Modeling Indoor Fire Evacuation with Adaptive Multi-Layer Cellular Automata

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1 Introduction

Safely evacuating the occupants of a building in case of fire is no easy task. Many ways exist to minimize casualties, but testing new strategies is difficult, as running experiments with actual fires is dangerous. Running simulations offers a safe alternative whilst also providing the ability to test multiple different setups with varying parameters efficiently. In this paper we take a look at the effectiveness of two evacuation aids using cellular automata (CA) as our basis for the simulation. Cellular automata have been used in the past to model fire spread, especially in forest areas and we will build on top of these models to work on an indoor environment fire spread model.

We begin by presenting the background of our research, followed by a detailed description of the methods, where we dive deep into the specifics of our implemented layers of the CA. Lastly, we present the experimental setup and conclude with a discussion of the results, the limitations and the possibilities for future work.

2 Problem Statement

In this project, we wish to look at the effectiveness of different evacuation guides and compare them with a situation without evacuation guides. By using a multi-layer cellular automaton to model the fire and the agents, we can simulate a varied number of situations to get a good overall impression of the effectiveness of each model. For this project, we test different floor plans, different combinations of the aids, and different densities of people. For simplicity there is always one fire source.

3 Related Work

Cellular automata have many different applications and are relatively easy to implement thanks to their discrete implementation. These, often stochastic, rules can create complex behaviors and interesting interactions, especially when using multiple layers. The cellular automata model at the basis of this project is the forest fire model by Drossel and Schawbl proposed in 1992 [1]. This model may not directly apply to an indoor situation, as it is more concerned with modeling different ecological environments with different tree densities, but it does serve as a basis for the rules the fire follows in our own implementations.

In the domain of evacuation, cellular automata are also used, both to model the fire spread as well as the crowd behavior of the human agents. In 2019, Li et al. did a *minireview* of different CA models for crowd evacuation [6]. It discusses various modeling approaches, such as floor field models, velocity models, and social-force-based CA adaptations. The paper highlights how CA can be used to model individual movement under constraints like exit capacities, environment topology, and panic scenarios. The authors highlight the difficulties in modeling panic, as there are many factors that need to be modeled for the simulation to be realistic; humans are unpredictable, and even more so in a crisis scenario. However, they also state that including certain "mentality properties" is very important for the simulations. We therefore tried to include as many of these aspects as possible in our own implementation discussed in the next section.

A specific example of a similar study is done by Zheng et al. in 2011 [8]. It provides an exploratory look at the interaction between fire spread and human agents with different parameters for both, looking at fire intensity, path blockage, and fire spread. The authors show that a faster fire spread makes evacuation more difficult and the location where the fire starts, greatly influences the final outcome, as well as the configuration of the room. Furthermore, several smaller exits lead to a better evacuation speed, instead of one big exit. We will test a similar scenario where we look at the same floor plan, but with different structures and exits.

More recently, Ji et al. (2022) proposed an adaptive emergency guidance system that introduces improvements over the standard signage [4]. The problem with standard signage is that is does not adapt to where the fire actually is, possibly guiding people into dangerous areas of a building, especially when the building structure is very complex. It combines the CA with a model from fluid dynamics to discover the safest paths and uses this to create intelligent signage systems adjusting in real time. The authors measured their results mainly in evacuation time, which we will be doing as well. Their method showed significant improvements, highlighting the importance of both a good path finding algorithm and the use of dynamic signage.

Within the domain of agent modeling there also exist models regarding agent behavior in indoor stress situations such as fire. A paper by Kasereka et al. (2018) defines a model for evacuation simulation where they highlight the different effects the fire and behavior of other agents might have on each individual agent [5]. Their definition, with both fire and smoke, as well as a clear overview of how each element affects the others, can help us give shape to our own implementation.

4 Methods

4.1 Baseline Model

Our implementation is based on a tutorial and git repository by Christian Hill [3]. It implements a classic forest fire model where trees are able to quickly regrow, allowing the fire to keep spreading and developing. We used this implementation because it gave us a nice and simple base to build on top off. Furthermore, we changed the behavior of the fire to behave more realistically by covering a larger area, rather than a single burn-line like in the tutorial.

