PRIORITEVAC, AN ADAPTIVE MODEL FOR EVACUATION:

AGENT BASED SIMULATION OF THE STATION NIGHTCLUB FIRE

by

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ABSTRACT

Fire evacuation modeling benefits from application of social science both in terms of accuracy and greater possibility of external validation. This thesis describes a novel simulation framework, PrioritEvac, which incorporates social dimensions of fire evacuation in an agent-based modeling framework. This model uses individual priorities, making for a dynamic approach that allows greater agency and nuance. The agent-based model was programmed in NetLogo and then validated using data from the Station nightclub fire, finding that it is in good agreement on multiple metrics.

Chapter 1

INTRODUCTION

In 2016, there were 475,500 structure fires in the United States (Haynes 2017). Combined, they caused 2,950 civilian deaths, 12,775 civilian injuries, and $7.9 billion in property damage (US Fire Administration 2018). Death rates - the number of people dead per million people in the population - by all fires in the US have decreased 15% in the last 10 years (US Fire Administration 2018). This implies that we are doing something better - responding, engineering buildings, and training people in how to respond on their own. But there is still a need for research into fires and evacuation so that we can understand what we need to do to save lives. This research seeks, in part, to answer that call.

This thesis describes a novel simulation framework that incorporates social dimensions of fire evacuation. Because its focus is on the software, it will follow the general format of a thesis in Computer Science, with major sections including a problem statement, definitions of terms, a literature review, my approach, implementation, evaluation of this implementation, and directions for further research.

Chapter 2

PROBLEM STATEMENT

Studies of evacuations have revealed that sociological as well as other personal and environmental factors influence behavior. Agent-based modeling allows for the input of social rules that impact evacuation behavior in a stochastic rather than deterministic way. It lets us input an initial state and then watch behavior rather than inputting the expected outcome and then attempting to reverse-engineer the social factors which led to it. The goal is finding a modeling framework that can a) adequately accommodate the social forces in the initial state and b) incorporate individual priorities.

Additionally, a framework that would be of use widely needs to be able to accommodate different buildings and scenarios with a minimum of programming in order to be accessible to practitioners. Beyond that, many modeling packages are expensive to access and use: accessibility also applies to price. Because of this problem, this agent-based model will be free and open source and designed to accommodate individual priorities, groups, leadership, and hazards, and be able to be used across multiple incidents. This framework was built using data from the Station nightclub fire. The Station nightclub in West Warwick, RI burned on Thursday, February 20, 2003. The fire began when the band playing that night, Great White, started their show with pyrotechnics. Of the 465 people in the club that night, 100 died and over 200 were injured. The evacuation was also completed in under three minutes. Extensive data is available for the fire, making it ideal as the baseline.

Chapter 3

DEFINITIONS OF TERMS

A:* A pathfinding algorithm, A* seeks to minimize the "cost" of a path by examining both distance and a problem-specific heuristic.

Agent: In agent-based modeling, an agent is something that has the ability to perform actions. In PrioritEvac, the mechanics of the model include fire, smoke, walls, and exits agents, in addition to people. For purposes of this thesis, 'agent' will refer exclusively to people.

Agent-based model: Computer simulation of interactions "among individual agents and their environment" (Goldstone and Janssen 2005).

Cellular automata: Individual cells have distinct states that influence the behavior of their neighbors, but do not allow for cognition.

Field: A constrained environment with forces that impact interactions in the environment; think of a table full of magnets that push and pull each other.

Git: A method of version control designed for software. It stores the most recent version of a program as well as information about changes that have been made.

Network model: A cellular automata model which incorporates interpersonal information.

Particle physics model: A model that treats people as primarily conforming to physics in their behavior, such as flow rates through a door that use fluid dynamics.

Patch: A patch is a physical location within the representation of the Station nightclub, .1m squared.

Stigmergy: Indirect coordination by way of influences on the environment, such as people responding to crowding.

Chapter 4

LITERATURE REVIEW

This model is founded on literature across the following disciplines: civil and safety engineering, psychology, computer science, and disaster science. All of them inform aspects of the model and also the ontology that developed the underpinnings of the model. The literature reviewed next focuses on the computer models as most directly relevant to the software development. Readers interested in literature concerning building safety and evacuation should consult Kobes et al. (2010, 1-11).

4.1 Models

Torres (2010) claims that emergency egress models will only produce useful findings if social science is incorporated in building the model, and that is borne out throughout the literature, wherein models that include social dynamics are overwhelmingly more accurate. There are multiple kinds of computer egress models that have been created over the years, and this is the case amongst those models that primarily examine the Station nightclub fire. There are three common types - those that employ particle physics, those that are more closely modeled on cellular automata (network models), and agent-based models (this program).

In one example of a particle physics model, Smith examined closely packed crowds with an eye to density, velocity and flow relationships. Smith acknowledged but did not quantify the importance of culture and social norms in predicting the way that people would behave within those crowds (Smith 1995, 321-327). It is one of the first studies that incorporated social factors.

Spearpoint created a network-based cellular automata model wherein people sought the closest exit. It tested the validity of the platform EvacuatioNZ and concluded that “it would be inappropriate to claim that this work has validated EvacuatioNZ” (Spearpoint 2012, 157-181). Another example of cellular automata is the model created by Zheng and Cheng, which additionally employs game theory to model evacuation (2011, 4627-4634). One of the underlying theoretical foundations of their model is a static floor field, similar to Cao’s (2014) work. Because of the combination of fields and game theory, their model allows for some examination of social behavior, even though the work is not externally validated.

As Shipman and Majumdar note, one of the major problems in modeling currently is that there is a dearth of models that incorporate both human behavior and emergency situations (2018, 183-197). The Station nightclub is one of few emergencies that offers sufficiently complete data to begin to assess the role that human behavior plays in crisis-originated evacuation. But neither particle models nor network models are structured appropriately to consider sociological factors sufficiently, which brings us to the third common type of model.

4.2 Agent-Based Models

Agent-based models (ABMs) are preferred because they allow for reasonably complex individual cognition and result in more valid findings. ABMs tend to possess computational description at the level of analysis of agents, stigmergic interactions, autonomy of the agents, and spatially distributed populations of agents (Goldstone and Janssen 2005, 424-430). Part of their strength is that they allow group-level social emergence from a foundation of individual behavior. In so doing, they can help isolate and verify plausible causes of those emergent behaviors (Squazzoni 2014, 827-840). ABMs have been employed in a variety of fields related to social science, from economics to epidemiology (Manzo and Matthews 2014, 433-462). The focus here is primarily on ABMs as used in evacuation modeling, and so the bulk of this literature review focuses fairly narrowly on this body of work, with a preference for the Station fire. For a broad overview of ABMs, see Bonabeau (2002, 7280-7287). Within ABMs, there are multiple different approaches. Two of the most common are pattern-based and force-based (Fang 2015). Table 1 shows the types of ABMs, with the number of dead that each model found.

Table 1: Types of ABM

Model	**Type**	**Dead**
Galea (2008)	Force	84
Best (2013)	Pattern	131
Chu (2015)	Pattern	100
Fang (2015)	Force	105
Valette (2018)	Pattern	121
Bourgais (2018)	Pattern	98

4.2.1 Pattern-based ABMs

Valette et al. (2018, 3-18) employed the GAMA agent-based modeling package, and focused primarily on individual motives. As a result of those motives, agents then follow specific patterns, like running away or searching for group members. Staff members additionally had specific patterns assigned to them, directing people towards exits. Bourgais (2018) built on Valette's work, incorporating social norms.

Chu (2015) developed an agent-based model that was primarily pattern-based and included significant examination of people as social entities. Group size and composition were found to impact outcomes, as well as leadership. Staff members participated in role extension, serving as "social control agents who regulate the actions of the individuals in the crowd" (Chu et al. 2015, 29). Chu's model was validated using models of real buildings, but not real incidents. It also used flow rates through exits as part of validation, which erroneously takes a particle physics model as sufficiently accurate to serve as a tool for validation.

