Agent-Based Simulation of Human Movements During Emergency Evacuations of Facilities

Joseph L. Smith, PSP
Senior Vice President
Applied Research Associates, Inc., USA

Abstract

During and after any extreme event of natural or man-made origin, getting people out of harms way and to an area of safety are primary objectives. Orderly and efficient evacuations are the key to saving lives. This was clearly demonstrated during the attacks on the Pentagon and World Trade Center towers on September 11, 2001. One of the major recommendations from the US Government's Draft Final Report on the World Trade Center Towers collapse was that building evacuation modeling and procedures should be improved to facilitate safe and rapid egress and support better occupant preparedness for evacuation during emergencies. Performing actual physical evacuations of large occupied facilities is expensive and disruptive to occupants and visitors. Accurately evaluating the affects of various events such as loss of power, smoke, fire, explosions, chemical contamination and structural collapse on human movements is not feasible in real world evacuation exercises. This paper examines a new technology, computer-aided, intelligent agent-based evacuation modeling, that can model and help plan emergency evacuations; run numerous, accurate event-driven evacuation scenarios; support the design of egress for new facilities or facility modernizations; support research in the areas of human behavior in disaster sociology; and model the movement of first responders and security personnel.

Keywords: emergency evacuation, scenario-based simulation, agent-based evacuation modelling, disaster management.

1 Introduction

Evacuating large crowds of people under any circumstance is a challenge. Evacuation of large facilities during an emergency or disaster is a much more complex task because of the added elements of chaos, panic, and the high density of the population. As terrorists move more towards preying on soft targets such as hotels, hospitals, airports, train stations and stadiums, the potential for large government, commercial, residential and sports facilities to become targets is a reality for which we must prepare. Non-terror related events and accidents involving inadequate planning and training for mass evacuations are also all too common. Examples include the February 2003 Rhode Island nightclub fire that killed at least 96 people and the August 2, 2004 supermarket fire in Asuncion, Paraguay, that killed over 300 shoppers. Determining the most effective evacuation plan for a large public facility requires in-depth analysis of multiple factors. Determining the best routes, foreseeing potential problems, addressing the chaos/panic factor, and orchestrating the evacuation are all critical aspects that should be evaluated in a well developed disaster management plan.

Figure 1. Recent evacuations have demonstrated the need to better understand and plan for large-scale movements of people under emergency conditions (World Trade Center evacuation, September 11, 2001 [left] and Evacuation of the US Capitol May 11, 2005 [right]).

To date, most egress planning has been accomplished with so-called hydraulic models where people are assumed to flow out of a facility much like water flowing out of holes in a water filled tube. Such models include typical rule-based speed limits for the occupants and calculate the flow of people as they pass through openings. These simplistic models are not generally capable of simulating human behaviour or the interaction of people with their changing environment, and are not capable of assessing the effects of various, perhaps even multiple, events that may occur during an evacuation.

While many facility owners do conduct evacuation drills, such drills are most often not accomplished during times of peak facility occupancy and do not include event based scenarios such as a bombing followed by fire, smoke, partial collapse and falling debris that would impair or preclude egress through various areas of the facility. Until recently, many evacuation plans called for phased evacuations of only affected floors or areas of large facilities (e.g., if a fire was detected in a high rise building, that floor plus the adjacent floors would be evacuated first followed by the adjacent areas). Hence, it has to date been difficult to accurately understand and predict full building evacuations under realistic emergency conditions. Mass or total building evacuations pose additional problems of stairwell congestion, chaos and potential stampeding of panicked occupants. This is even more important in the post-September 11th era where most people, especially in high rise facilities, now seem to demonstrate a higher propensity to evacuate quickly.

2 Event Simulation

It is now possible through the use of computer simulations to model the behaviour of human movements during evacuations that include events that impact the simulated humans' ability to successfully egress. Applied Research Associates developed an advanced computer program called ***E-SIM*** (Event Simulator) that employs an agent-based approach to modelling the behaviour of people attempting to evacuate a facility. Each agent (or simulated human) has unique properties such as size and speed that allow the realistic simulation of various physical and behavioural characteristics. The simulation updates agent positions and paths each time step during the model run. The following discussion presents some of the major features that are considered in such an advanced simulation tool. Since the ***E-SIM*** tool is one of the most advanced evacuation simulation tools currently available, it is used as an example to demonstrate the major considerations required for such analysis.