4.2 The full implementation

For the full implementation the baseline was changed extensively. Different layers were added for the fire, the smoke, the walls, the evacuation aids and, of course, the agents by using different class objects. The entire automaton is represented as an $N \times M \times L$ dimensional matrix, where N and M are the width and height of the floor plan, and L is the number of layers. We call this grid the *environment*. Below is a description of each of the six different layers in our model:

1. Structure layer The structure layer encompasses the walls and the exits, which can be loaded in from an image. Cells can either be empty, a wall, or a door (which functions as the exit). The structure layer does not change throughout the simulation, but the other layers are affected by its values.

2. Fire layer The fire layer is responsible for the logic of the fire spread. Cells can have three values being either unburned, burning, or burned. Burned cells still affect the agents' path finding, but do not spread to unburned cells or harm the agent anymore. In each update of the grid, the value of the new cell is determined by the value of the current cell, the surrounding cells, and the structure layer. If a cell is a wall, it will never burn and remain unburned.

Burning cells will continue to burn for a specified amount of time, a separate *timer* grid keeps track of the time each cell has been burning. Once a cell is done burning, it becomes burned. Burning cells will spread to neighboring unburned cells with a probability of 0.5. Cells that neighbor diagonally will only ignite with a probability of 0.25 to create a more realistic fire shape [3].

3. Smoke layer The smoke layer simulates the production and spread of smoke as a continuous density field across the grid, with each cell holding a value s between 0 (no smoke) and 1 (fully saturated). At every time step, if the corresponding cell in the fire layer is burning, its smoke concentration increases by a fixed emission rate (*emit_rate*), up to a maximum of 1.0. Simultaneously, smoke diffuses to the eight surrounding Moore neighbors according to a discrete diffusion rule, where for each cell (i, j) the change in concentration $\Delta s_{(i,j)}$ is given by

$$\Delta s_{i,j} = \text{diff\_rate} = \sum_{(k,\ell)\in\mathcal{N}(i,j)} (s_{k,\ell} - s_{i,j}).$$

Smoke concentration directly affects agents in three ways: first, it degrades their health each turn at a rate proportional to the local smoke density, i.e.

$$\text{health\_loss} = \text{smoke\_damage\_rate} \times s;$$

Second, once the smoke density in an agent's cell exceeds a predefined panic threshold, the agent immediately switches into a panicked state. Third, any extra (panic-driven) movement attempts become less reliable, since each hop fails with a probability equal to the current smoke density, so higher concentration of smoke makes additional moves increasingly likely to fail, resulting in no displacement for that sub-step.

4. Light Strip layer The Light Strip layer provides directional guidance toward exits using a color-coded exit system: exits are marked as either *safe* (cyan) or *unsafe* (red). Light strips are placed on the exits from the structure layer and start out as safe. Whenever fire spreads into the vicinity of the light strip, the status dynamically updates to unsafe. The light strips do not directly affect the fire or agent environment, but they significantly influence agent decision-making by altering the perceived availability of exits. Their functionality is not hindered by high smoke concentrations, reflecting a realistic approach where light can penetrate the smoke, effectively highlighting exit locations.

Each agent chooses their target exit based on several criteria. First, exits marked as safe are always directly considered. Second, exits marked as unsafe are conditionally considered. If an unsafe exit is close (Manhattan distance < 3), the agent will consider it regardless of safety status. This models the natural reluctance to alter direction abruptly at the last moment. On top of that, if an unsafe exit is farther away, the agent has a probability of 0.30 to ignore the safety status, mimicking uncertainty, panic, or hesitation in following guidance systems. Lastly, if all exits are marked as unsafe, the agent falls back to considering all exits as available to avoid a deadlock.

This logic introduces probabilistic rerouting and dynamic re-evaluation of paths, aiming to simulate how visual guidance, such as light strips, might realistically influence human decision-making during emergencies.

5. Fire Alarm layer The Fire Alarm layer simulates an auditory warning system. Fire alarms affect agents by alerting them to the spread of the fire, inducing panic, which further influences their urgency of movement and willingness to evacuate.

The fire alarm layer follows a global activation system. As soon as the fire reaches any tile with a fire alarm, all fire alarms present in the environment activate simultaneously. When activated, each fire alarm emits an alert within a predefined radius surrounding the fire alarm. This radius visualizes the *hearing radius*, which alerts the agents inside of this radius, that there is fire spreading inside the grid. Activation of the fire alarm changes the edge color from white (off) to lime (on). At each timestep, agents check whether they are within the hearing range of an activated fire alarm. If they are, they become panicked, which modifies their behavior. Further details regarding this behavioral modification will be provided in the dedicated agent layer paragraph.

The fire alarm design simulates a real-life emergency broadcast system where individuals might not be able to see danger, but can still respond appropriately based on environmental warnings.