Chris Johnson developed a primarily pattern-based ABM platform, the Glasgow Evacuation Simulator. This author argues in favor of models that account for the ingress and egress of emergency personnel. His research is based primarily on the September 11th terrorist attacks on the World Trade Center: in modeling the Station nightclub fire, however, there is so little time elapsing from the start of the fire to the total engulfment of the building in flame (approximately 180 seconds) that the presence of emergency personnel on the scene was largely irrelevant. Johnson's work primarily serves as an example of this type of model.

One exemplar of pattern-based ABMs specifically developed to study the Station nightclub fire is SocEvac by Eric Best (2013), which assigns behavior patterns to agents based on data gathered from interviews, codified analysis of witness statements by Fahy et al. (2011, 197-209), and extensive field work observations (Barylick 2012). Best went through multiple iterations of a pattern-based ABM, starting with a first-generation model that differentiated between three different levels of group cohesion: no cohesion, weak cohesion, and strong cohesion. The version with strong group cohesion produced the most promising results, as can be seen in Table 2.

SocEvac built on that, incorporating group leadership submodels and patterns of behavior that ranged from passive to aggressive.

These results more closely match the events of the fire (see Table 2) than any non-ABM model included or mentioned in the literature reviewed (Best 2013; Galea et al. 2008, 465-476).

4.2.2 Force-based ABMs

Galea et al. (2008) didn't employ the behavior vs. force distinction in their ABM, which used the commercial software buildingEXODUS. In creating their model, which coupled behavior with fire, Galea et al. added a 15 second delay to the fire because without the delay the simulation resulted in 180 fatalities and with the delay the model resulted in only 84 as compared to the 96 dead on site and 100 total dead in reality, which they considered as "in good agreement" (2008, 465).

Fang (2015) employs a force-based ABM in EgressSFM, specifically a scalar field model, which uses equations to represent forces that govern the ways agents approach goals, preserve personal space, and attempt to not bump into walls. This is framed as bounded rationality; agents are able to behave in a somewhat rational way - they are still responding to basic forces, but with some discrimination. Valuing social relationships is considered part of that bounded rational behavior, so the agents in the simulation primarily try to go towards their group members and ensure the survival of the group. This yielded promising results, and Fang concluded with recommendations for future research, some of which are pursued as part of the approach here.

Table 2 includes all of the published models of the Station fire, including those by Best.

Table 2: Outcomes of agent-based simulations of the Station nightclub fire

Model	Bar Exit	Bar Windows	Sunroom Window	Kitchen exit	Main exit	Stage exit	Dead	Total
Actual	78	71	34	17	128	24	100	452
PrioritEvac mean	134	34	38	9	142	22	85	465
Simulex (Grosshandler et al. 2005)	20	0	0	3	213	184	0	420
BuildingEXODUS (Grosshandler et al. 2005)	22	0	0	4	214	180	0	420
MASSEgress (Pan 2006)	36	0	0	4	293	87	0	420
Galea Scenario 3 (Galea et al. 2008)							84	460
Pathfinder (SFPE)	19	0	0	3	207	191	0	420
Pathfinder (Steering)	19	0	0	3	201	197	0	420
Minimum Distance (Spearpoint 2012)	31	0	0	42	0	347	0	420
Assigned (Spearpoint 2012)	20	0	0	3	212	185	0	420
90 Seconds (Spearpoint 2012)	22	70	31	17	129	41	145	455
First-Gen No Groups (Best 2013)	37	2	6	164	119	29	108	465
First-Gen Weak Groups (Best 2013)	34	10	6	177	105	29	104	465
First-Gen Strong Groups (Best 2013)	113	56	2	7	126	24	137	465
SocEvac (Best 2013)	90	73	26	2	107	36	131	465
SAFEgress (Chu et al. 2015)	84	111		4	117	36	100	452
EgressSFM (Fang 2015)	81	106		12	135	26	105	465
BDI (Valette et al. 2018)		112			161		121	455
BEN (Bourgais 2018)							98.4	455

Chapter 5

APPROACH

Fang (2015) made four recommendations for future research paths. This model fulfills two of them:

> 1) *Improving Building and Environmental Model*: PrioritEvac is equipped to use data from multiple sources, including events that impact the structural integrity of the building over time and the characteristics of the fire and smoke.
>
> 3) *Investigation of the Influence of Social Traits through Hypothetical Exercise*: PrioritEvac allows for the study of the impact of different levels of group loyalty and the breakdown of social relationships (Fang 2015, 123).

PrioritEvac, rather than being either pattern-based or force-based, is priority-based. Agents identify goals based on their priorities, and then pursue them. An individual agent's goals are designed to put social connections first, based on previous general findings that people value social relationships in a crisis even to their own detriment.

Norris Johnson documented and analyzed statements from "The Who Concert Stampede" of December 3, 1979. They argue that crowd models of panics or crazes are, at best, not useful (1987, 362-373). Thus, panic does not inform an agent's goals or social ties. There are also aggregated stories from the people who were at the fire, set out both in a narrative of events (Barylick 2012) and as their witness statements were analyzed (Fahy, Proulx, and Flynn 2011, 197-209). Those goals are not accompanied by pre-set patterns of behavior. They are, however, accompanied by preferences that act in some ways like forces.

Agents do not consciously debate the merits of each individual possible path, and it does not impact their goals, because deliberating on the path consciously would be too many choices all at once for someone to make comfortably or quickly (Iyengar 2010). Agents do, however, have hedonic motivation, which is articulated in this model primarily as their desire not to be near fire. In most instances, people prefer the avoidance of pain (Lewis 2017; Kahneman 2013). Smoke caused most of the deaths in the fire (Gill 2011), but fire is used here since it is still both painful and alarming, and thus avoided by agents.

Preferences are used in heuristics to determine paths because they allow for spontaneity. Snow and Moss (2014) argue that spontaneity has four basic requirements: nonhierarchical movements, ambiguous moments and events, behavioral/emotional priming and framing, ecological/spatial contexts and constraints. Their idea of nonhierarchical movements is rooted in the protest movements they studied, but when looked at in this context a concert audience at a nightclub is definitely a nonhierarchical atmosphere: even if employees were definitively part of a hierarchy, there were club employees, the band and their employees, and radio station employees in the club, creating a non-linear hierarchy that did not include all occupants.

The moment the fire started in the Station nightclub was an ambiguous event: the concert itself was just starting, and then people started becoming alarmed and their focus shifted.

The priming and framing in the case of the Station nightclub fire is the pre-existing social relationships of the occupants of the nightclub. The physical structure of the club provided the spatial context and constraints. Because of the presence all of these factors, preferences and priorities rather than strict behavioral patterns are indicated because they allow for spontaneity.

Livet et al. (2014) describe ABMs as having empirical, conceptual, and model domains. In this model, the empirical domain encompasses the facts of the Station nightclub fire. This empirical domain is used to validate the model domain by comparing outcomes of different simulation runs.

Thober et al. (2017) note that verbal descriptions of models tend to contain ambiguities that can obscure detail. Publicly viewable code is part of clarity and utility in communicating ABMs, as well as facilitating issues of replicability: anyone can run the model themselves to both generate and communicate the results and to verify how the Overview, Design, and Detail (ODD) protocol in the next chapter is executed in code.

Chapter 6

IMPLEMENTATION

6.1 Purpose

The following sections lay out the variables and implementations used based on the structure laid out in “The ODD protocol: A review and first update” (Grimm et al., 2010). The ODD protocol provides a formalized framework for describing exactly how an agent-based model works and why without the need for extensive example code, and provides a general idea of what to expect (Thober et al. 2017).

