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Fire-Induced Evacuation in Concert Venues: An Agent-Based Simulation Approach Using NetLogo

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Abstract. *Ensuring the safe and efficient evacuation of large crowds from event venues is a critical aspect of public safety and emergency management. This paper presents a simulation study employing an agent-based model to analyze evacuation dynamics in a concert venue with dimensions of 68 x 53 meters and a maximum occupancy of 3,500 individuals. Recent studies in crowd evacuation have increasingly utilized computational models to simulate human behavior and optimize escape strategies, with agent-based modeling standing out as a widely applied approach to study pedestrian movement and emergency responses. Previous research has examined factors like obstacles, exit placement, and fire spread to understand their impact on evacuation efficiency. This study advances the literature by using NetLogo to simulate two distinct evacuation scenarios: (1) a normal evacuation in which individuals exit in an orderly manner, and (2) an emergency evacuation triggered by a dynamically spreading fire, influencing agent decisions and movement patterns. The simulation accounts for crowd density, movement behavior, fire progression, and individual response times, providing a comprehensive evaluation of evacuation outcomes. Results demonstrate notable differences in evacuation efficiency between the normal and fire-induced scenarios, with fire emergencies leading to increased congestion and delays caused by agent rerouting behavior. This study highlights the role of agent-based simulations in improving evacuation modeling, providing valuable guidance for venue designers, emergency planners, and safety professionals. By emphasizing strategic exit placements and responsive emergency mechanisms, the findings aim to enhance crowd safety in large venues.*

Keywords: agent-based modeling, evacuation simulation, crowd dynamics, fire emergency response, pedestrian behavior.

Introduction

Evacuating large crowds from event venues is a critical aspect of safety management. Understanding human behavior in emergency situations can help optimize building designs, exits, and emergency response protocols. Emergency evacuations, particularly in the presence of hazards such as fire, require strategic planning to minimize congestion and ensure timely egress.

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This study investigates the efficiency of evacuating a concert venue under normal conditions and in the presence of a fire. The primary research question addressed in this study is: How does the presence of fire impact the evacuation efficiency of a large concert venue, and what factors contribute to delays and bottlenecks? The main hypothesis is that fire-induced evacuations lead to significantly increased congestion and evacuation time due to panic-driven behaviors and the need for rerouting around hazardous areas.

Previous studies, such as Helbing et al. (2000) on social force models and Pelechano & Badler (2006) on crowd simulation, have demonstrated the significance of modeling pedestrian behaviors in emergency scenarios. This study builds upon these works by incorporating a dynamic fire spread model into an agent-based evacuation simulation. The approach allows for the examination of both individual and collective behaviors in response to changing environmental conditions, providing insights into the impact of fire on evacuation outcomes.

The remainder of the paper is structured as follows: the next section is dedicated to the literature review, highlighting some of the main research directions in the area of evacuation, with a particular focus on simulation of evacuation situations using agent-based models. The third section is dedicated to methodology, underlying the main characteristics of the proposed agent-based model, along with the model's interface and the metrics used for the evaluation of the model. The fourth section provides and discusses the results of the scenarios envisioned. The paper ends with concluding remarks and future directions.

Literature review

The study of evacuation dynamics has been an area of active research, with multiple approaches ranging from empirical observations to computational modeling. Various simulation methodologies, including agent-based models (ABMs), cellular automata, and social force models, have been developed to understand and optimize evacuation strategies.

Agent-based models in evacuation studies

Agent-based models (ABMs) have been widely employed in evacuation research due to their ability to capture individual decision-making and emergent crowd behavior.

Various approaches have been used in scientific literature for modeling the evacuation behavior of people. One of the most well-known approaches is represented by the social force models. Helbing et al. (2000) introduced the social force model, which simulates pedestrian movement based on attraction and repulsion forces. Pelechano & Badler (2006) expanded upon this approach by integrating psychological factors such as stress and urgency.