6. Agent layer The Agent Layer models evacuees as intelligent agents capable of reacting to, perceiving and navigating within a dynamic, multi-layer environment affected by fire, smoke, and both evacuation aids. Each agent is implemented as an instance of the *EvacueeAgent* class, having internal state variables and a decision-making process that combines health degradation, panic behavior, path finding, and lastly hazard assessment.

Agents are initialized with full health. They are tracked during the simulation for three main states: *alive*, *panicked*, and *reached* (successfully reaching the exit). Agents' health reduces at an accelerated rate when in direct contact with fire, and slowly deteriorates over time when exposed to smoke. Health also further influences the movement speed of panicked agents, mimicking performance degradation under stress.

As previously mentioned, agents have the ability to get panicked. Agents can get panicked via three stimuli:

- **1. Line-of-sight detection:** panic state activates when agents get in direct line-of-sight of nearby fire.
- **2. High smoke concentration:** panic state activates when the local smoke concentration exceeds a panic threshold.
- **3. Fire alarms:** panic state activates whenever an agent is in the hearing radius of an active fire alarm.

The behavior of a panicked agent is modified by increasing their movement speed (based on health) and changing to goal-directed evacuation behavior, instead of a random walk. This evacuation behavior uses an adaptive filtering process heavily influenced by the previously discussed light strip layer. This mechanism captures nuanced behaviors, such as hesitation, sticking to initial choices, and limited situational awareness.

Movement occurs in discrete time steps, with the number of steps per update being determined by health and the current panic state. Agents have two kinds of movement behavior depending on their panic state. When panicked, agents attempt to execute multiple moves per turn, capped by an *A*-based* path finding routine [2]:

- A heuristic is used to estimate the Manhattan distance to the nearest exit.
- The cost function includes fire presence, areas burnt, smoke levels, and presence of other agents in different cells (to avoid collisions).

Secondly, non-panicked agents exhibit stochastic wandering behavior, simulating individuals engaging in their own activities during non-emergency conditions.

Adrenaline boost: panicked agents also receive a speed multiplier based on their current health. Specifically, if h is the agents health:

$$\text{mult} = \begin{cases} 1.0, & h \geq 80, \\ 2.0, & 40 \leq h < 80, \\ \max(0.1,\, h/40.0), & h < 40. \end{cases}$$

Their total moves per turn become

$$1 + \lceil \textit{panic\_speed} \times \text{mult} \rceil$$

so that moderately injured agents (health between 40 and 80) actually move fastest, simulating an adrenaline effect, while severely wounded agents slow down.

To conclude, agents operate in a multi-layered environment, interacting with multiple layers:

- **Structure Layer:** used for collision avoidance with walls/obstacles, and line-of-sight calculations.
- **Fire Layer + Smoke Layer:** influences the hazard assessment, path finding and health updates.
- **Light Strip Layer:** informs the agent about exit safety status.
- **Fire Alarm Layer:** activates panic through radius-based auditory detection and informs the agent of fire in the grid.

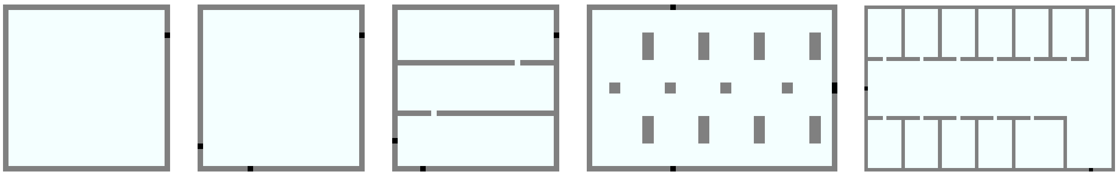
5 Experimental setup

In order to answer our research question we will be looking at several scenarios testing our implemented aids individually as well as combined. We will test five different floor plans the details of which are discussed below where we tried to create varying settings where we hope the aids can make a big difference in survival rate.

In total, five maps were created, becoming more and more complex to introduce new scenarios into the simulation one by one. For each map, the location of the light strips is determined by the exits and we only look at a situation where there are either no light strips, or all exits have light strips. For the fire-alarms a lot of possible configurations are possible, but due to the large number of experiments we already have, we decided to create a fixed configuration of the alarms for each map. This configuration is our attempt at an optimal configuration, meaning we are testing the effectiveness of this aid at it's most optimal use.