6.2 Entities, State Variables, and Scales

6.2.1 Physical Environment

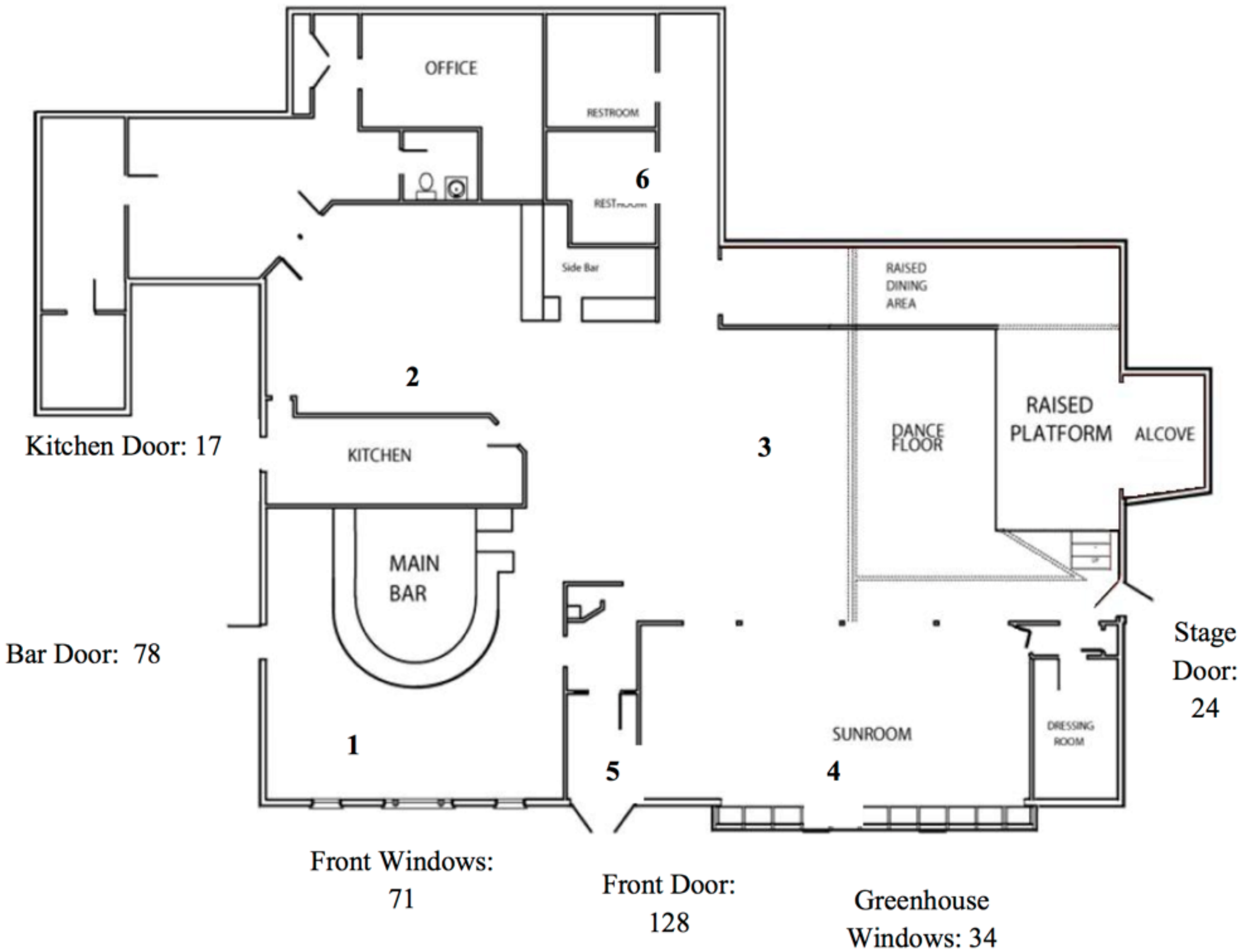

Figure 1: Layout of the Station nightclub (NIST 2004). It includes the egress exits from the building, the number of people who used each of them to escape the fire, and the various sub ecologies of the building.

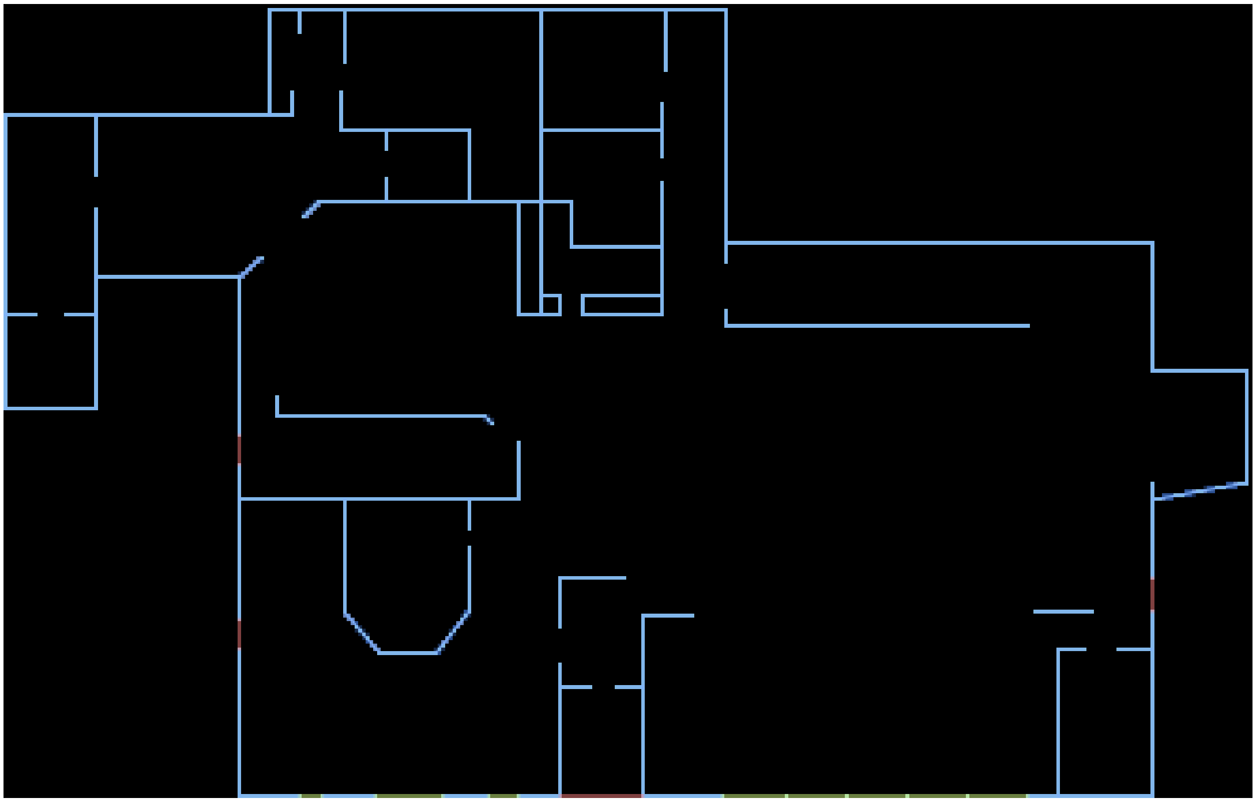

Figure 2: Station nightclub layout as rendered in NetLogo

The physical environment mimics the ground level of the Station nightclub in Warwick, Rhode Island. An image of the nightclub (Figure 1) was traced to give lines usable in the simulation. The simulation treats the length of one patch as one-tenth of a meter, which is reflected throughout the model. For instance, agents have a size of 5 - meaning they take up a circle with a diameter of .5 meters around a central point. To avoid confusion, further descriptions of sizes and units will be given in meters.

Additionally, the simulation's granularity is such that one tick is equal to one second of real time. This is in part because of the extremely short time-frame of the event itself, for almost all social activity occurred in the first three minutes after ignition (Grosshandler et al. 2005).

