# Fire Evacuation Simulation using Agent-Based Modelling

Martin Mitanoski (23385544) Kyle Dunstall (23616029)

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## 1 Introduction

Building fires are unpredictable and often chaotic, making it useful to understand how people behave during evacuations. Since real-world testing is risky and not really practical, computer-based simulations offer a safe way to study how factors like building design, exit placement, and fire spread affect evacuation outcomes.

This project develops an agent-based fire evacuation simulation built with Pygame. The program is designed to allow users to construct their own building layouts by placing walls, exits, and people on a 2D grid. Each person in the simulation is represented as an agent with customizable attributes such as age, movement speed, and panic level, allowing for realistic and varied behaviours. Fire and smoke spread dynamically from a user-chosen location, determining from where the fire will spread as agents attempt to reach the nearest exit.

The aim of this project is to explore how spatial design and individual differences affect evacuation efficiency. By adjusting parameters such as fire location, the number of people, and building layouts, the simulation can reveal how these variables interact in complex ways. In general, the project aims to demonstrate how an agent-based model can recreate realistic evacuation dynamics and provide insights into how people respond under emergency conditions. A tutorial on how to use our model can be found in our notebook file inside the **repo**.

## 2 Background and Related Work

Modeling fire evacuation in buildings requires combining models of human movement, decision-making under stress, and dynamic hazardous environments with fire and smoke. In this section We review and discuss key prior works relevant to our design goals, particularly agent-based and hybrid models that allow variation in individual attributes, which also integrate fire/smoke effects.

### 2.1 Crowd Dynamics & Panic Behavior

One major study in crowd and evacuation dynamics is Helbing, Farkas & Vicsek (2000) models panic as a collective phenomenon that emerges when individuals under stress begin to move faster, push others, and compete for limited exit space [1]. Treating each person as a "self-driven particle" subject to social and physical contact forces, they demonstrated the "faster-is-slower" effect: when desired walking speed exceed 1.5m/s coordination breaks down, producing clogging and reducing overall evacuation efficiency. Their simulation also showed that herding behaviour causes agents to over-crowd single exits, while excessive individualism leads to aimless wandering; optimal escape requires a balance of both individualism and herding behaviour.

In our project we'll adapt similar panic modelling to trigger new behaviours like agents moving the wrong way, clustering poorly, or even collapsing and becoming obstacles that other agents will have to deal with, causing potential crushing. We also plan to simulate how panic impacts coordination and crowd flow, hoping to observe the same "faster-is-slower" effect where rushing decreases efficiency.

### 2.2 Agent-Based + Fire / Smoke Coupling

Korhonen et al. (2010) modelled advanced agent based evacuation by including human movement with real fire and smoke dynamics inside the Fire Dynamics Simulator (FDS) [2]. Each agent has individual mass, speed, and familiarity with exits. This study links movement to the environment involving smoke concentration, temperature, and toxic gases which dynamically alter visibility and walking speed. Experiments based on real world geometries showed rising smoke density can reduce walking speed to below 0.8m/s while toxic gases eventually incapacitate agents who then become obstacles.

While our model will be simpler and built in Pygame rather than CFD-based, we plan to adapt several ideas and replicate the key principles of environment-agent interactions, such as smoke and fire spread, which will reduce visibility and increase panic. This will result in slow movement and influence the agent's path selection. Agents will individually decide which exit to pursue based on proximity, sometimes choosing inefficient routes when panicked. We also plan on simulating incapacitation similar to their model, where those who have spent a specific amount of time in smoke stop moving, becoming obstacles. The purpose of this is to make our model more hazardous and more realistic, allowing us to observe how environmental stress shapes evacuation outcomes.

