safely from Airport in an Emergency Evacuation. *Saf. Sci.* **2020**, *124*, 104584. [CrossRef]
22. Fu, Z.; Chen, Y.; Liu, Y.; Li, J.; Sun, C. Cellular Automaton Model for Pedestrian Evacuation Considering Impacts of Fire Products. *Fire* **2023**, *6*, 320. [CrossRef]
23. De Assis, R.F.; Guerrini, F.M.; Santa-Eulalia, L.A.; de Paula Ferreira, W. An Agent-Based Model for Regional Market Penetration of Electric Vehicles in Brazil. *J. Clean. Prod.* **2023**, *421*, 138477. [CrossRef]
24. Liu, D.; Deng, X. Investigating the Strategy on Path Planning on Aircraft Evacuation Process Using Discrete Event Simulation. *Mob. Netw. Appl.* **2021**, *26*, 736–744. [CrossRef]
25. Yuan, S.; Cai, J.; Reniers, G.; Yang, M.; Chen, C.; Wu, J. Safety Barrier Performance Assessment by Integrating Computational Fluid Dynamics and Evacuation Modeling for Toxic Gas Leakage Scenarios. *Reliab. Eng. Syst. Saf.* **2022**, *226*, 108719. [CrossRef]
26. Shang, H.; Feng, P.; Zhang, J.; Chu, H. Calm or Panic? A Game-Based Method of Emotion Contagion for Crowd Evacuation. *Transp. A Transp. Sci.* **2022**, *19*, 1995529. [CrossRef]
27. Makmul, J. A Pedestrian Evacuation Model with Leaders during the Smoke Dispersion Based on a Social Force Model. *Model. Simul. Eng.* **2023**, *2023*, 1029883. [CrossRef]
28. Wooldridge, M.; Jennings, N.R. Intelligent Agents: Theory and Practice. *Knowl. Eng. Rev.* **1995**, *10*, 115–152. [CrossRef]
29. Singh, V.K.; Modanwal, N.; Basak, S. MAS Coordination Strategies and Their Application in Disaster Management Domain. In Proceedings of the International Conference on Intelligent Agent and Multi-Agent Systems, Chennai, India, 7–9 September 2011; IEEE: Chennai, India, 2011; pp. 14–19.
30. Kaur, N.; Kaur, H. A Multi-Agent Based Evacuation Planning for Disaster Management: A Narrative Review. *Arch. Comput. Methods Eng.* **2022**, *29*, 4085–4113. [CrossRef]
31. Railsback, S.F.; Grimm, V. *Agent-Based and Individual-Based Modeling: A Practical Introduction*, 2nd ed.; Princeton University Press: Princeton, NJ, USA, 2019; ISBN 978-1-4008-4065-6.
32. Burrow, A.K.; McEntire, K.D.; Maerz, J.C. Estimating the Potential Drivers of Dispersal Outcomes for Juvenile Gopher Frogs (Rana Capito) Using Agent-Based Models. *Front. Ecol. Evol.* **2023**, *11*, 1026541. [CrossRef]
33. Kasereka, S.K.; Zohinga, G.N.; Kiketa, V.M.; Ngoie, R.B.M.; Mputu, E.K.; Kasoro, N.M.; Kyandoghere, K. Equation-Based Modeling vs. Agent-Based Modeling with Applications to the Spread of COVID-19 Outbreak. *Mathematics* **2023**, *11*, 253. [CrossRef]
34. Poledna, S.; Miess, M.G.; Hommes, C.; Rabitsch, K. Economic Forecasting with an Agent-Based Model. *Eur. Econ. Rev.* **2023**, *151*, 104306. [CrossRef]
35. Foramitti, J. A Framework for Agent-Based Models of Human Needs and Ecological Limits. *Ecol. Econ.* **2023**, *204*, 107651. [CrossRef]
36. Wijermans, N.; Schill, C.; Lindahl, T.; Schlüter, M. Combining Approaches: Looking behind the Scenes of Integrating Multiple Types of Evidence from Controlled Behavioural Experiments through Agent-Based Modelling. *Int. J. Soc. Res. Methodol.* **2022**, *25*, 569–581. [CrossRef]
37. Şahin, C.; Rokne, J.; Alhajj, R. Human Behavior Modeling for Simulating Evacuation of Buildings during Emergencies. *Phys. A Stat. Mech. Its Appl.* **2019**, *528*, 121432. [CrossRef]
38. Smaldino, P.E. *Modeling Social Behavior: Mathematical and Agent-Based Models of Social Dynamics and Cultural Evolution*; Princeton University Press: Princeton, NJ, USA, 2023; ISBN 0691224145.