Scenarios	**Maps**	**Densities**
no aids	single exit	small
light strips	three exits	medium
sound alarms	three exits + walls	large
combination	obstacles	
	Offices	

Table 1: Overview of the different possible values for each of the independent variables. Creating combinations of them all creates a total of 60 experiments.



(a) Single exit (b) Three exits (c) Three exits and walls (d) Obstacles (e) Offices

Figure 1: The maps used for the simulations

Within these maps, the different scenarios can the be run. We test a baseline, with no evacuation aids, a situation with only the light strips, a situation with only the fire alarms and a situation where both are present. Additionally, we also vary the number of agents present in each scenario. Since the maps are of different sizes, the density of the agents is determined by a percentage of the surface area of the map. We test the effectiveness of the aids under three densities: small (5%), medium (10%), and large (25%).

Both the agents and the fire are initiated at a random location and we do not control these parameters. We therefore do 10 runs for each setting, over which we average the results, to mitigate the effects of randomness and reduce the variance introduced by the starting location of the fire [8]. See table 1 for a full overview of all parameter settings.

5.1 Maps

Five maps were created, all of them are visible in figure 1. The first baseline map is a 30×30 space with a **single exit** in the bottom right of the room. This simple situation creates no obstacles for the agents, but provides only one possible escape. The second map has the same layout, but contains two extra exits in the top left (**three exits** in total). Agents can now change routes if one of the exits get blocked. The third map builds upon this second map by adding two **walls** in the middle. This introduces difficulty for the agents to get from one exit to the other and there is less space to possibly move around the fire.

The final two maps have a bigger floorplan. The **obstacles** map is 45×30 and contains several obstacles in the middle, mimicking a church or a classroom. This map has three exits as well. The last map is the most complex one and models a building with **offices** and has dimensions 68×45. The biggest obstacle here are the multiple small rooms, with only one exit, in which an agent can get locked, if the fire is at the entrance. This map was created based on the literature, where many simulations were done on similar situations with a multitude of small rooms [4, 7]. For the specific configuration of the light strips and fire alarms for each map, please see appendix A.

Map name	No aids	light strips	fire alarms	combination
Single exit	58.03	57.37(−0.66)	53.63 (−4.40)	52.37 (−5.66)
Three exits	54.40	55.37(+0.97)	45.37 (−9.03)	45.63 (−8.77)
Walls	108.13	106.40(−1.73)	62.37(−45.76)	65.40(−42.73)
Obstacles	82.37	81.13(−1.24)	71.80(−10.57)	71.70(−10.67)
Offices	148.97	147.00(−1.97)	126.90(−22.07)	128.37(−20.60)

Table 2: Average completion time for the different scenarios over all densities. The underlined items indicate the scenario that improved the most over the baseline.

5.2 Evaluation metrics

For all experiments we keep track of two things: the survival rate and the time until full evacuation. The ten runs create an average measure for both of these. The survival rate is measured as the percentage of agents that are still alive at each time step of the simulation. The time until full evacuation is the time step at which all agents have either exited the room or have died.

Besides this statistic evaluation, all of the runs were also exported to GIFs to be inspected manually and perform qualitative evaluation on

6 Results

The results of the experiments can be viewed in figure 3. This figure includes the different maps set out against the different agent densities. Each plot contains four lines of the survival rate over time for the different scenarios. Here, the densities were left separate as there was a lot of variation between the relative survival rates for these three groups. Additionally, table 2 shows the average evacuation time for each of the settings. The evacuation time was not only taken over the 10 runs, but also over the different densities to create a more comprehensive table. A few snapshots of a simulation from the obstacle map is included in figure 2 to shows how the simulation looks and changes throughout.

The resulting plots illustrate the difference in survival rate for each scenario. As the smaller maps have a smaller number of agents at the lower densities, these plots are more staggered, whilst the larger maps with more agents produce a smoother average. When a line stops, it indicates the simulation finished and all surviving agents have reached the exit. This way the plots do not only show the effect of the aids in terms of survival rate, but also in terms of completion time.