### 2.3 Evacuation Modelling Incorporating Age and Individual Characteristics

Studies have demonstrated the need for age-sensitive evacuation models. Research on elderly-care facilities using agent-based methods to capture how reduced mobility, slower reaction times, and dependency on staff impact escape efficiency [3]. Their work quantified speeds and pre-evacuation delays across self-sufficient, semi-disabled, and disabled adults, showing how assistance and room layouts affect evacuation time. By using realistic movement parameters such as reducing walking speed for older adults (between 0.6 m/s and 1.3 m/s) and representing "waiting for assistance" states, their framework demonstrated that differing age groups change crowd flow and congestion [3]. Another study extended this to rescue scenarios in senior residences, adding evacuee-rescuer interactions with algorithic wayfinding and invididual delay times [4].

Each of these studies provides valuable insights that can be applied to our project such as agents having varying ages, movement speeds, and panic thresholds. Specifically, this will help us understand how differing age groups will affect the other attributes of the agent, such as speed, vision, or pathfinding. We plan to simulate secondary behaviours such as disorientation (walking the wrong way), falling (immobilized agents acting as obstacles), and crowd crushing when multiple agents converge in tight spaces.

Our overall goal is to build a realistic, agent-based evacuation simulation that brings ideas from several study areas we've looked at. By combining ideas from crowd dynamics, fire-smoke interactions, and individual variability, such as age and mobility, we aim to create a system that mirrors how people actually behave under pressure while exiting a building. This will allow us to measure outcomes such as how many people successfully evacuate, how long it takes, and how different conditions affect overall survival and evacuation efficiency.

## 3 System Description

The purpose of our model is to simulate an agent-based fire evacuation scenario within a two-dimensional grid environment. Each cell in the grid represents a section of the map, and agents attempt to reach the nearest exit while navigating an environment affected by fire, smoke, and heat. The simulation progresses using time steps (ticks) in which fire and smoke spread, temperature diffuses, and agents move according to behavioural rules that attempt to get them closer to an exit. The purpose of this model is to analyze how factors like panic level, the speed of agents, and building layouts influence evacuation efficiency and the amount of casualties/injuries. A major part of our investigation was testing different building layouts to see how spatial configurations affect the outcomes.

The environment is represented as a grid where each cell can be empty, a wall, an exit, fire, or smoke. Fire and smoke behave dynamically, fire spreads more slowly, and smoke spreads faster through the nearby cells. Also, temperature is tracked in cells, which changes over time using a simplified finite difference diffusion process. This approach models conductive and radiant heat transfer from nearby fire tiles while allowing for cooling toward the lower temperatures. Walls act as insulators by significantly reducing heat transfer, while fire cells are fixed at 600°C. This provides realistic environment dynamics without adding unnecessary complexity.

Agents are placed manually throughout the map, or they can be added in through pre-loaded layouts and represent individuals attempting to escape. Each agent occupies a single cell and has attributes such as speed, panic level, and health state. An agent's health status progresses through the stages of Healthy, Injured, Fatally Injured, and Incapacitated, depending on their exposure to heat, smoke, and fire. Agents keep track of their exposure to fire and smoke, which accumulates over time. Randomness is introduced through each agent's panic scale, which increases the likelihood of them moving randomly as their panic level rises. This feature adds realism, reflecting how in real-life emergencies, people may panic, hesitate for friends, make poor decisions, or stumble when trying to escape.

Hazard behaviour follows guidance from ISO 13571 [5]. Heat thresholds were derived from ISO 13571 Equation 10 which calculates incapacitation time as $t_{\text{Iconv}} = (5 \times 10^7) \times T^{-3.4}$ minutes. The model implements three-stage injury progression, non-fatal injury (∼33% of incapacitation time), fatal injury (∼67% of incapacitation time) and full incapacitation which is a simplified assumption for modelling purposes but aligns with the ISO's documented thermal tolerance data. For simplicity the model assumes dry air, increased moisture content would greatly reduce time to incapacitation due to respiratory tract burns occuring at much lower temperatures.

Smoke inhalation thresholds were informed by the ISO's fractional effective dose model for asphyxiant gases. The implementation assumes post-flashover fire conditions (8000ppm CO, 8% $CO_2$, 150 ppm HCN). Based on these assumed conditions an ISO FED accumulation rate of 4.51 per minute was calculated leading to theoretical incapacaitation within ∼13 seconds. The simulator implements a threshold of 4 ticks which at 10fps correlates to roughly 24 seconds which is a conservative threshold, fatal and non-fatal injury ticks are calculated as discussed above giving 3 ticks to fatal injury and 2 ticks to injury.