The building had four doors (designated by red in the simulation) and eleven windows (yellow). The walls of the building (blue) remain intact throughout the fire. Three of the windows were broken before the fire reached them and used as means of egress: this is reflected in the simulation by having the windows become exits at times that correspond with those times indicated by NIST documentation, a video of the nightclub fire, and witness accounts (Thompson 2013; Thompson 2010). In PrioritEvac, when these windows become exits, they change their color from yellow to red to signify occupants are able to leave through them. At second 94, a window in the bar was broken, as was one in the sunroom. At second 105, a second window in the bar area broke. This program component was developed by Matt Saponaro and Nihar Junagade.

6.2.2 Fire

The fire and smoke models are based on the temperatures within in an area provided by the NIST documentation of both the fire and the detailed simulations they did of the fire. Based on NIST's temperature model, we assume that there were fires in locations exceeding 200° Celsius. The temperatures were taken at 1.5m height for the first 90 seconds, then at .6m height for the rest of the fire, on the assumption that 1.5m would be about eye level and then when the fire progressed, people would crawl, making eye level approximately .6m.

The fire started on the stage near the pyrotechnics and eventually spread throughout the nightclub.

6.2.3 People

The basic agent in this agent-based model represents a single person present in the building during the fire. Most of the information about these victims come from earlier studies of the fire (Aguirre et al. 2011a, 100-118 first presented the information. See also El-Tawil et al. 2017; Fang, El-Tawil, and Aguirre 2016, 40-47, Aguirre et al. 2011b, 415-432). Most of their behavior is governed by the design concepts (see 6.4) included in the simulation. Agents have a) traits obtained from the input data, b) traits assigned by the simulation, and c) behavior governed by the simulation wherein an agent's behavior and its response to their environment is influenced by their personal traits.

Traits assigned by the simulation include speed limit, vision, and the path they are on. Agents are also assigned a diameter of .5 meters. This diameter relates to the physical space people take up, approximately half a meter at the widest point for an average adult (Oberhagemann 2012). This doesn't account for the distance people prefer to keep from each other or the density of crowds that people tend to prefer. Density of crowds tends to be measured in square feet per person, with the standard for an extremely dense crowd being 2.5 square feet (McPhail and McCarthy 2004, 12-18). Those 2.5 square feet translate to .232258 square meters, which means that a circle with that area would have a diameter of .54 meters, making social space slightly greater than physical space. Less dense crowds can take up 7.5 to 10 square feet (.7 to .9 square meters) per person. Within the Station nightclub fire, we can infer crowd density near the stage from film footage and attendance numbers as well as having a record of who was in what area of the club when the fire started; people in that area near the stage experienced high density. But the high density is not absolute, so that people's preference for personal space is able to influence their placement: thus, people are assumed to preserve some space between them as they are distributed throughout their sub-ecology. One of these sub-ecologies is a distinct area, such as the dance floor or the main bar. Social space in the more fluid and changing environment of the evacuation itself and is not pre-set by the simulation. So agents are assigned a physical size and the simulation's adaptations include a slight preference for social space. This means that, by preference, agents avoid being in the same place as other agents when possible, avoiding some crush injuries and walking into each other.

6.2.3.1 Speed limit

Based on Isobe et al. (2004), this program assigns a randomized speed limit of between 1.1 and 1.3 m/s to each agent. This is also congruent with NIST's (Lord et al. 2005) suggested speeds for modeling this fire, which starts with a default of 1.0 m/s and additionally assigns probabilistic speeds within different age categories, as well as Gwynne and Rosenbaum's (2016) speed assessment of approximately 1.2 m/s unimpeded. This program uses a narrower range than the .95 m/s to 1.55 m/s range used in the scalar field model developed by Fang (2015). Instead it keeps the ranges more in line with the findings of Isobe and Gwynne and Rosenbaum. Speed limits are assigned rather than speeds, because the crowd was densely packed and actual executed walking speed needed to be responsive to the walking speeds of other agents in the evacuation. The assumption is that a person cannot walk faster than the person directly in front of them. Speed limit does not change over the course of the simulation. Using speed limits allows for the possibility of scenarios in which disability or age will impact mobility and thus maximum speed not just of the person but also of agents behind them.

6.2.3.2 Vision

Vision is impacted by distance, angle, and smoke. It starts with agents able to see in a cone of 10m, with an angle of 180° to include peripheral vision. These two dimensions decline linearly with the amount and proximity of smoke, to a minimum of 0, meaning that an agent would be completely blinded by smoke. This updates dynamically: agents see to their capacity whenever they need to. This means that it is not a stored variable, so that outdated values are never an issue.

6.2.3.3 Goals and paths

The A* pathfinding algorithm seeks the most efficient path from the existing point of a person to their goal, avoiding fire, walls and other agents in the simulation which represent people in the precipitated gathering as much as possible. The algorithm runs as soon as a person determines that they are going to move, and then every tick thereafter until they die or exit the building.

The goal is a stored variable and updated every tick, though this does not imply that it changes every tick. If someone is seeking a loved one, they continue doing so, and only turn to an exit when there is a substantial reason to change goals. How the goals are chosen and changed is detailed below under objectives, section 6.4.4.

The next desired patch is the immediate goal towards which the person is facing. It updates every time a person moves through that space.

6.2.3.4 Leadership

Leadership in small groups is an essential part of group behavior. For this simulation, people are given a numerical artificially constructed leadership score, with points assigned for being an employee of the club (Chu et al. 2015) and for having previously visited the club, based on the assumption that those known to be more familiar with the club would be more trusted by their group-members to find an exit. Also, based on Enarson (2008) and Goktepe and Schneier's (1988, 29-36) findings that men are more often leaders in responding to emergencies, male gender is also considered as contributing to likelihood of emergent leadership in groups faced with the Station emergency. This gender and other assumptions leading to this synthetic approach to leadership will be reexamined during the simulations to see if they make a significant contribution to the patterns observed, in an effort to simplify this leadership function.

People are also assigned a randomized number - less than any other single factor - that contributes to their score. This is primarily to serve as tie-breaker when people have the same base attributes, but also mimics the more ephemeral qualities of emergent leaders who have no formal authority but may use charisma or a more goal-oriented mindset to take leadership roles in crisis (Norton, Ueltschy Murfield, and Baucus 2014, 513-529). Additionally, anyone already in the role of group leader has their leadership score doubled, both to reduce turnover (except in extenuating or extraordinary circumstances) and to reflect Best's finding that being a leader already was the highest single factor in whether or not someone was selected as a group leader (2013).