7 Discussion

Looking at the results in figure 3 and table 2, we can see the aids help in reducing both evacuation time and improving the overall survival rate. Generally the shape of the survival plots follow an s-curve where the number of deaths start slow and then increases steeply, after which it slows down towards the end when either all agents are safe or have died. The shape of the plots is very similar over the different densities, but we can see that the final percentage of surviving agents differs. When the density is higher, a relatively smaller number of agents survive. This makes sense as there are more bottlenecks that occur when there are more people, even if they can reach the exit quickly thanks to the evacuation aids. Especially the obstacles map seems to have late and sudden drops in survival rate. Here, agents might see the fire later, after which they

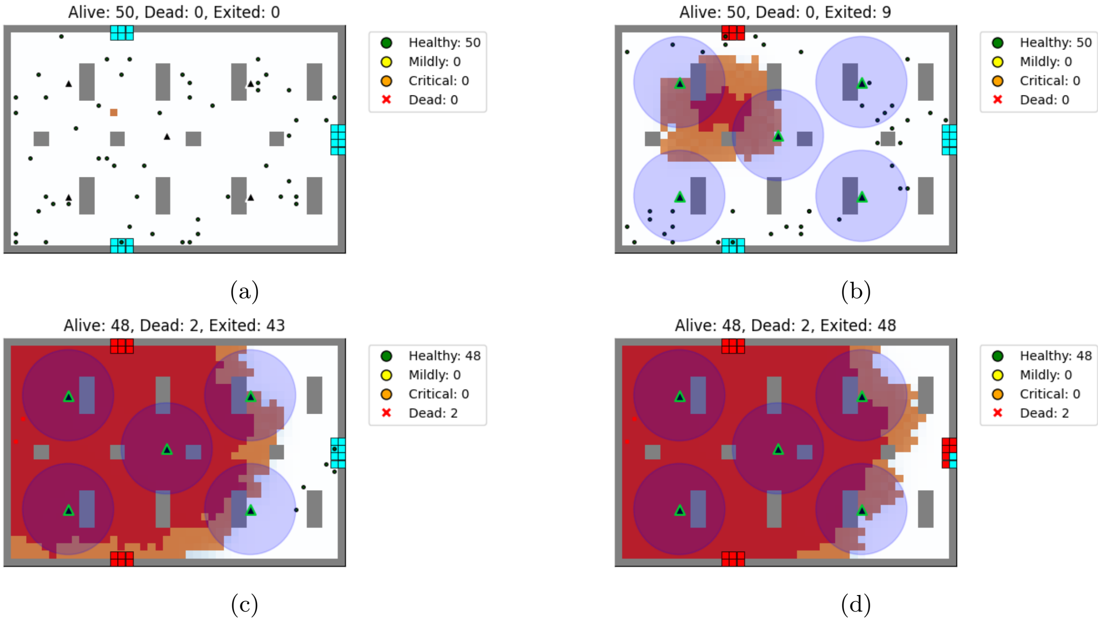


Figure 2: A example progression of the fire spread and the activation of the different aids. (a) shows the beginning of the simulation with the fire just igniting. (b) shows the activation of both the fire alarms and the light strip at the top exit. (b) and (c) show the further progression of the simulation.

have no time to reach an exit anymore; once all agents start to evacuate it is already too late. The difference in survival rate between the different densities for the no-aids scenario remains relatively constant between the different floor plans always staying between 10% and 20%. This indicates that the amount of agents and the type of floor plan do not really correlate.

Looking at the different scenarios we can immediately see that the light strips perform very similar to the baseline; sometimes worse; sometimes better. In evacuation time, we can see the light strips are a bit faster, but often more agents die. This could be due to agents having to suddenly change direction when a light strip changes color and take a longer route to an available exit. The other door might be too far away for the agents to reach in time as the fire keeps spreading. The 'bad' results make sense, since light strips are meant as a support evacuation aid, assisting different main evacuation aids (in our case; fire alarms). A supportive evacuation aid on its own, is not enough to improve evacuation.

The fire alarms have a huge influence on both evacuation time and survival rate. In the single door map, the difference is the smallest, but this is to be expected as the map introduces no difficulties that the aids can help with. In the offices map we see that for the small and medium densities the fire alarms plateau really fast compared to the baseline, but for the larger density this flattening does not happen. Here we can see that even if the aids are effective, if there is a bottleneck at the exit, casualties still happen.

The combination of the two aids is very similar to that of the fire alarms. In the more complicated floor plans, the light strips do seem to aid the fire alarms a little bit, but the difference is minimal. Looking at evacuation time, the results are similar where the differences between the fire alarms and the combination are really quite small.