2.1 Model Basis

Calculating the movement of people in a virtual environment poses considerable problems. Where do they go? How do they know where to go? What if they encounter an unforeseen obstacle on the way? What if something impedes their movement? While humans may instinctively react and adapt to their environments, getting a simulated human to do so is a difficult task.

Agent routing in ***E-SIM*** is computed using a two level hierarchical path finding approach based on the A* algorithm. The A* search algorithm (pronounced "Ay-star") is a tree search algorithm that finds a path from a given initial node to a given goal node. It employs a heuristic estimate which ranks each node by an estimate of the best route that goes through that node. Using this approach, a high level pathfinder determines the route from the agent's current position to the destination using a graph of rooms connected by exits. Once the high level path is defined, a low level pathfinder is executed each time an agent transitions from one room to another. The low level pathfinder is a basic A* approach which treats each room as a triangular mesh with holes where obstacles prevent agent movement (see Figure 2). This allows the agent to intelligently navigate around corners or obstacles such as furniture that may be in a room.

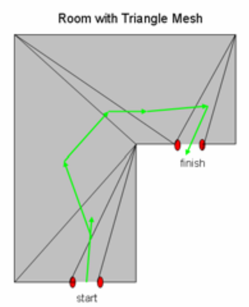


Figure 2. Basic path finding algorithm uses a triangular mesh.

Each agent also has the ability to remember problems or obstructions that they encountered while attempting to exit the facility. This memory is used by the pathfinder to avoid routing an agent back to a blocked exit. Agents that pass within a threshold distance can also communicate their knowledge of blocked exits and other observations/problems to other simulated humans. If the agent gains information from another agent that they did not previously know, and the information identifies a problem along their current path, the high level pathfinder is invoked to determine an alternate route to their destination.

Most people in the real world often do not choose the optimal path out of a facility. Studies clearly indicate that most people normally will first select the path they used to come into the facility even when other paths are shorter. Hence it is important to consider alternates that are not necessarily optimal. An ***E-SIM*** user can specify which exit(s) are primary exits and determine what percentage of the population in the building will use these exits. During an emergency, people will likely use the exit they are more familiar with and/or the exit they used to enter the building that day. "Since people are continually exposed to exit signs but are rarely, if ever, required to use non-familiar exits, they may have learned to filter out this information. During an emergency, it is unlikely that occupants will be prepared to try a route they have never used before to leave the building." (Reference 1).

3 Agent Information

In a model such as ***E-SIM***, agents may be defined by their position, condition, size, speed, and response time. The condition of the agent is whether or not they are dead, waiting because someone is in their way, waiting because of their response time to external stimuli, etc. When modelling an individual or a few simulated humans it is readily possible to manually describe individual unique characteristics for specific agents. However in large simulations involving hundreds or thousands of agents, it is important to be able to statistically describe groups of agents. ***E-SIM*** was develop to handle this by allowing a group of agents to be added to a room or to building floor level in either a random or a specific pattern. When adding a group, the size and speed of the group can have either a uniform distribution or a normal distribution of characteristics. A normal distribution assigns agent attributes along a bell shaped curve. The uniform distribution assigns values within the interval of possible values, with any value as likely to occur as any other value. An agent type can also be given a unique color in order to visually distinguish one agent type from another (i.e., male, female, child, handicapped, and visitor).

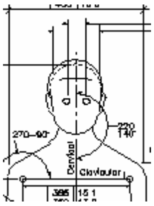
3.1 Size

In an agent-based simulator, the physical size of the simulated humans is important especially when egress is considered in close quarters such as elevators, stairwells, and corridors. A good source of information on standard sizes is the 2000 Architectural Standards (Reference 2). Typical agents are assumed to have sizes defined by minimum and maximum diameters (see Table 1). E-SIM users are not limited to using standard dimensions. First responders and emergency personnel should be assumed to be equipped with material that will effectively make them larger in confined spaces (i.e., they may be carrying axes, oxygen equipment, fire fighting equipment, etc.). Hence, provisions must me made in agent-based simulations to account for the additional space required by such agents. Fully equipped first responders may be assumed to be 50 to 100% larger other than normally dressed adults.

3.2 Speed

E-SIM has built in speed ranges for predefined types of people. A maximum and minimum speed may be specifically assigned to individual agents or randomly distributed to each simulated person in that particular category. The user may change the maximum and minimum or define their own class of people. The maximum speed a user can enter for any one person is normally limited to 1.8 m/s (Reference 3). It is important that agent-based simulations also take into account that the speed of an individual will decrease when ascending or descending stairs or if the individual is disabled. Further, when a person approaches another person in their path, the person behind will try to go around the person in the way. That person’s speed will decrease as he/she approaches the other person. Typical human speeds are given in Table 2.