6.3 Process Overview

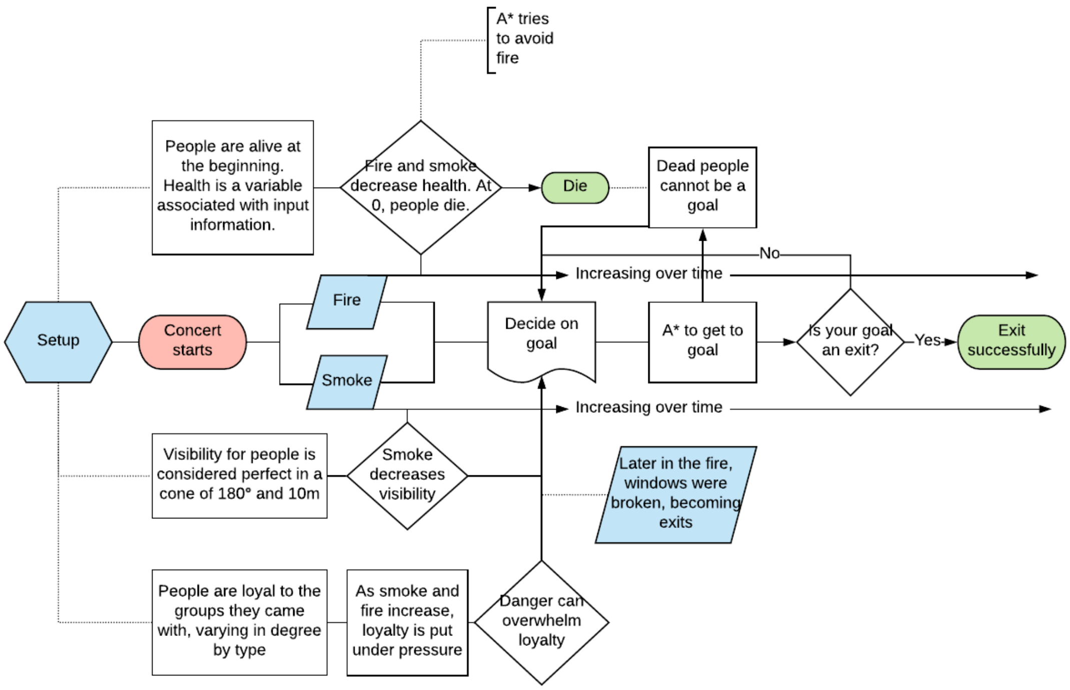

Figure 3: Overall process flowchart

The Figure 3 flowchart represents the overall flow of logic through the simulation, starting with the setup and moving through both the simulation and time as read from left to right. The setup function calls in external .csvs that establish the physical environment, smoke, fire, and agents. More details are in section 6.6.2.

```
to setup
        Clear-all
        reset-ticks
        set-default-shapes
        Read-data-from-files “file-name.csv”
        set max-wall-distance (max [size] of walls) / 2
       soclink
        ask people [preferreddirection
               set-speed-limit
```

```
            set speed 1 + random-float 4
            set leadership-quality 0
            set-group-constant]
        ask patches [set values to 0]
end
```

Figure 4: Setup Command

The setup is the basis for everything that comes next, so it merits unpacking exactly what happens and in what order. First, the setup clears everything else: all of the data and changes from previous runs, so that they will not influence the new run of the simulation. This means that there is no carry-over or learning on the agents' part between runs.

Time, as represented by ticks, needs to be reset separately. It is reset to 0 by the setup command. This allows the simulation itself to be run for an arbitrary number of seconds before the operator decides that a particular simulation instance is done.

Next, default shapes are assigned to all of the components. Walls, windows, and doors are set as lines, since that is the shape they take. Fire and smoke are both assigned the shape "square" so that they visually overlap with the patch that they occupy. Agents are assigned a default shape of a circle to represent an approximation of a top-down view.

Once these default shapes are assigned, the fire, smoke, building, and agents can be read in from .csv. More details about that are in section 6.6.2.

```
to go
 tick
set fire heuristics
  ask people [prioritize-group
    ifelse alarmed? != true        [alert]
                                   [move]
    experience injury]
```

```
 if ticks = 94 [ ask windows with [who = 57 or who = 34] [ set as exits]]
 if ticks = 105 [ ask windows with [who = 59] [ set as exits]]
 recolor-patches
end
```

Figure 5: Master Command

Figure 5 is the overall master command to run the simulation. The physical environment changes first, so that agents are responding to changes that they can perceive. A second advances, the fire spreads, and so the heuristic of danger associated with each patch updates.

Agents determine whether the danger they perceive and other factors overwhelm their group loyalty - group loyalty being the default if they came with a group. The level of group loyalty is one of the experimental variables assigned in the interface, to test which levels most closely correspond with reality.

The next line determines if agents are alarmed. Agents do not begin to evacuate unless they are alarmed by their surroundings; that is unless they perceive some threat. The ‘alert’ function allows agents to assess their surroundings. Things which are considered alarming are fire, smoke, and nearby agents who are alarmed. Agents require multiple of those inputs to become alarmed themselves - smoke without fire might be ignored, particularly in context of a concert, in which the fire itself was initially considered a regular part of the show’s pyrotechnics. Furthermore, a single person becoming alarmed might be dismissed as irrelevant. So the program requires that agents notice multiple alarming sources before they become alarmed and start attempts to escape.

Once they are alarmed, though, they start to move, and remain alarmed for the duration of the simulation. They select a goal according to the objectives and process in 6.4.4 and their goal is stored. Then, using the A* search algorithm, agents find a path to their goal.

Movement is accomplished in stages.

The next desired patch is the first patch beyond the one where the agent is standing that is on the path to their goal. A person then travels to their next desired patch. They travel at their set speed in meters per second, but the code is phrased as:

repeat speed [move-to next-desired-patch set-next-desired-patch]

This allows agents to follow the paths they set, avoiding obstacles. Agents then experience injury from the smoke and fire in their environment. The windows break in accordance with records and NIST documentation. Even though they were broken by people, they are treated as part of the environment and not as a result of behavior.

'Recolor patches' is a final step that functions primarily for visual examination of the model and generating images. Patches that have fire are recolored red, patches that have smoke are recolored a shade of grey on a gradient that corresponds to the local density of smoke, with white indicating smoke dense enough to occlude any vision.

6.4 Design concepts

6.4.1 Basic principles

The basic principles of the model are that agents behave in predictable ways based on individual imperatives that can be determined using sociological principles. Those individual imperatives are broken down into, first and foremost, the desire to live. This is expressed in the desire to not be in a burning building and the preference to be far away from fire. Agents are also expected to have interpersonal relationships that they value - they want those agents to live as well.

Additional principles include that smoke makes it hard to see: it restricts both the depth and field of vision in a linear fashion as it accumulates over time.

6.4.2 Emergence

Group behavior can be an emergent phenomenon. Those facets of code contributing to emergence are expressed in the movement of individuals; the results of that emergence will be addressed in the evaluation section.

6.4.3 Adaptation

The A* search algorithm is the primary way agents adapt to their environment. The basic A* algorithm uses two different components that make it ideal for pathfinding. The first component is equivalent to counting the steps to a destination: the more steps between the starting point and ending point, the more a path 'costs.' The second component is a heuristic, of which the basic building block is distance: paths that minimize that distance are preferred. A* selects the next possible place to go that has the lowest total steps plus heuristic. It then only explores additional possible places to go from it to the next place, rather than exploring in all directions like some other search algorithms. Since it explores a limited number of places A* is faster and takes less computing power than other search algorithms, which is important for the overall simulation. A* is also fairly accurate to human behavior, since humans use similar heuristics.

This implementation of A* tries to be more accurate to human behavior by using an enhanced heuristic. The heuristic is enhanced by taking into account not just distance to the goal but also distance to fire and smoke and level of crowdedness. So a person will end up preferring to go to a place that is primarily closer to their goal, but also one that is farther from fire and less crowded. This becomes important because the nightclub didn't operate like a maze, where the right path would be closely delineated. Instead, it had a lot of open ground, allowing for different degrees of preference to provide nuance in regards to the paths agents took.

It is important to note that A* does not impact objectives. Instead, A* is the mechanical way agents pursue those objectives and adapt to their environment as they try to accomplish them.

Objectives being so intimately tied to groups, it is worth explicating the mechanics of groups. There are several types of groups for those who did not come alone. Coworkers, friends, dating partners, family members or spouses, and agents with multiple types of relationships. This last would be typified by, for example, someone who was in the company of family and work associates, so their group at the Station was both business associates and family. Group prioritization is managed in a multi-tiered way, and it does impact objectives. For each type of group, there is a preliminary arbitrary value assigned indicating level of commitment to the group: that level is adjusted in the interface, to allow for ease of testing with the finalized software.