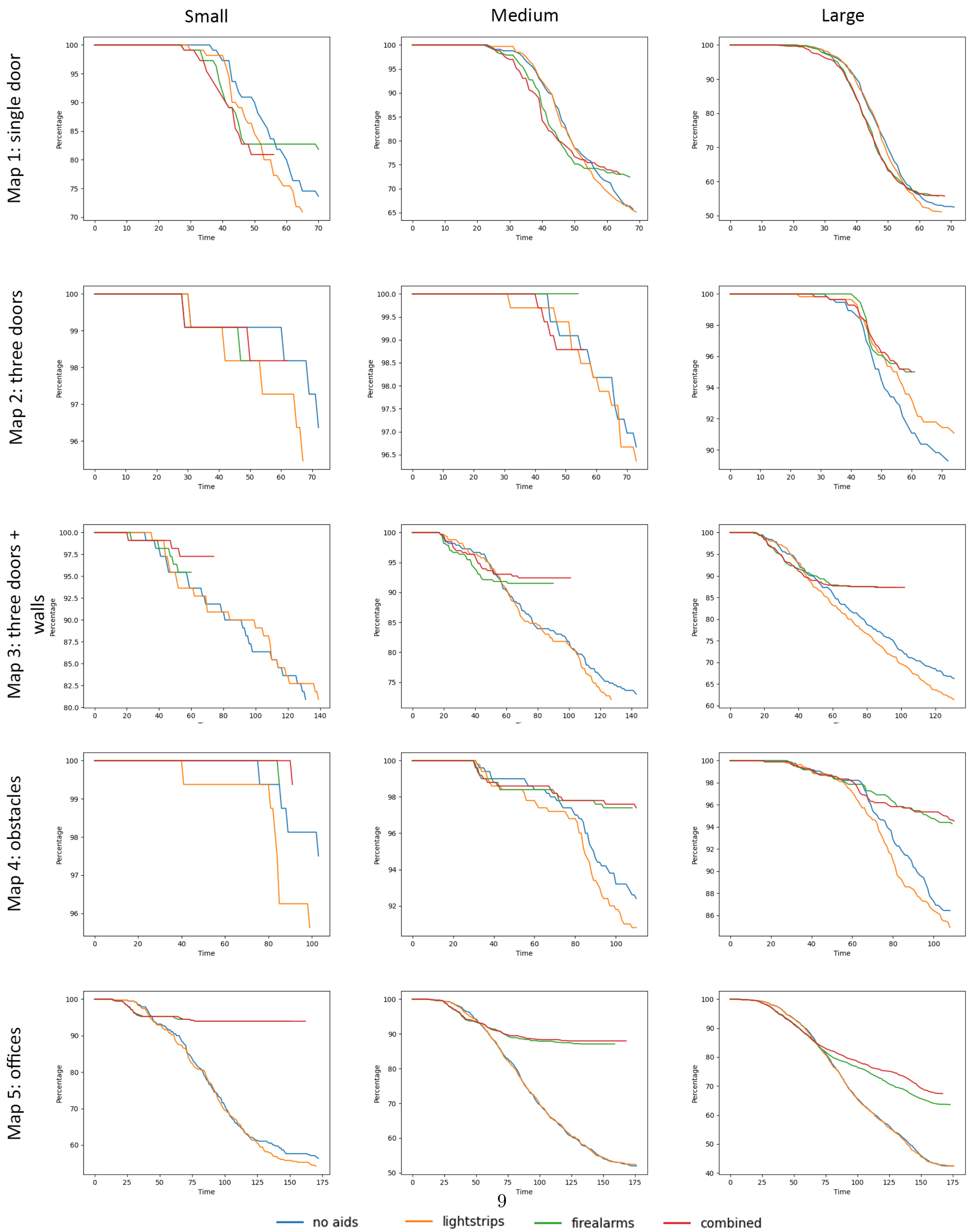


Figure 3: The average survival rate in each scenario for each map and the different densities.

8 Limitations and future work

While the current work offers valuable insights into both the effects of evacuation aids, and the evacuation dynamics under fire spread emergencies, several limitations limit its scope. First, we only explore two evacuation aids, light strips, and fire alarms, limiting the diversity of guidance systems studied. Moreover, fire alarms were evenly distributed and globally activated, meaning different spatial configurations and agent-based activation mechanisms were not explored. On top of that, light strips were implemented solely at exit locations, excluding their potential use along obstacles, doorways, or passageways. This approach could provide more granular directional guidance throughout the environment by actively guiding the agent to the right exit, and improve the effectiveness of that evacuation aid.

Another limitation lies within our evaluation metrics. Currently our analysis is based on survival rate over time, which shows how many agents are alive at each timestep in the simulation, as well as the average completion time of the evacuation. The survival rate does not show us which of the surviving agents escaped until the very end, when we know all living agents must have reached safety. Measuring the completion time throughout the simulation instead of just at the end, would have provided us with more insight in the evacuation process and speed itself.

