Behavior Modeling in a Disaster Situation

New Mexico
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Table of Contents

Executive Summary

The goal of this behavioral science project was to create a computational model that would both simulate the movements of people and fires in a disaster situation and analyze the results so that survival rates in these situations might be improved. The agent-based model was created in the Python language. The model takes an image file of a floorplan as an input and uses agent-based methods to simulate the propagation of a fire through a building and the reactions of the people inside the building to the fire. Several postulates were developed to ensure that each person reacts in a similar manner as they would in real life and that fires spread realistically. The simulation was run on many different types of maps, each designed as a different type of building. Twelve maps were designed in total, and each was modeled several times. The final data for each map - total number of people who escaped, total burned, total trampled, and total fire size - were exported to a separate file to be later analyzed.

The results of the project suggest that the layout of the building is crucial in determining the survival rate of the people. Since the floor layout was the only parameter changed and the data varied greatly across the layouts, it can be reasoned that difference in the floor layouts was the main factor in determining the survival rate of each floor. This is evident as it appears that final fire size seems to be independent of the survival rate on the floor. A measure of the complexity of the floors was proposed, but no strong correlation between this factor and the data existed. The floors with the greatest death rate were examined to determine qualitative features that may have caused the extreme data. The narrow hallways and bottlenecks, which severely limited the flow of people toward the escape, were major factors affecting death rates. In all, the model was effective in providing relevant data to address the problem.

The Problem

Fires are an unpredictable and dangerous aspect of modern life. For this reason, many precautions are taken to prevent fires and prepare evacuation plans in case one does occur. The goal of this project is simple: to develop a model that accurately models fire propagation and human reaction to a disaster situation in order to determine how buildings and human responses might be altered to maximize survival rate in a disaster situation.

Simulation is an effective tool to design buildings to avoid loss of life in fires. It can identify design issues before the building is constructed and provide a solution before a disaster occurs.

"In 2015, there were 1,345,500 fires reported in the United States. These fires caused 3,280 civilian deaths, 15,700 civilian injuries, and $14.3 billion in property damage.

- 501,500 were structure fires, causing 2,685 civilian deaths, 13,000 civilian injuries, and $10.3 billion in property damage.
- 204,500 were vehicle fires, causing 500 civilian fire deaths, 1,875 civilian fire injuries, and $1.8 billion in property damage.
- 639,500 were outside and other fires, causing 95 civilian fire deaths, 825 civilian fire injuries, and $252 million in property damage."

-- "Fires in the U.S", The US National Fire Protection Association

Computational Model

The model takes a 32 pixel by 32 pixel 16-color bitmap as an input argument and uses this to create a map of a floor on which the fire spreads and the people move. The bitmap is parsed, and the color of each pixel is used to determine the type of tile to be created at a congruent position in the model. This creates an instance of the 'floor' class, which is the base class for each other object in the simulation. The floor class consists primarily of an array called the definitemap, which consists of nested lists. The nested lists allow each tile to be reached by calling its coordinates, and so the definitemap functions as an array. Each member of the definitemap is a tile, which models a square meter region. There are four types of tiles: walls, which slow fires and through which people cannot travel; locations of people, which each create a person object at the beginning of each trial; locations of fire, which create a fire object at the beginning of each trial; and escape tiles, which each person object moves toward. The tiles each have four characteristics, which are stored in the definitemap: type of tile, whether the tile has a fire occupying it, how many people are in the tile, and the direction in which a person at the tile needs to move to reach the exit. After the graphic input is parsed, person objects and fire objects are created at the locations determined by the parsed file, which then begin to iterate in a recursive process which simulates the passing of time. Each iteration increases a variable in the floor class, and depending on whether this variable is evenly divisible by the person and fire speeds determines whether the person and fires move respectively. Finally, the data collected at each iteration are exported to a csv file, which can later be opened to examine and draw conclusions.