On the other hand, ABMs allow for detailed scenario analysis, enabling researchers to examine factors such as exit selection, congestion formation, and emergency response times (Lovreglio, 2016). Gutierrez-Milla et al. (2014) have represented the "Fira de Barcelona" pavilions using NetLogo and have determined the evacuation time by considering a large number of evacuees. Liu et al. (2016) have considered a classroom evacuation made by 28 students and have underlined the fact that the evacuation time is shortened when two exits are available and when the evacuees are following the given instructions. Faroqi and Mesgari (2015) considered the role of emotions in evacuation problems in large rooms, concluding that a particular number of agents is needed for a faster evacuation process. Furthermore, Cotfas et al. (2022) have used ABM and NetLogo in order to simulate the evacuation rom large event halls, highlighting the importance of agent-based simulations in identifying the main factors that can contribute to prolonging the evacuation process. Almeida et al. (2012) have used NetLogo for implementation of evacuation scenarios. Evacuation from collaborative rooms has been studied by Delcea et al. (2020), showing that different configurations of desks within a collaborative room have influence on evacuation time. Also, the desk and doors placement within rooms have been proved to have an influence of the evacuation time (Delcea, Cotfas, Bradea, et al., 2020; Delcea et al., 2019).

Fire and evacuation modeling

Fire emergency evacuation modeling incorporates additional complexities, such as smoke spread, heat effects, and panic-induced behaviors. Studies by Gwynne et al. (1999) and Kobes et al. (2010) highlighted how fire dynamics significantly alter human movement patterns. Evacuees tend to avoid fire zones and smoke-filled areas, leading to congestion at alternative exits. Korhonen et al. (2005) propose advancements in pedestrian evacuation modeling by integrating fire dynamics with agent-based movement simulations, highlighting the need for improved computational techniques to enhance the accuracy of emergency planning and fire safety assessments.

The role of venue design in evacuation efficiency

Building design and layout play a crucial role in determining evacuation outcomes. Research by Kirchner & Schadschneider (2002) and Moussaïd et al. (2011) suggests that the number and distribution of exits, corridor width, and placement of obstacles influence evacuation flow rates. Studies have shown that venues with evenly distributed exits and clear egress routes experience faster evacuation times compared to those with poorly placed exits and bottlenecks (Kobes et al., 2010).

Influence of human behavior on evacuation

Evacuation behavior is influenced by psychological and social factors. Studies indicate that individuals do not always behave rationally during emergencies. Panic, herding behavior, and familiarity with the environment significantly impact evacuation efficiency (Helbing et al., 2000). Additionally, leadership and trained personnel can help guide evacuees and improve response times (Pelechano & Badler, 2006). Moussaïd et al. (2011) demonstrated that pedestrian interactions and decision-making heuristics can either accelerate or hinder evacuation processes.

Evacuation strategies and optimization techniques

Recent studies have explored advanced evacuation strategies, including real-time adaptive routing and AI-driven decision-making. Lovreglio et al. (2016) reviewed the use of optimization algorithms to identify the most efficient escape routes under varying conditions. Machine learning techniques have been applied to predict congestion points and suggest alternative paths dynamically. Research in this area continues to evolve, aiming to enhance real-world emergency preparedness and reduce casualties in large-scale evacuations.

This literature review establishes the foundation for the present study by highlighting key advancements in evacuation modeling, fire dynamics, and human behavior analysis. By integrating these insights, this research aims to contribute to the ongoing development of effective evacuation strategies through agent-based simulations.

Methodology

Simulation environment

The concert venue is modeled as a rectangular space measuring 68 meters by 53 meters, with a maximum occupancy capacity of 3,500 individuals. The layout is designed to closely reflect real-world venues, with multiple entry and exit points strategically positioned across the venue. The venue is designed to scale with a detailed set of parameters for crowd movement and emergency behavior, incorporating features that represent both the physical space and its usage during an event.

To accurately replicate crowd movement and emergency evacuation scenarios, the venue layout includes several key elements:

Obstacles: These include dining areas, barriers, and stage structures, which influence agent movement patterns by blocking paths and forcing rerouting. The obstacles are positioned based on typical venue designs, with a central stage and standing arrangements that extend throughout the venue.

Exits: Multiple exits are strategically placed around the perimeter, each with varying capacities. These exits are critical in the simulation as they determine the efficiency of crowd flow during an evacuation.

Fire propagation: In the fire-induced evacuation scenario, a simulated fire spreads dynamically across the venue, creating additional barriers that force agents to adjust their movement paths. The fire propagation is modeled to increase in intensity over time, impacting the behavior and decision-making of the agents.