The group constant is the numerical measure of a person's loyalty. That constant is then impacted by proximity to fire and degree of smoke - basically, how dangerous a situation seems. The higher the danger, the more it will impact the group loyalty number. When that number, multiplied by the group constant, reaches a certain threshold (which threshold is an experimental variable controlled in the interface) agents stop prioritizing their group and act as individuals. Subsequent analysis will examine the extent to which types of relationships among group members, such as married couples, dating pairs, friendships, and work associates affect the results. The code that defines loyalty can be expressed:

When (group-constant * perceived-danger) < threshold, ties break

So agents are all responding to the same stimulus, with variations in response based on their loyalty. Their individual exposure will depend partly on their location in the building, but the expectation is that the outcomes will primarily differ based on their group ties. Loyalty to group members is an experimental variable, with a preliminary number set by group type in the interface. This can be varied between individual runs of the simulation. The hypothesis is that the more loyal they are to their particular group, the more danger it will take before they decide to prioritize themselves instead of their group. Some of agents may never shift their priorities to themselves away from their groups - whether this is true and if so on what contexts will be part of the results.

The expectation is that as fire and smoke increase, agents become alarmed, and as the distance to their group leaders increase the agents will eventually decide that they care more about getting out themselves than making sure other members of their group do. A group of friends is assumed to default to self-preservation much more quickly and abandon their group-mates as compared to a group consisting of a married couple based on Trinke and Bartholomew’s (1997) finding that both men and women ranked relationships, prioritizing first partners, then family, then friends. Each group will disintegrate at a different point - if they do disintegrate - but it is theoretically possible for it to happen at any time. Figuring out whether they are still prioritizing their group, and what the stressors are, is the first thing agents do every second, before they decide whether they're moving and where they're moving and before they take a step. It should be stressed, however, that these substantive questions associated with group loyalty will not be addressed in this master's thesis but will be pursued later on during my doctoral work.

6.4.4 Objectives

The various components of agents' decision-making processes are all triggered when agents start to move. They move when they notice fire, smoke, or agents around them moving. Figure 6 demonstrates the logic at play.

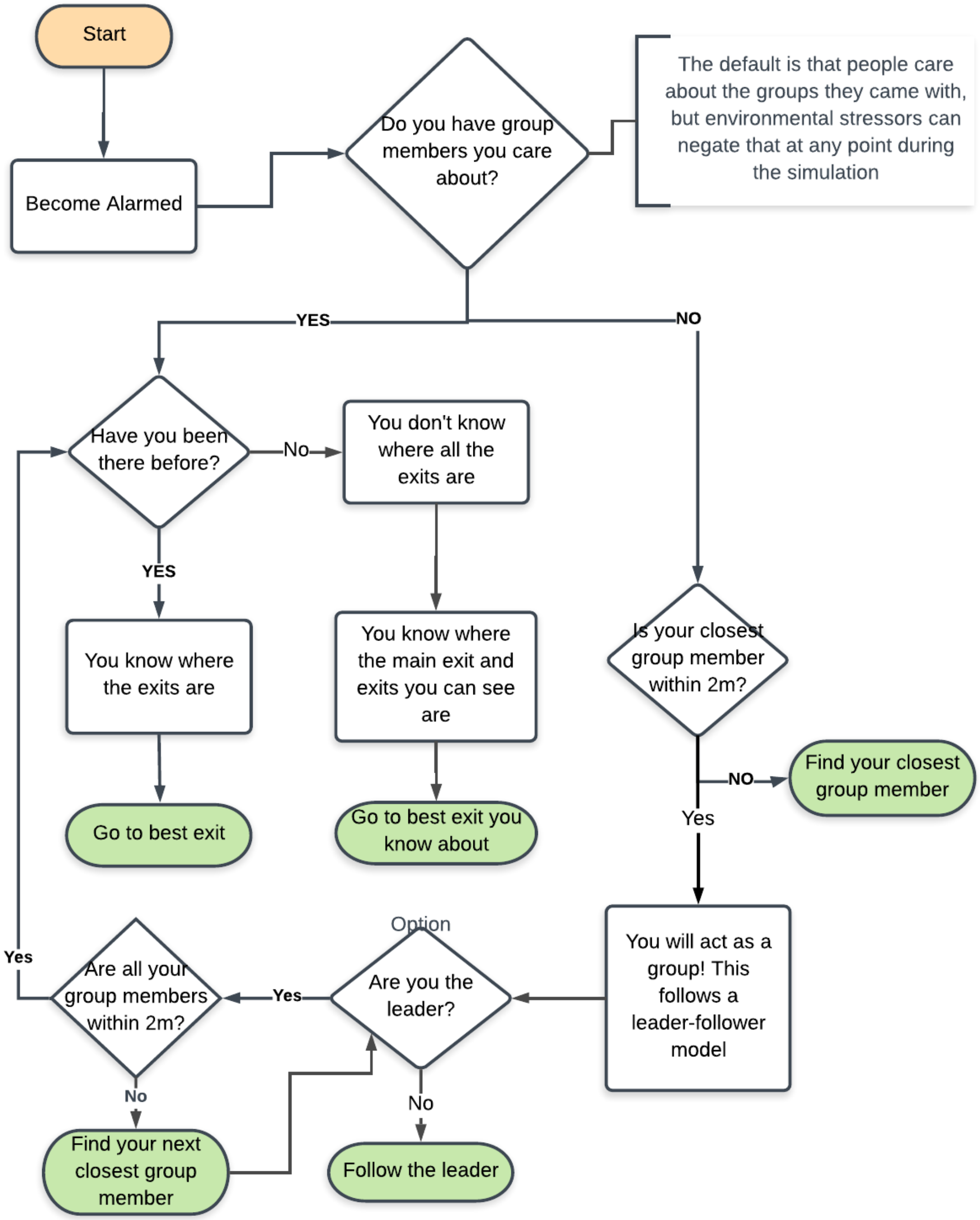

Figure 6: Decision-making flowchart

First, agents need to decide what their goal is: where they're heading. Several factors determine this, as reflected in the decision-making flowchart in figure 6.

The primary determinant is whether agents came by themselves, because there is evidence that those who came alone had a higher rate of survival (Aguirre et al. 2011a, 100-118). If someone came alone, they then set a goal based on whether or not they have previous familiarity with the building. Those who had previously visited the nightclub are assumed to be familiar with its layout and use the best exit (based on proximity and lack of danger), regardless of whether or not they can see it. Those who had not previously visited then seek either the closest visible exit in a cone of visibility that is impacted by smoke or, if they are unable to see a close exit, the main entrance. It is assumed that people would have entered through the main entrance and therefore remember approximately where it is.

For agents who came in groups, their goals are more complicated. At the outset, agents search for their nearest group-member, and so that person becomes their goal. However, group members already in close proximity to each other - roughly arm's length, 2m - are considered to be able to act as a group: they know where that group-member is and so no longer have to seek them. At that point, those group members in proximity to each other transition to leader-follower behavior. The leader decides the subsequent goal and the followers keep the leader as their goal, setting up a follow-the-leader pattern. The way leadership is determined is explained in section 6.2.3.4. A group leader will continue to try to locate and accumulate group members until all are in close proximity, and then will search for either the closest or closest visible exit. If two sub-groups are formed out of one group that is searching for each other, when the groups meet up, leadership will be reassessed and the person with the highest leadership score will become the overall leader.

Because we are using a limited number of traits to identify the leaders, there is also a random number generator that assigns a value greater than zero but always less than even one of the other factors. The range lets the random number serve as a tie-breaker in groups in which two or more members have the same score while not letting it be the primary determinant of the leader. To guard against the potential volatility of leadership within a group, the leadership score of agents who are already leaders is doubled, to allow groups to move with greater stability (Best 2013).

6.4.5 Learning

Agents do not learn from previous iterations of the program. It is inappropriate to have agents learn from multiple iterations of one simulation.

6.4.6 Prediction

A* is inherently predictive; it chooses the best path to a destination. One of its shortfalls is that it does not account for where the fire and smoke will be, only where it is at a given moment. It is a shortfall that very often also plagues humans, and so we treat it as a feature and not a bug.