The ‘person’ class defines a person whose goal is to reach an escape tile. The route-finding system for the person class is created by the createpriorities method in the floor class. Each tile that is visible in a straight line from the exit in one of the four basic directions is denoted by a certain priority: +1 y, +1 x, -1 y, and -1 x. Then, each tile visible in a straight line in one of the four basic directions from the newly created priority tiles are given a lower priority. This process keeps repeating until every non-wall tile is given a priority, which is one greater than the lowest number of 90 degree turns required to reach the exit from the tile. Each person tries to move to a higher priority tile, a process which eventually takes them to the escape. The person will only deviate from their path if there is an object in the way - either a fire or a group of people - and will always attempt to follow their current path. If there is an obstacle in their path, they will attempt to change their route in the manner that affects their path the least. If there are too many hazards in the region surrounding the person, they will die. If the person finds himself or herself on an escape tile, he or she will leave the floor and increase the number of survivors. At each iteration, each person moves, checks whether they have escaped, and checks whether they have died.

The ‘fire’ class defines a fire, which moves semi-randomly about the floor. Each iteration, the fire checks the surrounding 25 tiles for tiles that are devoid of walls and randomly chooses to spread to one of them. Fires are slowed by walls; they have a small chance of moving through a wall if the tile it chooses a tile separated from the original by a wall. The speed at which the fire propagates can be changed by allowing it to iterate more or less frequently than the person class iterates. The speed of the fire changes when it reaches a certain size; this simulates real world fire propagation, which speeds up after the fire reaches the ceiling, which lacks obstacles and allows it to travel freely. Fires do not die out over the course of the simulation.

The model can be run in two different ways. First, the model can be displayed in the graphics interface, which displays the movement of the fire and the people with the progression of time. This method of running the simulation is useful because it shows the progression of the model visually, which can be more easily understood by the person collecting data from it. However, it can also be run without the graphics interface; in this case, it returns certain statistics about the model to a CSV file, which can later be used to analyze many trials of the model. This allows for faster acquisition of data and larger volumes of it, which makes the trials performed by the model more reliable.

Validation

The model will be validated in two ways. The first is to make the input parameters as close as possible to experimental data so that the model is as realistic as possible. As discussed later, this is not possible in all cases, so in addition, basic postulates will be adopted to match the behavior of the model to the real world.

Baldwin, Melinek, and Thomas give the probability of a fire spreading to an adjacent room as 0.1. This will be adapted to the model as the probability of a fire going through a wall. If a fire chooses to spread to a square separated from the original by a wall, it will have a 10% chance of success.

A typical walking speed is an average from 7 to 9 kilometers per hour, which equates to 2.5 meters per second. Each iteration of a person gives 1 meter worth of movement, so people should iterate 2.5 times per second. Fires spread quite slowly - Baldwin, Melinek, and Thomas give the fire spread constant, *a* in the equation $S_t = S_0 e^{at}$, as 0.1 min^{-1}, which is equivalent to 0.00167 s^{-1}. Since the fire is likely to spread from one square to another at the beginning of the fire propagation given in the model, it can be modeled by $S_{Iteration} = 2^{Iteration}$. The conversion between iterations and time can be calculated by equating $S_{Iteration}$ and S_t in the previous two equations, which yields that the fire should complete 0.0024 iterations per second, or iterate about once per every thousand iterations of a person. Fires move quite slowly when compared to people; as such, if the model were run with these parameters, it would merely be a test of the route - finding system. However, more valuable data can be obtained by using much faster fires, ones that iterate much faster than experimental data show. Faster fires will more clearly demonstrate the effect of poor map design or poor people movement, and so the less realistic model may still provide more valuable data.

Another method that may be used to validate the model is to define prior postulates and ensure that the model follows them. The postulates should follow clearly from sources of data and common sense. The following are the ones used in the current model:

People Postulates and Reasoning

1. People will always attempt to take the shortest route.

The shortest route is generally the fastest path to a target, and as such people will take it. People want to minimize the time, distance, and discomfort to their target (Treuille), and so they will attempt to take the shortest route.

2. (Corollary to 1): People will always try to move in straight lines.

3. (Corollary to 1): People will only change course if they encounter an obstacle.

4. People will never intentionally endanger themselves.

Humans have a strong self-preservation instinct.

5. People will never prioritize other people's safety over their own.

People, in general, will very rarely seriously endanger themselves for others. They choose, in general, to optimize their own path, much in the same way as in Postulate 1, not trying to help optimize the survival rate of others.

6. (Derived from 1, 4, and 5): A person will endanger another person if and only if it improves their own chance of survival.

7. People move more slowly through densely packed (people or hazards) space.

The more people in a space, the harder it is to find a space to move into (Karamouzas).