The venue's physical characteristics and obstacle placements are based on realistic designs commonly seen in large concert venues, but simplified for the sake of simulation. Specific agent behavior and interactions with the environment are modeled using an agent-based framework.

Figure 1 presents the user interface (UI) of the evacuation simulation model developed in NetLogo (Wilensky & Rand, 2015). The interface allows users to configure various environmental and population parameters to analyze different evacuation scenarios.

The central area of the interface displays the simulated environment, which represents the layout of a venue with key elements such as exits, obstacles, and emergency points. Users can visually monitor the real-time progression of the simulation through dynamic indicators, including: a graph of evacuees, displaying the number of people evacuated over time, categorized by age groups and mobility; live counters for the number of people present in the simulation, segmented by adults, seniors, children, and individuals with disabilities; evacuation time tracker, monitoring the duration required for a complete evacuation; and fatality counter, indicating the number of casualties in the event of a hazardous scenario.

Users can customize population demographics by adjusting sliders that determine the percentage of children, elderly individuals, and people with disabilities present in the venue. The inclusion of obstacles (such as food courts, storage areas, and health points) can be toggled on or off, adding complexity to the evacuation process.

A key feature of the model is the ability to control exit accessibility, allowing users to set doors as fully open, half-open, or completely closed to simulate various emergency conditions. Additionally, users can customize the color scheme of different elements within the environment for better visual clarity.

The right panel of the interface contains fire-related controls, where users can specify the starting location of a fire and enable randomized fire behavior. This feature directly impacts evacuation patterns by influencing route selection and movement dynamics.

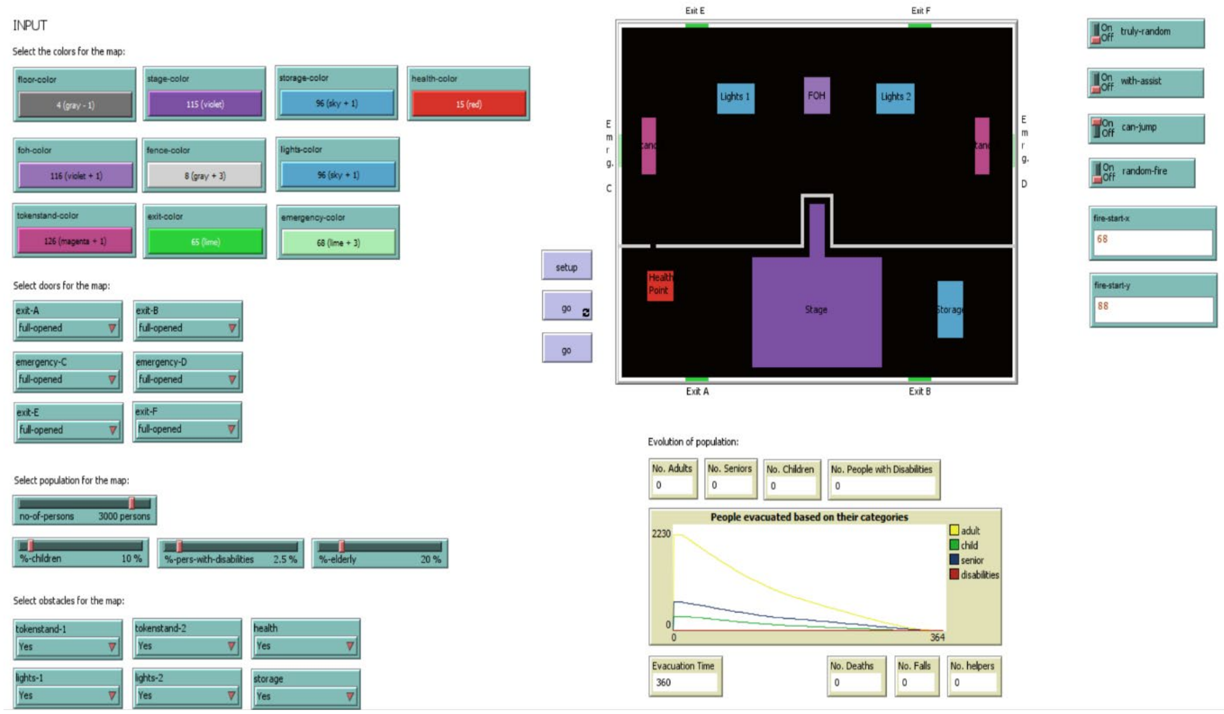

Figure 1. The model's user interface

Source: Authors' own research.