Direct flame exposure is implemented as an immediate fatality as ISO 13571 Equation 10 with assumed 600 degree Celsius fire temperature provides a theoretical time to incapacitation of approximately 0.0009 seconds, this is effective grounds to assume immediate incapacitation can be safely assumed from direct exposure to the fire before even considering additional radiant heat burns and respiratory tract damage.

Before the simulation begins, a Breadth-First Search (BFS) algorithm is used to generate a distance map from every cell to the nearest exit. This map is then used throughout the simulation to allow agents to identify which adjacent cell moves them closer to safety each tick.

Movement is limited to the four cardinal directions, and only one agent can occupy a cell at a time. Because of this, when multiple agents try to occupy the same cell, one is chosen at random to proceed while the others stay in place for that tick, representing crowding congestion and hesitation. Not only that, but exits have a set capacity per tick, so only a limited number of agents can pass through while others queue around the exit. Panic is implemented as a probability factor for agents' movement. Each agent has a panic value between 0 and 10, which is divided by 10 to give a probability between 0 and 1. When choosing a move, if a random number between 0 and 1 is less than this probability, the agent ignores the most optimal move and instead selects a random valid neighbouring cell.

The simulation runs in PyGame with color-coded tiles showing environmental conditions. Agents change color based on their health: blue for healthy, orange for injured, red for fatally injured, and purple for incapacitated. Users can manually design or load different building layouts to test how structural variations influence evacuation times and survival rates. The program has global controls that let users adjust the panic levels and speeds of all agents at once, making it easy to test different conditions. During simulation, the HUD at the top of the screen displays live statistics such as survivors, injuries, fatalities, and casualties.

## 4 Model Design and Implementation

To analyze how building structure, mobility, and panic influence evacuations, we designed and tested three building layouts that represent different architectural conditions. Each of our layouts is stored inside a JSON configuration file and can be loaded directly into the simulation using the 'l' key with the selected design. The first layout shows a building with a Close Exits Layout, containing three exits, two of which are placed very close together, while one sits farther away. The design may appear safe with its multiple escape options, however, a fire outbreak near the grouped exits quickly makes two exits unusable. Agents are left with only a single exit, resulting in crowding effects, and highlighting the idea that poorly distributed exits can create a false sense of security.

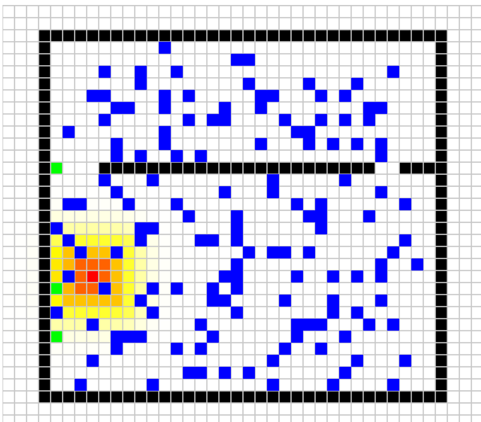

Figure 1: Close Exits layout showing clustered exits leading to congestion near shared escape routes.

The second layout is a Dense Corridor Layout, which represents a large open room leading into a single narrow corridor that contains one exit at the end. The layout highlights single-file congestion and queue formation. When the fire starts at the far end of the room, agents rush towards the only exit, resulting in clusters and stop-and-go waves as they compete for limited space. The design shows how narrow pathways restrict agents and reduce flow efficiency. This layout was particularly useful for analysing emergent crowding behaviour, showing how groups react differently when speed and panic levels change.