8. If an area is too densely packed (people or hazards), people will start to die.

Crushing and trampling commonly occur in panicked and cramped situations.

9. People know the direction of the exit.

Since the people in the simulation entered the building, they will know how to exit it.

Fire Postulates

1. A fire will spread pseudo-randomly

Floor Postulates

1. Each tile is one meter wide

Conclusions

The model was run several times per map without graphics. The results of each trial - number of people escaped, trampled, burned, trapped, and the size of the fire - were used to find correlations between different aspects of the data.

One interesting conclusion is that the final size of the fire seems to have little effect on the final mortality rate. This is clearly demonstrated in the trials on the Bottleneck and the Auditorium map, the two with the highest mortality rates (see Bottleneck and Auditorium - Appendix B). The fire spreads in the Bottleneck map more rapidly than on most other maps, which may be interpreted as a cause for its high lethality. However, the fire on the next most lethal map, the Auditorium, grew more slowly than on other maps (see Fire Size - Appendix A). This can be attributed to the high density of walls, which block the spread of fire, on that map; these walls serve to restrict the flow of the fire, but since they also restrict the flow of people, the mortality rate remains high. Similarly, in the Bottleneck map, the long, narrow corridors block the flow of people; this causes a large number of trampling deaths, which are rare among data from other maps (see Final People on Each Map - Appendix A). From this analysis, it seems likely that floor design plays a greater role in the success of an evacuation than does the random spread of fire.

One hypothesis formed prior to running the model was that the maximum priority of each floor would be a good indicator of the complexity of the floor and therefore a measure of the lethality of the floor. No strong correlation was found between these sets of data (see Lethality Against Maximum Priority - Appendix A).

Another interesting aspect of the data is that the burned curve, in several cases, seems to follow the escaped curve. This trend is most noticeable in the Cubicles data, where the curves nearly exactly match (see Cubicles - Appendix A, and Cubicles - Appendix B). It is visible to a lesser extent on the Conferences map, which may be due to the erroneous placement of three starting fire tiles instead of one on the map, increasing the burned death toll (see Conferences - Appendix A, and Conferences - Appendix B). This reveals a fundamental insight into the nature of the model; the burned curve lagged slightly behind the escaped curve in many cases, suggesting that the majority of the people were approaching the exit as the fire increased in lethality. It has already been discussed that the fire iterates much faster in the model than in real life, and so it is likely that the death toll in the model is far greater than to be expected in real life.