6.4.7 Sensing

Those agents in the simulation which represent people have vision: they are assumed to see things around them, including fire, smoke, exits, and other agents. Their default field of vision includes peripheral vision in a 180 degree cone that extends 10m. This decreases with increased smoke.

There are also more inexpressible events sense by agents: agents can tell when agents around them are alarmed, with no further qualification. This is assumed to be communicated through visual, auditory, and haptic feedback, such as shuffling in the crowd or cries of alarm, but these individual factors are not represented in the code. In this simulation, agents are just assumed to know.

6.4.8 Interaction

Agents are assumed to decide collectively who is going to act as leader of their mostly small groups, based on which member fulfills the most qualities itemized in section 6.2.3.4. That is, specific leadership is not pre-set as part of the input variables, and is generated within the simulation.

Agents modulate their speeds based on the speeds of those in front of them. Agents also interact when within 2m of their group members, which in Fang's (2015) work it is referred to as a "conferral zone" in which people can more easily communicate. When this distance is accomplished with all group members, then the goal of finding the other agents is considered accomplished and the group members move to the next goal.

Agents are assigned an initial health level based on Best (2013), who indicated in an email to me that he assigned scores "based on mean scores calculated using a combination of gender, age, [and] known prior medical condition". Being in close proximity to fire and smoke reduces their energy (health). This applies in and around smoke and fire. More dense smoke reduces energy levels more quickly. When energy reaches 0, agents are assumed to die of injury. Dying removes agents from the simulation and outputs the relevant information at that point in time.

6.4.9 Stochasticity

The simulation is stochastic in that none of the code contains a predetermined destination. Agents have goals based on internal rules, but those rules are not generated directly by input data. This means that the average results of multiple simulations will be used to determine whether the results are significant.

6.4.10 Collectives

Collectives are both emergent and pre-set in the simulation: people who came as a group with other people are considered to still belong to that group, they are a type of pre-set collective. They have links to each other which are articulated in the code but not visible in the display. Emergent collectives happen when agents are seeking their group members or the exits from the building. They are people who form groups that seek either other group members or the exits, some of which form knots of people, a form of collective as the people in the Station tried to escape the fire.

6.4.11 Observation

Currently, observation can be done visually, though it takes a significant amount of time at the full scale, or by running a procedure called ‘master-run’. ‘Master-run’ runs the simulation for 180 seconds of simulated time and then exports all the results to a .csv with a random numeric ending so that files are not overwritten. The .csv can then be analyzed in a number of different ways; the ones used for calibration are in Table 1.

6.5 Initialization

The simulation requires NetLogo to be installed to run. When NetLogo is installed and open, it can be used to open the program file 'prioritevac.nlogo.' The program and other files need to be downloaded locally, in the same subfolder. The easiest way to accomplish this is by importing the Git from either Github or Bitbucket. Once prioritEvac is open, “Setup” will set up the simulation.

6.6 Input data

An in-depth description of the original effort to get the input data for the Station fire is in Aguirre et al., 2011a. It involved collecting data on every victim present in the fire from reports by the state attorney's office, the sheriff’s department, and the local newspaper.

NISTs Fire Dynamic Simulator (FDS) simulation for the Station nightclub fire provided the data used for the smoke and fire inputs. Because FDS is computationally intensive and high-detail, the inputs have been simplified to .csvs and are granular to a tenth of meter, not the significantly more detailed information FDS produces as a default. The .csv provides location and the time at which that location exceeded 200 degrees. 200° is considered the cutoff point at which point that location is on fire.

All of the relevant input data can be swapped for files from other fires. To perform the substitution, it is necessary to make sure the relevant files are in the same folder prioritevac. nlogo is loading from. The file names in the code and the size that the canvas needs to be need to be canged as well. Details such as the main entrance and any broken windows would also need to be adjusted.

6.6.1 People

The People .csv has data pulled together from various interviews and other official sources (Torres 2010, Aguirre et al. 2011a). All of the data has been anonymized: there are no names or other information identifying the victims of this fire in the .csv that is used for the simulation.

6.6.1.1 Location

Location in the building at the start of the fire is part of the input data, drawn from the information available and then with agents randomly placed within their initial sub-ecology. That is, if someone stated that they were in the bar area when the concert started, they will still be located in the bar area, but randomly placed within that area.

6.6.1.2 Basic Biometric Data

Gender and age are included because they allow for greater ease of searching for the same person in the non-anonymized data file if anything needs to be cross-checked. Their inclusion also allows for observation of emergent trends that might relate to either trait.

6.6.1.3 Prior Visits

Whether someone had previously been to the nightclub impacted their survival and ability to find exits, and so impacts behavior (Best 2013). People who had previously been to the club are supposed to be more familiar with the placement of exits, so the program assumes that agents know the locations of all exits and can choose the closest, while agents who did not previously visit only know the locations of those exits they could see before the fire started (as dictated by their position and field of vision) and of the main entrance which they are presumed to know from using it to enter the building.

6.6.1.4 Group-number and group-type

These two variables are considered in tandem to make links to connect agents who came together to the nightclub. Groups are differentiated by type. Coworker bonds are different from familial bonds, for example. The types of groups are coworker, friend, dating partner, familial (including married couples), and agents who have multiple kinds of relationships. These classifications are based on Fahy et al. (2011) and culturally-based assumptions on the types of groups that would be most relevant.

6.6.2 Smoke and Fire

Smoke and fire are input in separate .csvs, based on FDS results as they were converted to video. Fire is structured as having locations and arrival times – that is, times at which a location is considered as being on fire - and was based on a top-down video sliced from a three-dimensional simulation in NIST's Fire Dynamic Simulator. These slices were taken at 1.5m height for the first 90 seconds of the simulation, then at .6m height for the rest of the simulation, with the idea that it is roughly head height at first and then lowers at the point when agents are expected to largely be crawling.

Smoke is structured along the same lines, with not only arrival times but five degrees of gradation, for 0%, 25%, 50%, 75%, and 100% smoke density. The 0% gradation denotes absence of smoke, and 100% smoke density means a completely opaque smokescreen. Higher density causes more injury more rapidly.

The videos for smoke were split into sections rather than the whole-building top-down view of fire, and they were categorized according to their corresponding locations within the nightclub and in our schematic.

6.6.3 Building

A layout of the Station nightclub was acquired from NIST, and then the location of walls, windows, and exits was input into a .csv, using the beginning and endpoints of the straight lines that comprised those aspects of the building. That .csv is read into the simulation, and the composition of the resultant physical environment is addressed in 6.2.1.

Additionally, a PNG with only the walls in the floorplan was uploaded to make them a feature of the map in addition to agents. This will need to be revisited for simulations where structural integrity is compromised. The size of doors and windows is accurate to those in the building.

6.7 Submodels

In addition to the setup and go functions, there are a number of submodels that contribute to the overall function of the simulation. The submodels can be roughly grouped by category, which corresponds to the file in which they can be found in the program.

6.7.1 Heuristics

The various heuristics submodels cover factors in judgement and preference. The first of these is the alert function, which has agents assess their surroundings and become alarmed enough to evacuate if there are sufficient warning signs.

Heuristics also include assessing how dangerous a particular direction is, including crowdedness and proximity to smoke and fire. The final and most important submodel in the heuristic section is that which governs group loyalty, discussed in 6.4.3.

6.7.2 Leave simulation

Agents can leave the simulation in two ways: through death or through reaching an exit. These submodels track how and where and when agents exit.

6.7.3 Speed

The speed submodel is taken directly from the NetLogo model library - specifically a network traffic model (Wilensky 2003). Agents match the speed of the agent in front of them, if there is one, or accelerate if there is not.