By integrating real-time monitoring with an array of customizable parameters, this NetLogo simulation provides a flexible and interactive platform for analyzing evacuation dynamics under diverse conditions.

Agent-based model

In this study, we employ an agent-based model (ABM) to simulate the behavior of individuals (agents) within the venue during an evacuation. The model operates on the principle that agents make decisions based on their local environment and predefined behaviors, rather than relying on a central controller. Each agent represents a single individual within the crowd, and their actions are driven by a set of rules that account for physical movement, social behavior, and emergency response.

Movement patterns: Agents are programmed to move through the venue in a way that reflects realistic crowd behavior. This includes walking speed, pathfinding, and jumping over obstacles, as described in the following. *Walking speed:* Agents' movement speed is influenced not only by crowd density, but also by the fire's location. The movement speed used in this model is taken from the work of Korhonen et al. (2005). Individuals adjust their walking speed dynamically, slowing down in congested areas, but increasing their speed when approaching fire-affected zones due to heat and perceived danger. This behavior can significantly impact evacuation efficiency and route selection. *Pathfinding:* Agents use a simple pathfinding algorithm to navigate through the venue, avoiding obstacles like stage structures while trying to reach the nearest exit. If fire or other barriers block a direct path, agents reroute their movement in search of alternate exits. *Jumping over obstacles:* Additionally, certain agents, specifically those categorized as adults, have the ability to jump over obstacles such as fences. This capability allows them to access alternative escape routes that are unavailable to children, seniors, or individuals with disabilities, potentially reducing their evacuation time and improving overall crowd flow.

Fire response: In the fire-induced scenario, the agents' decision-making is influenced by the spread of fire. The fire is modeled as a dynamic hazard that grows in size and intensity over time. Agents near the fire must decide whether to flee in the opposite direction, adjust their path to avoid fire-blocked exits, or wait for a safer route. These decisions are based on proximity to the fire and perceived escape routes.

Exit choice: Agents prioritize exits based on distance, visibility, and perceived safety. However, during fire scenarios, their decision-making is altered by the presence of fire hazards near certain exits, forcing them to reassess their optimal exit path.

Figure 2 depicts the simulated environment, with circle figures representing the agents that simulate the population: yellow for adults, green for children, navy for seniors, cyan for staff (which are treated as adults, but spawn in predefined areas), and red for people with locomotor impairments. The fire is shown in orange, with varying shades of orange surrounding it to represent the spread of heat. The obstacles, which include various colored areas such as red for health points and purple for the stage, are also visible. Agents navigate this environment by selecting the nearest available exit, while avoiding both the fire and its heat spread, as well as the obstacles in their path.