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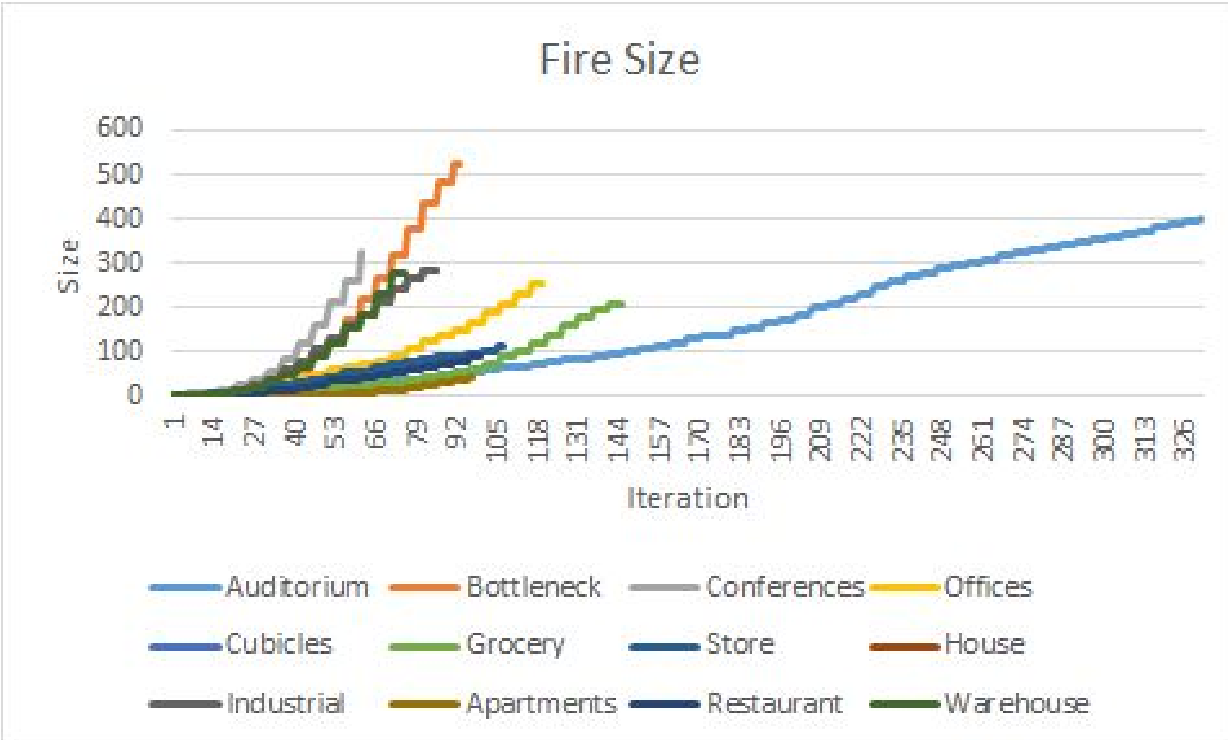