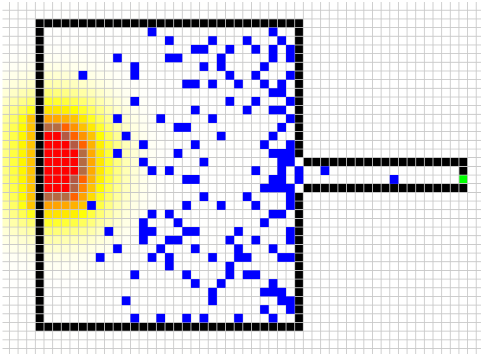

Figure 2: Dense Corridor layout showing a single narrow exit that creates strong bottlenecking and queuing effects during evacuation.

The third layout was a Maze Layout, containing many small rooms and tight turns. The purpose of this configuration was to test the model's ability to simulate confusion, misdirection, and agent interactions in highly constrained/confusing spaces. In this layout, agents often collided or blocked each other, especially at corners, showing how complex layouts can lengthen evacuation times even when multiple exits exist.

Figure 3: Maze Building layout illustrating the maze-like structure with narrow pathways and multiple turns that increase evacuation difficulty.

Across the layouts, six main experiments were conducted, which varied panic and speed parameters. Panic values ranged from 1 to 4 (the realistic bounds), while speeds ranged from 0.1 to 1.0. For the runs, a subset of agents was assigned slower speeds to represent elderly or mobility-impaired individuals. For example, in some tests, only 33% of agents moved at 0.5 while the rest moved at 1.0, and in others, up to 50% were slowed to 0.5. The purpose of varying these controls was to allow us to investigate how both behavioural (panic) and physical (speed) variations produce emergent crowd behaviours such as clustering, clogging at exits, and uneven evacuation patterns.

Each simulation uses a fixed random seed to ensure reproducibility while keeping fire-spread, smoke diffusion, and exit capacity constant. The model records agent health states, survivor counts, casualties, and total evacuation time. Results are displayed through PyGame's HUD and compared across layouts, with congestion and movement analysed visually as agents attempt to escape.

# 5 Experiments and Results

Table 1: Evacuation outcomes for six test partitions across each layout

| Panic (%) | Slow Agents | Exited | Injured | Fatal | Casualties | Time (s) |
|---|---|---|---|---|---|---|
| | | | **Close Exits** | | | |
| 2 | 0 | 137 | 2 | 0 | 13 | 9.1 |
| 2 | 75 | 129 | 4 | 1 | 21 | 12.1 |
| 3 | 50 | 121 | 3 | 2 | 29 | 13.3 |
| 3 | 75 | 123 | 1 | 7 | 27 | 14.8 |
| 4 | 50 | 113 | 3 | 4 | 37 | 23.4 |
| 4 | 75 | 113 | 7 | 3 | 37 | 25.9 |
| | | | **Maze Building** | | | |
| 2 | 0 | 140 | 0 | 0 | 10 | 16.0 |
| 2 | 75 | 142 | 1 | 0 | 8 | 19.4 |
| 3 | 50 | 130 | 1 | 0 | 20 | 24.1 |
| 3 | 75 | 132 | 4 | 0 | 18 | 23.1 |
| 4 | 50 | 117 | 3 | 4 | 33 | 33.4 |
| 4 | 75 | 118 | 7 | 1 | 32 | 32.1 |
| | | | **Dense Corridor** | | | |
| 2 | 0 | 149 | 0 | 0 | 1 | 40.7 |
| 2 | 75 | 149 | 0 | 0 | 1 | 50.2 |
| 3 | 50 | 140 | 1 | 1 | 10 | 56.7 |
| 3 | 75 | 144 | 1 | 1 | 6 | 54.4 |
| 4 | 50 | 131 | 2 | 1 | 19 | 57.1 |
| 4 | 75 | 124 | 1 | 0 | 26 | 60.3 |

The results in the table above show how evacuation outcomes changed across the three building layouts, which were Close Exits, Maze Building, and Dense Corridor, as panic levels and the number of slower agents were adjusted. Overall, increasing panic resulted in an increased number of deaths and total evacuation time. On the other hand, increasing the amount of slower agents was not always straightforward. In several runs, increasing the number of slower agents resulted in fewer casualties, reflecting the "faster-is-slower" effect where rushing behaviour decreases group efficiency.