39. Plikynas, D.; Miliauskas, A.; Laužikas, R.; Dulskis, V.; Sakalauskas, L. The Cultural Impact on Social Cohesion: An Agent-Based Modeling Approach. *Qual. Quant.* **2022**, *56*, 4161–4192. [CrossRef]
40. Zhang, J.; Qu, Q.; Chen, X.B. A Review on Collective Behavior Modeling and Simulation: Building a Link between Cognitive Psychology and Physical Action. *Appl. Intell.* **2023**, *53*, 25954–25983. [CrossRef]
41. Rahmani, P.; Peruani, F.; Romanczuk, P. Flocking in Complex Environments—Attention Trade-Offs in Collective Information Processing. *PLoS Comput. Biol.* **2020**, *16*, e1007697. [CrossRef]
42. Kinsey, M.J.; Gwynne, S.M.V.; Kuligowski, E.D.; Kinateder, M. Cognitive Biases within Decision Making during Fire Evacuations. *Fire Technol.* **2019**, *55*, 465–485. [CrossRef]
43. Zarboutis, N.; Marmaras, N. Design of Formative Evacuation Plans Using Agent-Based Simulation. *Saf. Sci.* **2007**, *45*, 920–940. [CrossRef]
44. Turner, J.C.; Reynolds, K.J. Self-Categorization Theory. *Handb. Theor. Soc. Psychol.* **2011**, *2*, 399–417.
45. Reicher, S. Mass Action and Mundane Reality: An Argument for Putting Crowd Analysis at the Centre of the Social Sciences. *Contemp. Soc. Sci.* **2011**, *6*, 443–449. [CrossRef]
46. Turner, R.H.; Killian, L.M. *Collective Behavior*; Prentice Hall: Englewood Cliffs, NJ, USA, 1987.

47. Ding, N.; Chen, T.; Zhu, Y.; Lu, Y. State-of-the-Art High-Rise Building Emergency Evacuation Behavior. *Phys. A Stat. Mech. Its Appl.* **2021**, *561*, 125168. [CrossRef]
48. Zander, K.K.; Nguyen, D.; Mirbabaie, M.; Garnett, S.T. Aware but Not Prepared: Understanding Situational Awareness during the Century Flood in Germany in 2021. *Int. J. Disaster Risk Reduct.* **2023**, *96*, 103936. [CrossRef]
49. Huang, Q.; Xiao, Y. Geographic Situational Awareness: Mining Tweets for Disaster Preparedness, Emergency Response, Impact, and Recovery. *Int. J. Geo-Inf.* **2015**, *4*, 1549–1568. [CrossRef]
50. Endsley, M.R. Toward a Theory of Situation Awareness in Dynamic Systems. *Hum. Factors* **1995**, *37*, 32–64. [CrossRef]
51. Salmon, P.M.; Stanton, N.A.; Young, K.L. Situation Awareness on the Road: Review, Theoretical and Methodological Issues, and Future Directions. *Theor. Issues Ergon. Sci.* **2011**, *13*, 472–492. [CrossRef]
52. Endsley, M.R. Situation Awareness Global Assessment Technique (SAGAT). In Proceedings of the National Aerospace and Electronics Conference, Dayton, OH, USA, 23–27 May 1988; IEEE: Dayton, OH, USA, 1988; pp. 789–795.
53. Townsend, P.S. Crowd Modelling for Quasi-Real-Time Feedback during Evacuation in a Situational Awareness System. *Transp. Res. Procedia* **2014**, *2*, 550–558. [CrossRef]
54. Kang, Z.; Zhang, L.; Li, K. An Improved Social Force Model for Pedestrian Dynamics in Shipwrecks. *Appl. Math. Comput.* **2019**, *348*, 355–362. [CrossRef]
55. Laurila-Pant, M.; Pihlajamäki, M.; Lanki, A.; Lehikoinen, A. A Protocol for Analysing the Role of Shared Situational Awareness and Decision-Making in Cooperative Disaster Simulations. *Int. J. Disaster Risk Reduct.* **2023**, *86*, 103544. [CrossRef]
56. Kobes, M.; Helsloot, I.; de Vries, B.; Post, J.G. Building Safety and Human Behaviour in Fire: A Literature Review. *Fire Saf. J.* **2010**, *45*, 1–11. [CrossRef]