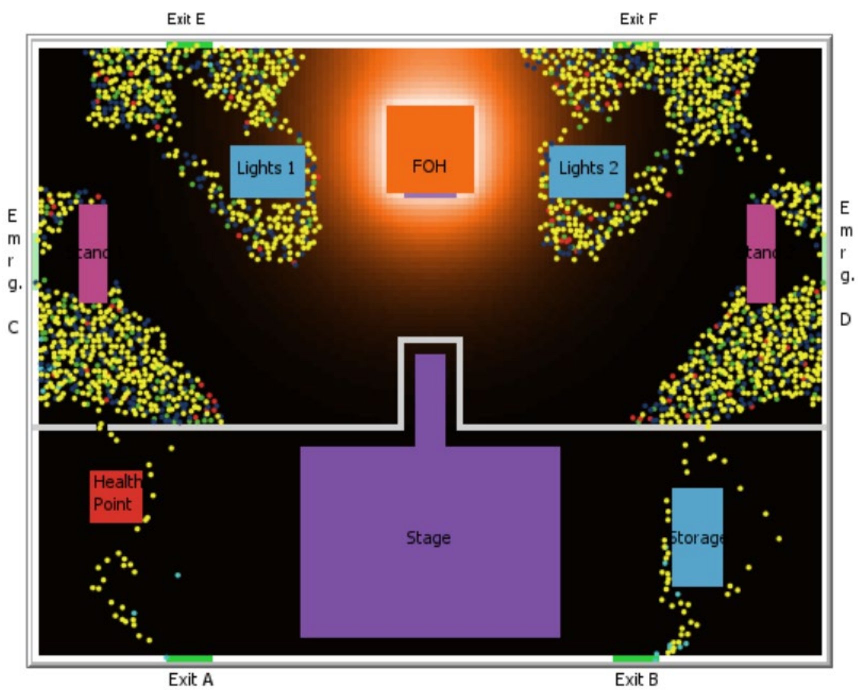

Figure 2. Simulated environment with fire spawn

Source: Authors' own research.

Fire simulation

The fire is modeled to spread dynamically within the venue, influencing evacuation paths and crowd behavior. The fire simulation is based on a grid-based approach, where each cell in the grid represents a section of the venue. The fire spreads from one grid cell to adjacent cells over time, with the spread rate influenced by factors such as proximity to fuel sources, obstacle materials and the geometry of the venue.

Key elements of fire dynamics include:

Fire spread rate: The fire spreads at a constant rate based on its current size and intensity. The spread rate can be modified by environmental factors such as the presence of fire-resistant materials (e.g., walls or barriers) and the geometry of the venue.

Fire impact on agents: As the fire spreads, agents located in or near the affected areas change their behavior. Agents may evacuate more urgently or attempt to reroute to avoid fire-blocked exits. The simulation accounts for the psychological impact of fire, including panic responses and heightened urgency, by adjusting agent speeds and movement patterns.

The fire simulation interacts with the agent-based model to create realistic emergency scenarios. This dynamic interaction between agents and fire is essential for analyzing the effects of fire on evacuation efficiency.

Metrics for analysis

The simulation runs produce data that are used to evaluate the effectiveness of evacuation strategies in the presence of fire. Key metrics include:

Evacuation time: The total time it takes for all agents to evacuate the venue (measured in seconds).

Exit availability: The status of each exit, categorized as fully opened, half-closed, or fully closed, and how these conditions affect evacuation routes.

Number of deaths (persons): The number of agents who are unable to evacuate safely due to the spread of fire, representing fatalities within the simulation.

Tools and software

NetLogo (https://ccl.northwestern.edu/netlogo/) was selected for this study due to its robust capabilities in handling agent-based modeling (ABM) and dynamic environmental interactions. The simulation framework was built using NetLogo's core functionalities, which include:

Agent definition: Agents, referred to as "turtles" in NetLogo, represent individuals within the crowd. Each agent follows specific movement rules, decision-making processes, and evacuation behaviors based on real-world crowd dynamics.

Environment representation: The concert venue is modeled as a grid-based environment (also called "patches" in NetLogo), where each grid cell represents a portion of the venue. Obstacles such as food courts, barriers, and the stage are implemented as immovable patches that restrict agent movement, while exit locations are designated as patches with specific properties that allow agents to transition out of the simulation.

Agent behavior and decision-making: Each agent continuously evaluates the shortest path to an exit based on a pathfinding algorithm and local movement heuristics. In normal evacuations, agents follow direct paths to exits, while in fire-induced evacuations, they adapt their behavior based on fire spread, congestion, and perceived risks.

Fire propagation module: Fire is simulated and spreads from one patch to adjacent patches based on predefined probabilities. The rate of fire spread depends on environmental conditions. Agents dynamically respond to fire hazards by altering their movement paths and adjusting their decision-making priorities.

Results and discussions

The simulation results provide valuable insights into how fire influences evacuation times and casualty rates, highlighting the complex interplay between environmental hazards, human behavior, and infrastructure accessibility.

To analyze the impact of fire on evacuation efficiency, the study employed two primary scenarios: *Scenario 1* – Evacuation without fire, and *Scenario 2* – Evacuation with fire.

Each of these scenarios was further divided into three sub-scenarios, depending on the availability of exits. The objective was to examine how different levels of exit accessibility influence evacuation times and casualty rates, both in normal conditions and under the presence of fire.