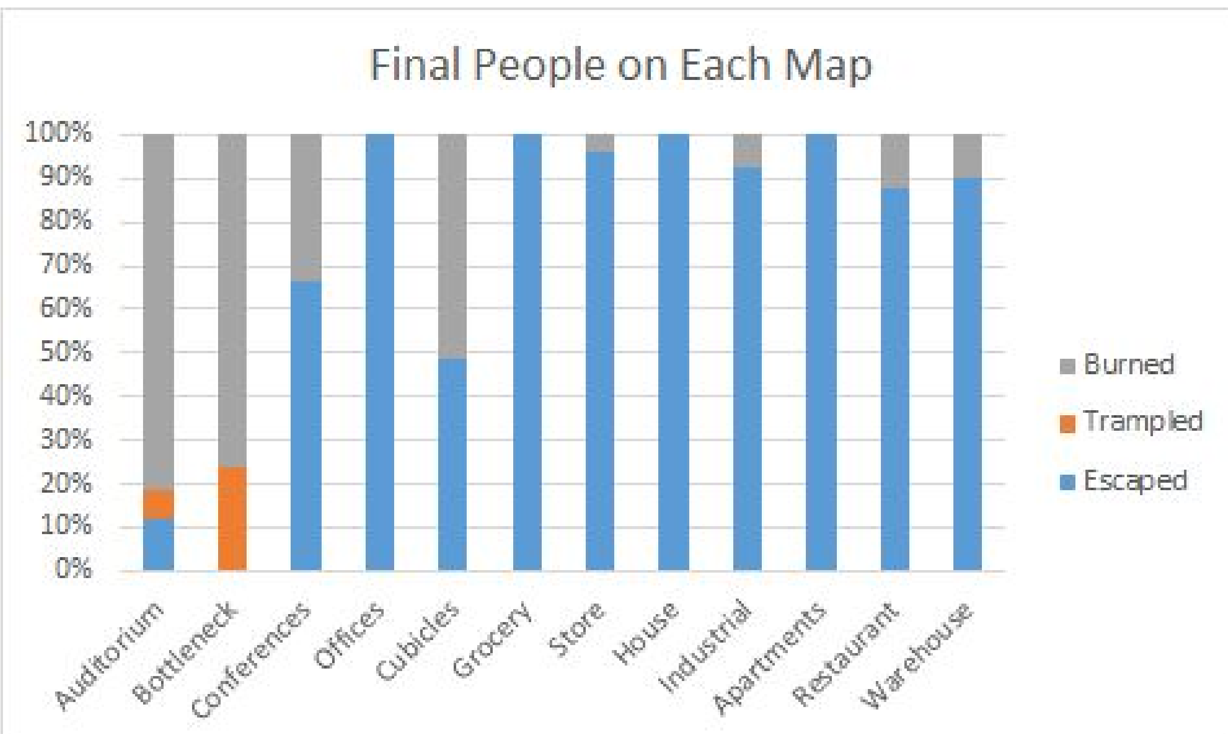
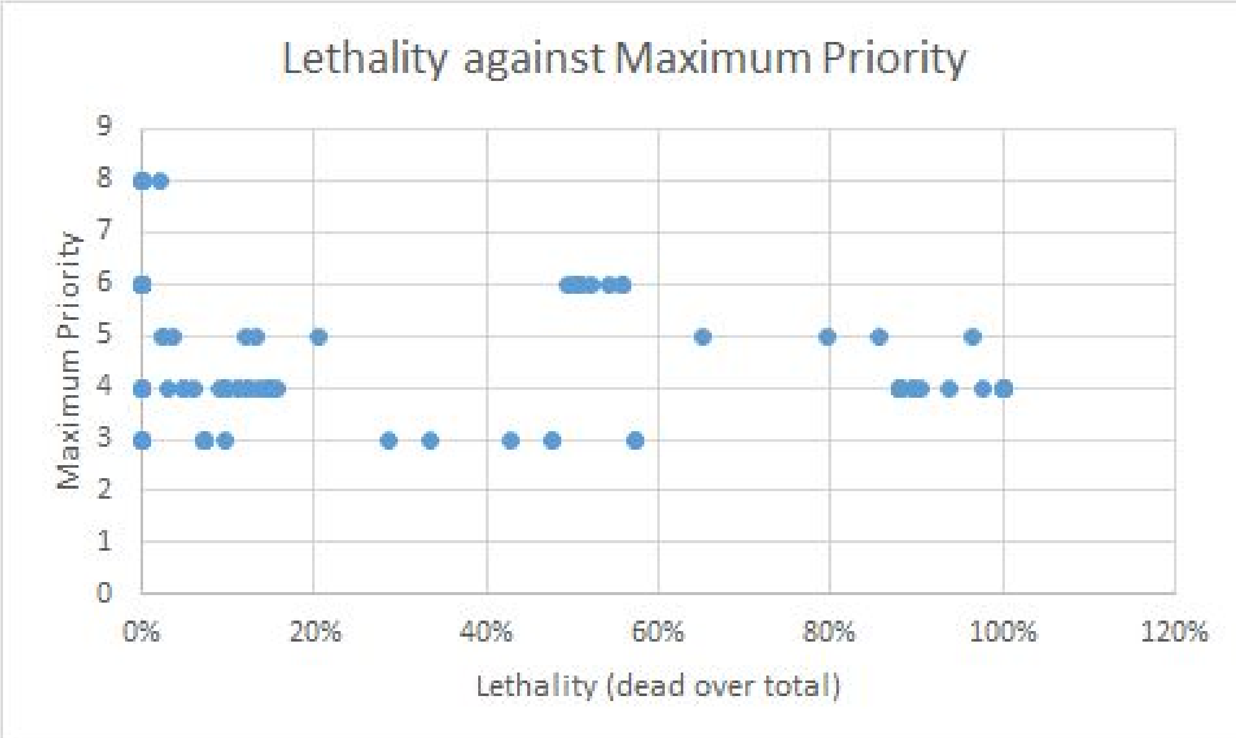