In future work, several extensions could enhance the realism and applicability of the simulation. The agent's pathway-finding logic could be further refined to allow for more strategic, and memory-informed navigation, particularly in larger or more complex layouts. To build onto this, expanding the complexity of the environments, such as larger or multi-floor environments, would provide more insights into evacuation strategies in complex settings. Finally, adding new types of evacuation aids could offer deeper, more interesting insights. A possible idea for this; mobile agents, such as drones could be introduced to simulate first responders who locate and assist trapped agents, dynamically guiding them toward safe exits.

9 Conclusion

In this project we took a look at modeling an indoor fire and the evacuation of agents using a cellular automaton. From the Forest Fire model we created our own multi-layer implementation to test the effectiveness of two different evacuation aids. Running experiments with different floor plans and different agent densities we were able to have a good look at the aids in different settings. Of the two aids we tested, the fire alarms function really well, but the light strips only create minor improvements. However, in combination with the alarms they show more improvement, but any significant effect was not measured in our small scale experiments. Expanding the simulations with more evacuation aids and more complex floor plans will help further this research.

References

[1] B. Drossel and F. Schwabl. "Self-organized critical forest-fire model". In: *Phys. Rev. Lett.* 69 (11 Sept. 1992), pp. 1629–1632. DOI: 10.1103/PhysRevLett.69.1629.

[2] Peter E. Hart, Nils J. Nilsson, and Bertram Raphael. "A Formal Basis for the Heuristic Determination of Minimum Cost Paths". In: *IEEE Transactions on Systems Science and Cybernetics* 4.2 (1968), pp. 100–107. DOI: 10.1109/TSSC.1968.300136.

[3] Christian Hill. *The Forest-fire model.* Dec. 1, 2016. URL: https://scipython.com/blog/the-forest-fire-model/ (visited on 05/07/2025).

[4] Yanping Ji et al. "Real Time Building Evacuation Modeling with an Improved Cellular Automata Method and Corresponding IoT System Implementation". In: *Buildings* 12.6 (2022). ISSN: 2075-5309. DOI: `10.3390/buildings12060718`. URL: `https://www.mdpi.com/2075-5309/12/6/718`.

[5] Selain Kasereka et al. "Agent-Based Modelling and Simulation for evacuation of people from a building in case of fire". In: *Procedia Computer Science* 130 (2018). The 9th International Conference on Ambient Systems, Networks and Technologies (ANT 2018) / The 8th International Conference on Sustainable Energy Information Technology (SEIT-2018) / Affiliated Workshops, pp. 10–17. ISSN: 1877-0509. DOI: `https://doi.org/10.1016/j.procs.2018.04.006`. URL: `https://www.sciencedirect.com/science/article/pii/S1877050918303569`.

[6] Yang Li et al. "A review of cellular automata models for crowd evacuation". In: *Physica A: Statistical Mechanics and its Applications* 526 (2019), p. 120752. ISSN: 0378-4371. DOI: `https://doi.org/10.1016/j.physa.2019.03.117`. URL: `https://www.sciencedirect.com/science/article/pii/S0378437119303528`.

[7] W. Weng, H. Yuan, and W. Fan. "A cellular automaton evacuation model based on mobile robot's behaviors". In: *CHINESE SCI BULL* 52 (2007), pp. 680–684. DOI: `https://doi.org/10.1007/s11434-007-0096-1`.

[8] Ying Zheng et al. "Evacuation dynamics with fire spreading based on cellular automaton". In: *Physica A: Statistical Mechanics and its Applications* 390.18 (2011), pp. 3147–3156. ISSN: 0378-4371. DOI: `https://doi.org/10.1016/j.physa.2011.04.011`. URL: `https://www.sciencedirect.com/science/article/pii/S0378437111002858`.

A Map configurations

See figure 4 on the next page for the configurations of the light strips and the fire alarms.