To ensure consistent and reliable results when comparing the two scenarios (with fire and without fire), the number of agents remains fixed at 3,000 people, and the distribution of age and mobility is consistent (10% children, 2.5% persons with disabilities or locomotor impairments, and 20% seniors, the rest being adults). Obstacles are identical across both scenarios, and all adults are capable of jumping over them. The fire is always spawned in the same location (in the front house, where the sound engineers are present with a lot of equipment), and the spawning of people is done in the same manner each time. The only variable element between the scenarios is the modification of the exits.

The first scenario, Scenario 1 – Evacuation without fire, represents an idealized emergency evacuation where no fire is present, meaning evacuees can move freely toward the available exits without external hazards obstructing their path. It serves as a baseline to compare against fire-affected conditions. The following sub-scenarios were tested:

Scenario 1.1 – All exits are open: This situation represents the optimal evacuation condition, where all exits remain accessible, allowing for a smooth and evenly distributed flow of evacuees. The evacuation time recorded in this scenario was 360 seconds, with zero casualties.

Scenario 1.2 – All emergency exits are half-closed: In this case, some emergency exits were only partially available, simulating situations where structural damage, locked doors, or overcrowding could limit access. The reduced number of functional exits caused a slight increase in congestion, leading to a moderate increase in evacuation time to 370 seconds, but no fatalities were recorded.

Scenario 1.3 – All emergency exits are closed: This sub-scenario represents a worst-case non-fire emergency, where emergency exits are completely inaccessible, forcing evacuees to rely on main exits only. The evacuation time increased significantly to 452 seconds, indicating that blocked exits substantially hinder escape efficiency. However, no casualties occurred, as individuals still had sufficient time to evacuate through the remaining available routes.

Simulation results are presented in Table 1.

Table 1. Evacuation times in Scenario 1

Scenario	*Exit availability*	*Evacuation time (seconds)*	*Number of deaths (persons)*
Scenario 1.1	All exists are open	360	0
Scenario 1.2	All emergency exits are half-closed	370	0
Scenario 1.3	All emergency exits are closed	452	0

Source: Authors' own research.

The second scenario, Scenario 2 – Evacuation with fire, introduces a fire outbreak, which spreads dynamically within the environment, affecting evacuees' movement and decision-making. Fire serves as both a physical barrier and a psychological stressor, leading to increased congestion, rerouting, and panic-induced inefficiencies in movement. The fire was set to spread at a rate of one patch (0.5m in real life) per 10 seconds, forcing individuals to quickly adjust their evacuation strategy. The sub-scenarios in this category assess the combined impact of fire and exit restrictions on evacuation time and survival rates.

Scenario 2.1 – All exits are open: Despite the presence of fire, all exits remain fully functional, allowing evacuees to reach safety more efficiently. Fire introduces an increase in evacuation time to 575 seconds, marking a 59.7% rise compared to the equivalent non-fire scenario (Scenario 1.1, 360 seconds). A total of six casualties (0.2% of the population) were recorded, due to individuals being trapped in fire-affected zones before reaching the exits.

Scenario 2.2 – All emergency exits are half-closed: With fewer exits available, evacuees were forced to navigate longer distances or use more congested routes. The evacuation time increased slightly to 582 seconds, with five casualties recorded, indicating that even partial exit closures can exacerbate the dangers posed by fire.

Scenario 2.3 – All emergency exits are closed: This case represents the most extreme and hazardous scenario, where all emergency exits are blocked while fire spreads throughout the environment. The evacuation time extended drastically to 670 seconds, as individuals struggled to find viable escape routes. The fatality rate was alarmingly high, with 1,398 deaths (46.6% of the population), demonstrating the devastating impact of restricted exits in fire emergencies. Congestion and lack of alternative escape paths contributed to this significant loss of life.

Simulation results are presented in Table 2.

Table 2. Evacuation times in Scenario 2

Scenario	***Exit availability***	***Evacuation time (seconds)***	***Number of deaths (persons)***
Scenario 2.1	All exists are open	575	6
Scenario 2.2	All emergency exits are half-closed	582	5
Scenario 2.3	All emergency exits are closed	670	1398

Source: Authors' own research.