57. Robert, C.; Casella, G. *Introducing Monte Carlo Methods with R*; Springer: New York, NY, USA, 2010.
58. Fishman, G.S. *Monte Carlo: Concepts, Algorithms, and Applications*; Springer: New York, NY, USA, 1996.
59. Dunn, W.L.; Shultis, J.K. *Exploring Monte Carlo Methods*; Elsevier: Amsterdam, The Netherlands, 2011; ISBN 9780444515759.
60. Zhang, X.; Li, X.; Hadjisophocleous, G. A Probabilistic Occupant Evacuation Model for Fire Emergencies Using Monte Carlo Methods. *Fire Saf. J.* **2013**, *58*, 15–24. [CrossRef]
61. Lovreglio, R.; Fonzone, A.; dell'Olio, L. A Mixed Logit Model for Predicting Exit Choice during Building Evacuations. *Transp. Res. Part A Policy Pr.* **2016**, *92*, 59–75. [CrossRef]
62. Zhang, X.; Chen, L.; Jiang, J.; Ji, Y.; Han, S.; Zhu, T.; Xu, W.; Tang, F. Risk Analysis of People Evacuation and Its Path Optimization during Tunnel Fires Using Virtual Reality Experiments. *Tunn. Undergr. Space Technol.* **2023**, *137*, 105133. [CrossRef]
63. Thunderhead Engineering Pathfinder Software. Available online: https://www.thunderheadeng.com/pathfinder (accessed on 15 August 2023).
64. FING-USACH Building—Teaching Innovation Rooms Faculty of Engineering. Available online: https://www.fing.usach.cl/es/noticias/facultad-de-ingenieria-inauguro-nuevo-edificio-salas-de-innovacion-docente (accessed on 14 August 2023).
65. Qin, J.; Liu, C.; Huang, Q. Simulation on Fire Emergency Evacuation in Special Subway Station Based on Pathfinder. *Case Stud. Therm. Eng.* **2020**, *21*, 100677. [CrossRef]
66. Reynolds, C.W. Steering Behaviors for Autonomous Characters. In Proceedings of the Game Developers Conference, Citeseer, San Jose, CA, USA; 1999; pp. 763–782. Available online: https://www.red3d.com/cwr/steer/gdc99/ (accessed on 2 October 2023).
67. Amor, H.; Murray, J.; Obst, O. Fast, Neat, and under Control: Arbitrating between Steering Behaviors. *AI Game Program. Wisdom* **2006**, *3*, 221–232.
68. Xiong, Q.; Zhu, Q.; Du, Z.; Zhu, X.; Yeting, Z.; Niu, L.; Li, Y.; Zhou, Y. A Dynamic Indoor Field Model for Emergency Evacuation Simulation. *Int. J. Geo-Inf.* **2017**, *6*, 104. [CrossRef]
69. Rahouti, A.; Lovreglio, R.; Dias, C.; Kuligowski, E.; Gai, G.; La Mendola, S. Investigating Office Buildings Evacuations Using Unannounced Fire Drills: The Case Study of CERN, Switzerland. *Fire Saf. J.* **2021**, *125*, 103403. [CrossRef]
70. Soto-Jancidakis, L. Simulation of the Evacuation of the Youth Profile Using Strategy 2 with Pathfinder Software. Available online: https://www.youtube.com/watch?v=bU_ZNPBqjQ8 (accessed on 25 September 2023).
71. Soto-Jancidakis, L. 360° View of the Evacuation Integrated in a Virtual Reality Lens. Available online: https://www.youtube.com/watch?v=AsrWMKT0E5w (accessed on 25 September 2023).
72. Rafi, M.M.; Ahmed, S.; Lovreglio, R.; Dias, C. Investigating a University Library Building Evacuation in Pakistan during a Semi-Announced Fire Drill. *Fire Mater.* **2023**, *47*, 693–704. [CrossRef]
73. Zhang, Q.; Yu, F.; Gao, S.; Chang, C.; Zhang, X. Experimental and Numerical Study on Rapid Evacuation Characteristics of Staircases in Campus Buildings. *Buildings* **2022**, *12*, 848. [CrossRef]