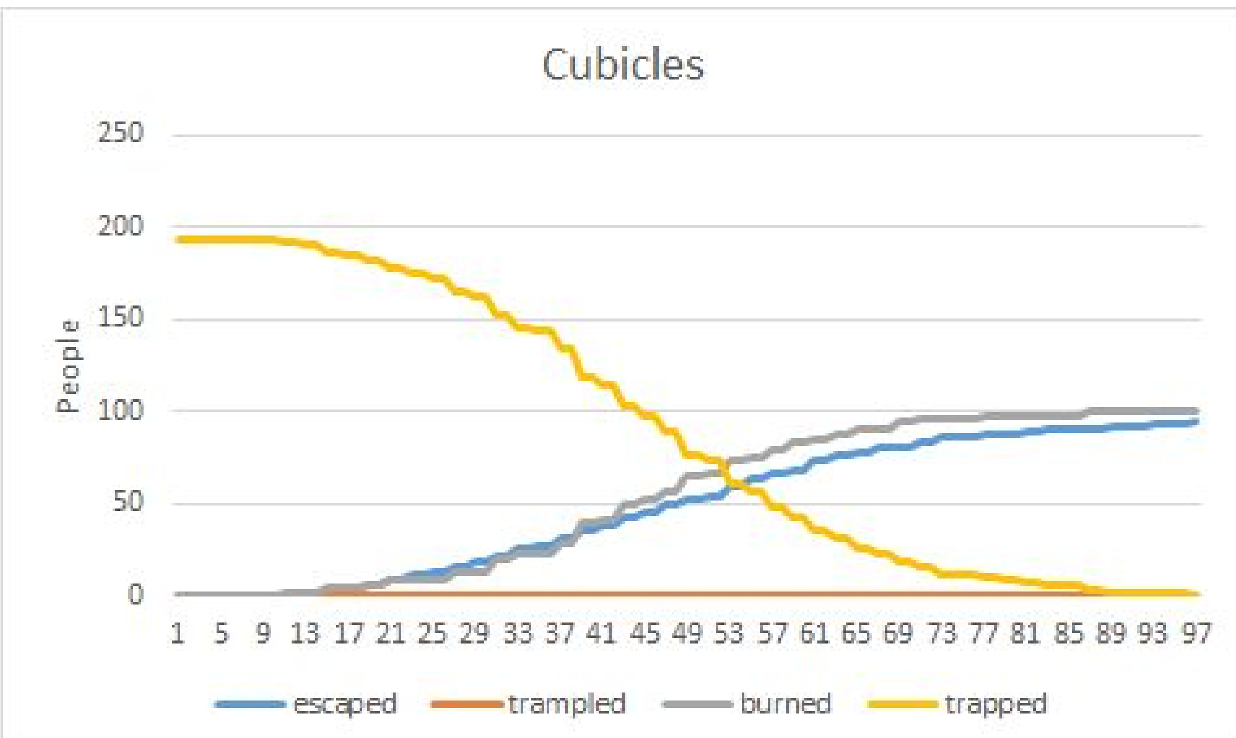
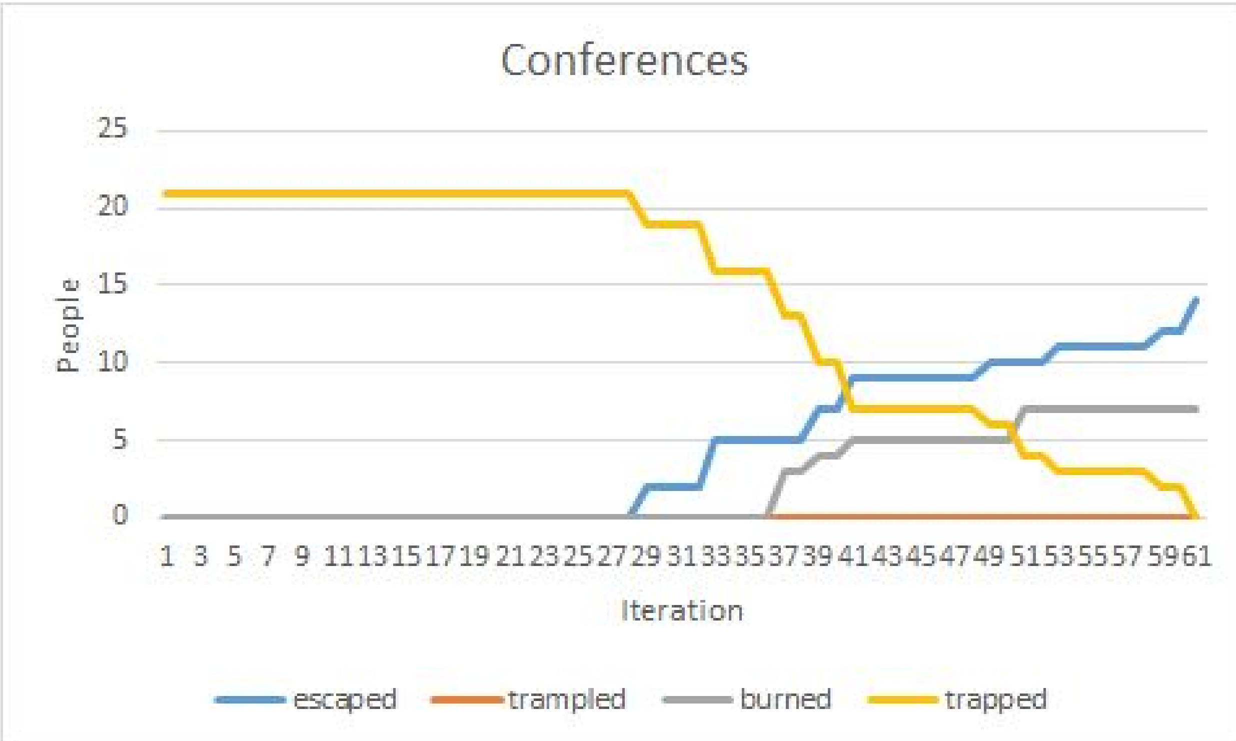
Appendix A