A comparative analysis of Scenario 1 (without fire) and Scenario 2 (with fire) reveals substantial differences in evacuation efficiency, underscoring the critical role of exit availability and fire propagation in emergency situations. In fire-free conditions, evacuation times remained relatively stable, with only moderate increases when exits were partially or fully restricted. However, once fire was introduced, the evacuation process was severely impacted, leading to increased delays and, in extreme cases, catastrophic loss of life. The presence of fire not only obstructed direct evacuation routes but also heightened psychological stress and panic, which may have contributed to inefficient movement patterns and congestion at exits. The results emphasize the urgent need for robust evacuation planning, improved public awareness, and enhanced fire safety measures to mitigate risks in real-life emergency scenarios.

The presence of fire consistently increased the time required for evacuation across all sub-scenarios. In the best-case fire scenario (Scenario 2.1, all exits open), the evacuation time was 575 seconds, compared to 360 seconds in the corresponding no-fire scenario (Scenario 1.1). This represents a 59.7% increase in evacuation time, highlighting the substantial delays caused by fire-related obstacles, congestion, and panic.

The availability of emergency exits played a decisive role in evacuation efficiency and survival rates. In the scenario where all exits remained open, the number of casualties was minimal (six fatalities in Scenario 2.1). However, when all emergency exits were closed (Scenario 2.3), the evacuation time increased to 670 seconds, and fatalities rose dramatically to 1,398 deaths (46.6% of the total population). This demonstrates that blocked exits in fire emergencies can lead to catastrophic outcomes.

Even partial closures of emergency exits resulted in longer evacuation times. In the no-fire condition, blocking half of the emergency exits (Scenario 1.2) increased evacuation time by 10 seconds compared to having all exits open. In the fire condition, partial closures (Scenario 2.2) led to a small but noticeable increase in evacuation time (582 seconds) and five fatalities. These results indicate that any restriction on exit accessibility can have significant consequences, particularly in emergency situations involving fire.

The increased evacuation times and fatalities observed in fire scenarios suggest that fire-induced panic, combined with limited escape options, significantly disrupts orderly evacuation. Individuals are forced to reroute, avoid hazardous zones, and navigate through bottlenecks, which can slow movement and increase the risk of being trapped. The findings emphasize the need for well-planned, clearly marked evacuation routes and structured emergency drills to minimize confusion and delay.

Although some casualties were unavoidable in fire scenarios, better emergency planning, clear evacuation instructions, and proper infrastructure could greatly reduce fatalities. Implementing frequent evacuation drills, increasing public awareness, and ensuring that emergency exits remain accessible at all times are critical steps in improving survival outcomes in real-life fire incidents.

These findings underscore the importance of fire safety regulations, well-maintained evacuation infrastructure, and efficient emergency response strategies in ensuring public safety during evacuation scenarios.

Conclusion

This study presents a detailed analysis of fire-induced evacuations in concert venues through an agent-based simulation approach using NetLogo. By modeling a 68 × 53-meter venue with a capacity of maximum 3,500 individuals, the research highlights the significant impact of fire on evacuation efficiency, leading to increased congestion, rerouting behavior, and prolonged escape times. The findings underscore the importance of strategic exit placement, fire safety protocols, and crowd management strategies to enhance emergency preparedness in large venues.

The study contributes to evacuation modeling and emergency planning by integrating fire spread dynamics into agent-based simulations, offering valuable insights for venue designers, emergency responders, and policymakers. By identifying key evacuation challenges, the research provides practical recommendations for optimizing exit locations and availability, fire drill strategies, and smart evacuation systems. Additionally, the results support the development of real-time guidance technologies to enhance crowd safety.

Despite its contributions, the study has certain limitations. The simulation assumes rational decision-making, whereas real-world evacuations often involve panic, hesitation, and social influence. Additionally, fire spread modeling does not account for factors such as smoke visibility, heat effects, or ventilation systems, which could influence evacuation behavior. Furthermore, while the findings are based on simulated scenarios, real-world validation through historical case studies or live evacuation drills would strengthen the model's applicability.

Looking ahead, future research should explore AI-driven evacuation strategies, adaptive multi-agent coordination, and the integration of real-time environmental sensors to improve emergency response systems. By leveraging advanced simulation techniques, this research paves the way for more effective fire safety planning and disaster preparedness, ultimately contributing to safer large-scale events and public spaces.

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