In the Close Exits layout, which contained two exits near each other and one further away, the results showed the effects of congestion. As panic increased from 2 to 4, the total casualties increased from 13 to 37, and evacuation time almost tripled, from 9 to 25.9 seconds. As panic increased, agents made more random, non-optimal moves, which increased crowd density near the grouped exits. This led to blockages and higher fatality counts, even though the other exit remained open. Interestingly, increasing the number of slower agents from 50 to 75 did not always make things worse, in some cases the additional slower agents slightly reduced fatalities by spacing out the agents and reducing crowd pressure.

The Maze Building layout, which had a maze-like structure with small rooms and tight turns, had more varying results. Although higher panic again caused more fatalities, increasing the number of slower-moving agents once again improved survival rates. At a panic level of 2, the number of casualties dropped from 10 to 8 when 75 of 150 agents moved at half speed. This is a clear example of the "faster-is-slower" effect that we saw in the evacuation research, where individuals move too quickly, resulting in blocked pathways emerging and slowing others down. However, at higher panic levels, this benefit disappears. Once panic reaches level 4, the crowds of agents become disorganised, and agents often struggle to get through tight gaps that are clogged with other agents, leading to over 30 casualties in both runs.

The Dense Corridor layout consistently showed the highest survival rates but the longest evacuation times. With only one narrow exit and the fire being on the opposite end of the room, almost all agents eventually escaped. However, total evacuation time increased with both panic and the proportion of slower agents, from roughly 40 seconds in the calmest test to just over 60 seconds in the most panicked one. The emergent patterns in this layout displayed "stop-and-go" waves, where slower agents at the front propagate backwards through the line, delaying everyone. Once again, on this layout the tests with slower agents revealed emergent behaviour, where even though total time increased, the flow through the exit became steadier and less chaotic, with fewer collisions for slower agents. This again supports the idea that agents moving fast is not always optimal and that coordinated flow can result in safer outcomes.

Across the three scenarios, the results show that evacuation efficiency depends on more than just speed or panic levels. It is also shaped by how agents behave and how the building is structured. High panic makes movement more random and increases congestion, but having a mix of fast and slow agents can make the group more stable. The emergent patterns like bottlenecks, queues, and the faster-is-slower effect show how simple rules can create realistic crowd behaviour.

# 6 Conclusion and Future Work

Overall, the evacuation model successfully demonstrates how simple rules can produce realistic and complex crowd dynamics. Across the three layouts, the simulations revealed patterns that resemble real-world evacuation behaviour, such as crowding and congestion waves, and the faster-is-slower effect. The results showed that increasing panic generally results in more casualties, but introducing slower agents can sometimes improve survival rates by reducing crowding.

The model was able to explore how panic and movement speed affect evacuation outcomes within differing building structures. By using a BFS pathfinding system with probabilistic panic behaviour, it was able to model a range of realistic scenarios. Having the ability to adjust global controls for agents' speed and panic made testing differing layouts systematic and simple.

However, several limitations exist and can be improved upon for future improvement. Most of these are due to the limited time required for the project. Firstly, agents that have died were not implemented as physical objects. As a result, surviving agents can still pass through these cells, reducing realism slightly, especially when crowd density is high. Second, agents do not actively avoid fire or smoke when determining routes, instead, they move toward the nearest exit purely on distance, even if it leads through a hazardous area. Implementing avoidance would significantly enhance the model's realistic nature. Finally, the model does not simulate physical crushing or trampling effects, which are common in real evacuations when panic levels are high and crowd density exceeds a certain limit. Future versions could include collision-based injury or crowd pressure, which were analyzed in our literature review above.

Despite the limitations, the model was still able to capture emergent behaviour during evacuation settings. It displayed how building designs, panic, and speed interact to influence overall survival, making it a solid foundation for future work in agent-based emergency simulation.

## References


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