B Author contributions

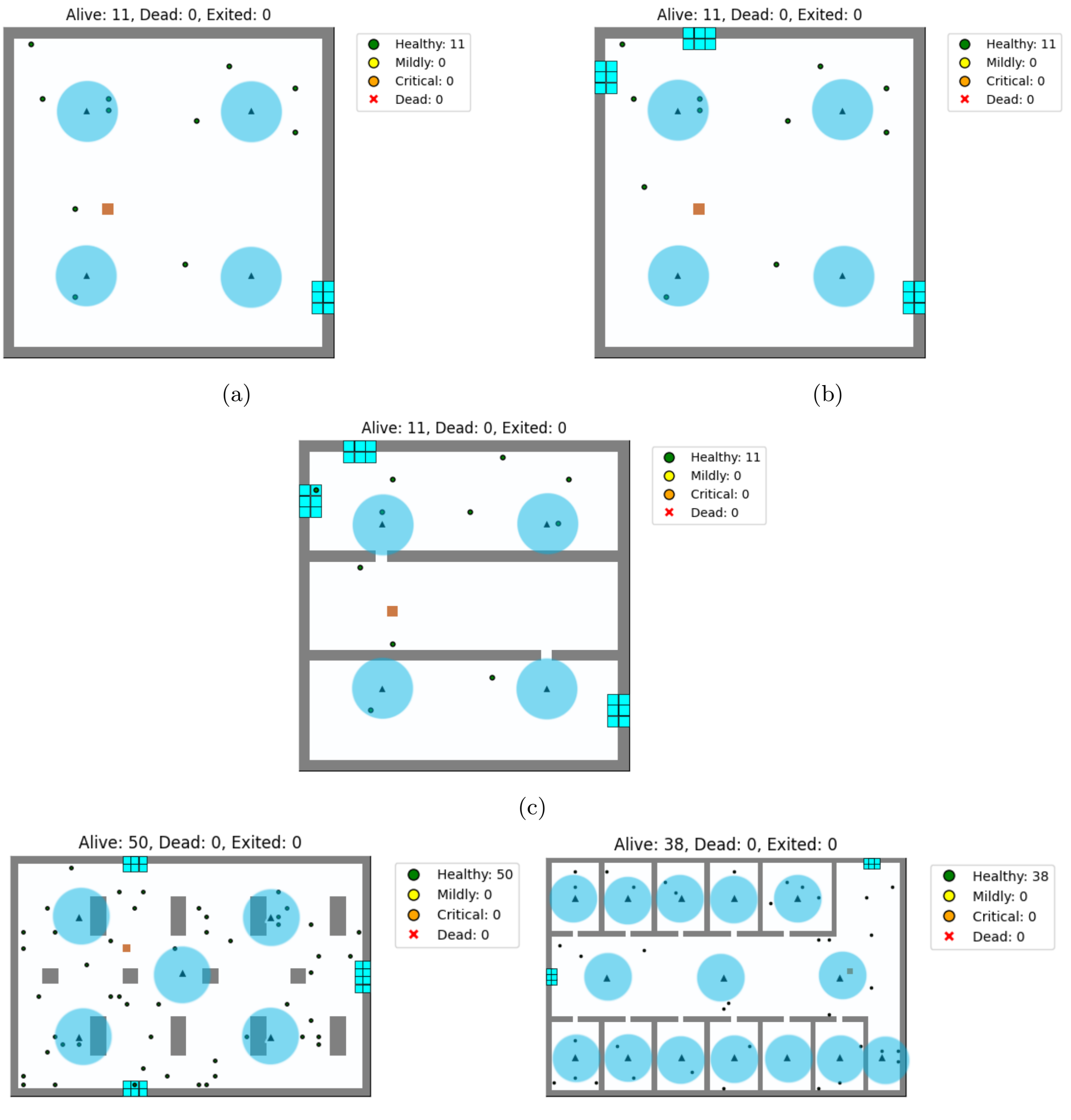
Below is a table detailing each author's contribution to the project. Overall we each contributed to the code and the report equally, working on many of the same classes and sections.

Name	Tasks
Michael	Literature review, fire and smoke simulation model layer implementations, structure and environment implementations, agent implementation, simulation animations, experiment loop implementation, refactoring, running experiments, report
Owen	Literature review, evacuation aids implementation, changes to the fire and smoke layers, agent implementation, metrics implementation, Fire Layer configurations, experiment loop implementation, report
Mieke	Literature review, baseline fire model implementation, agents implementation, changes to the fire and smoke layers, map designs, map-loader implementation, bug fixing, running experiments, statistical analysis, report

Table 3: Team Member Contributions

C Code

The code for this project can be found on GitHub at: `https://github.com/CornelisseMichael/Natural-Computing/tree/main/Project`.



(a) (b) (c) (d) (e)

Figure 4: The location of the fire alarms and the light strips for each map. The fire alarms are marked with light blue dots, to better show their location on these small maps.