Fire Size
600
500
400
300
200
100
0
Size
1
14
27
40
53
66
79
92
105
118
131
144
157
170
183
196
209
222
235
248
261
274
287
300
313
326
Iteration
Auditorium
Bottleneck
Conferences
Offices
Cubicles
Grocery
Store
House
Industrial
Apartments
Restaurant
Warehouse

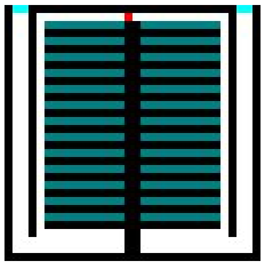
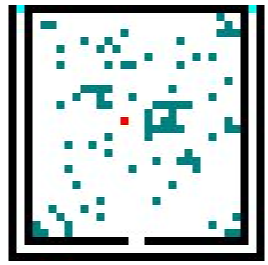
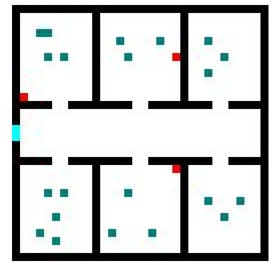
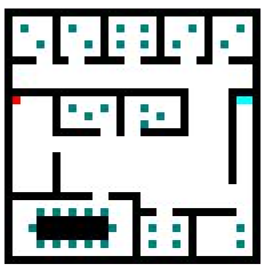
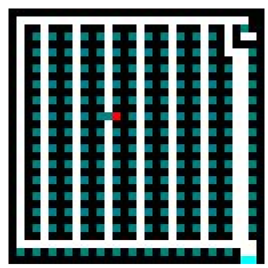
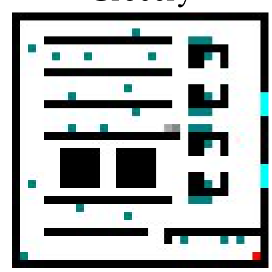
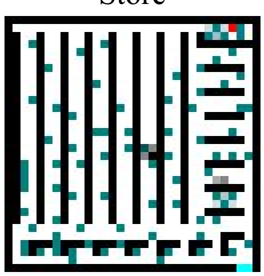
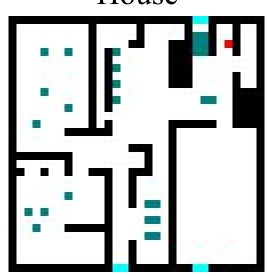
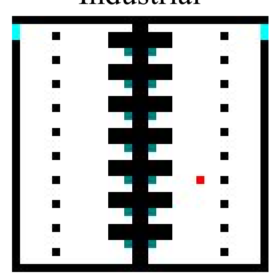
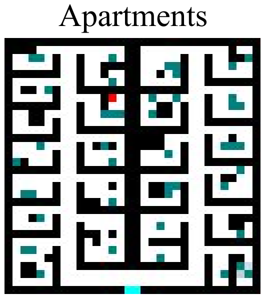
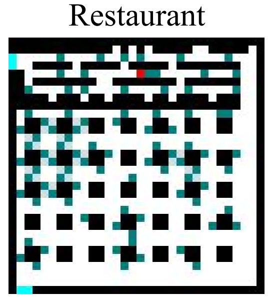

Final People on Each Map
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Auditorium
Bottleneck
Conferences
Offices
Cubicles
Grocery
Store
House
Industrial
Apartments
Restaurant
Warehouse
Burned
Trampled
Escaped


Lethality against Maximum Priority
Maximum Priority
0
1
2
3
4
5
6
7
8
9
0%
20%
40%
60%
80%
100%
120%
Lethality (dead over total)


Cubicles
People
0
50
100
150
200
250
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97
escaped
trampled
burned
trapped


Conferences
25
20
15
10
5
0
People
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59 61
Iteration
escaped
trampled
burned
trapped

Appendix B

Auditorium 	Bottleneck 	Conferences 
Offices 	Cubicles 	Grocery 
Store 	House 	Industrial 
Apartments 	Restaurant 	Warehouse