Chapter 7

EVALUATION OF IMPLEMENTATION

Because the code needs to demonstrate what it is purported to do to ensure that the results have meaning, tests were performed on smaller units of code. Unit tests ensured that each building block in the simulation worked as it should. Those unit tests run for this simulation are recorded in tests.nls. Some tests were not run: those for setup of the building and agents, because their effectiveness is demonstrated by being able to see a layout and agents represented in the simulation. All of the tests, as well as a complete changelog with accompanying notes, reside on https://bitbucket.org/efyoung/stationfire/commits/all.

Evaluation of the implementation as a whole involves looking at the outcomes that the program generates in terms of accuracy, contribution to the field, and limitations.

7.1 Accuracy

The most straightforward way to assess the accuracy of this software is to determine how divergent the results from PrioritEvac are from what actually happened in the Station fire. There are a number of different metrics. Two such metrics are available: the number of people who died, and the number of people using the various exits (doors, windows.) To compare the relative accuracy of the overall findings of the various ABM software available for the Station fire, it is possible to subtract the actual results from the simulation results and then adding up the absolute value of those individual differences for a measure of total difference. This avoids privileging any particular individual metric. Table 3 presents both the individual differentials along various metrics as well as the total differential. Since Best (2013) suggests that analyzing the squares of differences highlights outliers in the differences in results, I have included those totals in the last column of Table 3. Results from PrioritEvac are bolded for emphasis.

Table 3: Differentials of simulation results

Model	Bar Exit	Bar Window	Sunroom window	Kitchen exit	Main exit	Stage exit	Dead	Total	Square Differential Total
Actual Results	78	71	34	17	128	24	100		
PrioritEvac mean	**52**	**-34**	**2**	**-8**	**17**	**-2**	**-15**	**130**	**4446**
PrioritEvac example	**30**	**-15**	**-6**	**-7**	**1**	**-3**	**13**	**75**	**1389**
Simulex (Grosshandler et al. 2005)	-58	-71	-34	-14	85	160	-100	522	52582
BuildingEXODUS (Grosshandler et al. 2005)	-56	-71	-34	-13	86	156	-100	516	51234
MASSEgress (Pan 2006)	-42	-71	-34	-13	165	63	-100	488	49324
Galea Scenario 3 (Galea et al. 2008)	-78	-71	-34	-17	-128	-24	-16	368	29786
Pathfinder (SFPE)	-59	-71	-34	-14	79	167	-100	524	54004
Pathfinder (Steering)	-59	-71	-34	-14	73	173	-100	524	55132
Minimum Distance (Spearpoint 2012)	-47	-71	-34	25	-128	323	-100	728	139744
Assigned (Spearpoint 2012)	-58	-71	-34	-14	84	161	-100	522	52734
90 Seconds (Spearpoint 2012)	-56	-1	-3	0	1	17	45	123	5461

Table 3 continued.

First-Gen No Groups (Best 2013)	-41	-69	-28	147	-9	5	8	307	29005
First-Gen Weak Groups (Best 2013)	-44	-61	-28	160	-23	5	4	325	32611
First-Gen Strong Groups (Best 2013)	35	-15	-32	-10	-2	0	37	131	3947
SocEvac (Best 2013)	12	2	-8	-15	-21	12	31	101	1983
SAFEgress (Chu et al. 2015)	6	40	-34	-13	-11	12	0	116	3226
EgressSFM (Fang 2015)	3	35	-34	-5	7	2	5	91	2493
BDI (Valette et al. 2018)	-78	41	-34	-17	33	-24	21	248	11316

As shown in Table 3, PrioritEvac's square differential is one of the better results of those available for comparisons, lower than those from other well-known studies of the Station fire. These comparative results are promising, with an overall differential in the means of 130, indicating an acceptable agreement with the patterns observed during the fire. Additionally, this dynamic of group loyalty contrasts to PrioritEvac as run with no group loyalty, which had a mean number of dead of 45 and a mean differential of 332, demonstrating that it is indeed group loyalty and not just modelling approach that yielded the results in Tables 3 and 4.

The probabilistic results of the ABM simulation method make the PrioritEvac's numbers in Table Two only one of a potentially large distribution of similar numbers. Thus, Table 4 shows the means and standard deviations of these numbers generated from 37 runs of the program PrioritEvac, all with the same parameters in place. 37 was chosen because the standard deviations had stabilized, indicating that further runs would not necessarily produce further insight.

Notably, the mean number of dead and mean number of people who used the main exit, stage exit, and sunroom windows are all within one standard deviation of the actual results. The usage of the bar windows is one of the areas of further interest, given the large variation in the results. The coefficient of variance for this metric is .59, which is extremely high, and much higher than any other metric. This is explained somewhat by a Pearson correlation of -.905 between usage of bar windows and the main exit, significant at the .001 level: people who are using one are not using the other, and appear to be choosing between those two rather than most other options.

Table 4: Descriptive statistics of PrioritEvac results

Variable	Actual	Minimum	Maximum	Mean	Std Deviation	Coefficient of Variance
Dead	100	29	140	85	25.6	0.30
Bar exit	78	80	176	130	26.4	0.20
Bar windows	71	1	98	37	21.9	0.59
Kitchen exit	17	8	12	9	1.3	0.14
Main exit	128	65	191	145	25.3	0.17
Stage exit	24	17	29	22	3.4	0.15
Sunroom window	34	13	54	36	9.4	0.25

The only other statistically significant difference is for kitchen exit, because the actual outcome was more than three standard deviations from the mean of the distribution from the simulation. At this moment it is unclear why this significant result is produced, although it was not readily visible, which may have helped produced the large discrepancy. Future work on this simulation program will explore the role of communication in exit selection.

7.2 Contributions

PrioritEvac is a contribution to the field of fire evacuation studies. It is a novel framework in which to study human behavior. Malleable priorities as a foundation for decision making and behavior is not a usual approach in agent-based models, and presents an option that is different from both pattern-based and force-based agent-based models. This allows for a diversity of approaches in further research, aided by the fact that PrioritEvac is designed to be adaptable and simulate multiple scenarios. PrioritEvac also performs demonstrably and significantly better than models which do not take human behavior into account.

7.3 Limitations

One notable limitation is in the fact that agents immediately stop prioritizing dead agents. This is not dependent on agents witnessing the death of other agents, and so implies an unsupported kind of limited omniscience. The limit is in place because of coding restrictions around the prioritization of agents which have been removed from the simulation. Even though the dead could become an obstacle to movement, they are ignored by this program due to the lack of specific information. There are also limitations in that adaptations for mobility issues have not been included.

Runtime is also a limitation: it takes approximately 13 hours to run the simulation on a computer with a 3.19GHz processor and 10GB of RAM set aside for the use of NetLogo. While PrioritEvac will run on any modern Mac or Windows computer, more limited specifications will result in even longer runtime, creating more time needed to collect information. This limitation is primarily a function of the A* pathfinding algorithm, which implies that larger physical environments might cause further delays.

Chapter 8

IMPLICATIONS AND FUTURE DIRECTIONS

8.1 Directions for Further Research

The program can now be used to explore substantive questions of interest to disaster and fire sciences. Primary among them is further exploration of the specifics of group loyalty in fire evacuation, looking at relative levels of loyalty amongst different groups. In addition to the study of group loyalty, nuances in group leadership can be explored using this software. These different ways of examining social factors allow for this software to be used to further social science in fire evacuation.

A question that emerged during the process of evaluation is the role of communication and perception of danger as influencing exit choice, as well as exploring the impact of the knots of people on evacuation efficiency.

Future research during my doctorate will consider the extent to which the findings using this program can be generalized using the information from other historical cases of fires in public buildings, in effect testing its external validity. The Beverly Hills Supper Club fire, for which considerable information is available, would be an ideal case study.

8.2 Implications for Practice

The practical implications of the results of this program are primarily in the fields of architecture and emergency planning. A better understanding of likely evacuation behavior – not just rational, or ideal, but likely – means that both new buildings and evacuation plans for existing buildings can be more accurate and hopefully further reduce civilian injuries and casualties in structure fires.

Chapter 9

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