Table 1. Typical simulated human dimensions (inches).



	Minimum (2.5 percentile)	Maximum (97.5 percentile)
Men	16	19.4
Women	14.4	17.7
Children Age 1	8	8
3	9.5	9.5
5	9.1	11.5
7	9.9	12.6
9	10.5	13.8
12	11.9	15.6
15	14.8	18.2

Table 2. Typical movement speeds (meters/second) for simulated agents.

	Min.	Max.	Min Down Stairs	Max Down Stairs	Min Up Stairs	Max Up Stairs
Men	1.10	1.60	0.85	1.05	0.85	1.05
Women	1.05	1.45	0.85	1.05	0.85	1.05
Disabled	0.71	1.25				
Locomotion Disability	0.57	1.02	0.22	0.45	0.26	0.52
Disability No Aid	0.70	1.02	0.20	0.47	0.35	0.55
Disability Crutches	0.67	1.24	0.22	0.22	0.26	0.45
Disability Walking Stick	0.49	1.08	0.24	0.46	0.35	0.35
Disability Walking Frame	0.34	0.83				
Disability Electric Wheelchair	0.89	0.89				
Disability Wheelchair	0.38	0.94				
Disability Assisted Wheelchair	1.02	1.59				
Disability Assisted Walk	0.58	0.92	0.53	0.90	0.55	0.78

3.3 Response Time

The response time of an agent varies depending on their particular situation. Response time is defined as the time span between when a person first hears an alarm or signal until he/she starts their exit out of the building (Table 3). For instance, a person asleep in a hotel will have a longer response time than if he/she were awake because he/she will have to first wake up, get oriented, get dressed, and then leave. Another factor that effects response time of a person is the type of alarm. An alarm with a live voice giving instructions is more effective with a shorter response time than just an alarm sounding. ***E-SIM*** allows the user to define any value for the response time of any individual. Some agents may take tens of minutes to respond (e.g., the guy who just has to make that last phone call or who just doesn't believe this is "real" alarm).

Table 3. Typical ranges of response time (seconds).

	Min.	Max.
Awake Familiar	0	60
Awake Unfamiliar	0	120
Asleep Familiar	15	120
Asleep Unfamiliar	30	180
Required Assistance	60	600

For example, a typical male office worker could have the following characteristics. His size would be that of a typical male; therefore his diameter would be between 16 and 19.4 inches. His speed would be between 1.10 to 1.60 m/s on a flat surface and between 0.85 to 1.05 m/s going up and down stairs. His response time would be that of an awake and familiar person, between zero and 60 seconds. If this typical male office worker has broken his leg and is now using crutches, his speed would reduce to that of a person who uses crutches. So his speed on a flat surface would be between 0.67 to 1.24 m/s, 0.22 m/s going down stairs, and between 0.26 to 0.45 m/s going upstairs.

Special cases must also be considered in advanced evacuation simulations. For example, the speed and behaviour of a mother with small children will be significantly different than if the same woman were alone. Another example would include caregivers and patients. Any advanced event/evacuation simulation tool must be able to account for such behaviours and speed restrictions. Finally, in order to populate large facilities, an event simulator should provide a method for groups of agents to be added to each layer or floor of the facility using either a uniform or normal distribution incorporating the minimum and maximum speed and response time.

4 Scenarios and Results

The types of scenarios that may be simulated in an agent-based event/evacuation simulation are numerous. The significant advantage of an advanced simulation tool such

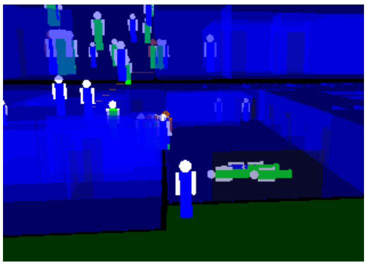


Figure 3. Sample simulation showing injured agents.

as ***E-SIM*** is the ability to introduce multiple events within a single evacuation scenario that allows the user to evaluate potential real world situations that could not be safely or economically reproduced in an actual evacuation drill. ***E-SIM*** is configured to simulate any combination of two types of events. These are classified as either “environmental” that will slow or impede an agent’s progress, or “standard” that will kill all agents within the designated event area and deny all access to others attempting to pass through an area. Examples include:

Environmental Event	Standard Event
Loss of power	Explosion
Loss of light (darkness)	Toxic chemical exposure
Water (flooding)	Structural collapse
Smoke (light)	Smoke (heavy)
Biological agent exposure	Fire blocking egress

4.1 Example

Figure 4 shows a sample output from an ***E-SIM*** analysis. Data can be presented as static snapshots or as movie media. Such graphical display of the information allows the users to readily identify areas of concern and take corrective actions or make plans as necessary. In one case analyzed for a large facility, a client recently discovered unforeseen problems. In that case, a shelter-in-place plan was evaluated. The simulation clearly showed that the facility had inadequate interior shelter areas and potentially produced a crowd control problem due to the large number of visitors expected in the facility. It would not have been feasible to quickly and clearly identify this as an issue without an advanced simulation of the plan.

4.2 Validation

E-SIM has been validated at the component level, through planned comparison to evacuations conducted on small facilities, and through comparison to anecdotal information available from actual large scale evacuation events. Data such as that shown in Figure 5 from a simulation of a small facility evacuation have been shown to be useful in comparing to actual observed data. Figure 5 shows the number of people on a particular floor as well as the number of people entering and leaving that floor level as a function of time during the evacuation. There is no known substantial documentation of full building evacuations of large and heavily populated facilities at this time.

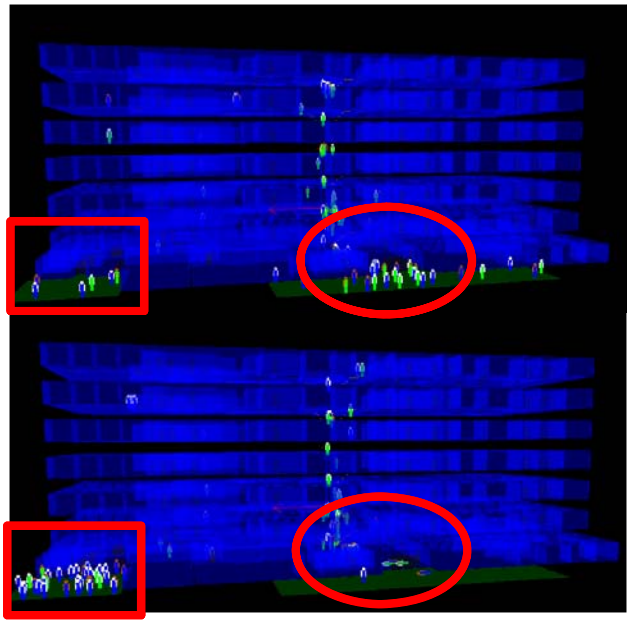


Figure 4. Sample simulation. Top – normal evacuation where most people exit from main exit (oval). Bottom – agents exit from alternate exit (rectangle) due bombing in lobby that killed simulated agents.

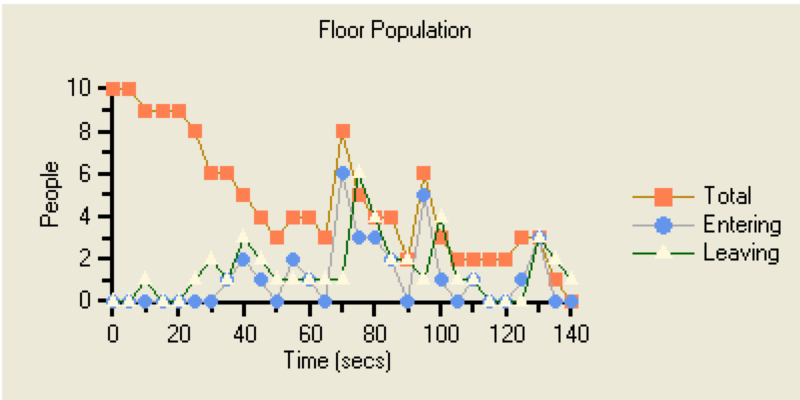


Figure 5. Data from a sample simulation (agent count on a specific floor).

5 Conclusion

Modelling emergency evacuations through the use of computer aided, agent-based simulation offers significant advantages over more simplistic modelling approaches. Such tools may be used to evaluate egress and events in existing facilities as well as in the design and layout of new facilities. Future versions of the ***E-SIM*** tool will include enhancements to address evolving egress problems. One such new issue is the use of hardened window systems in hurricane and terror resistant construction. Such windows (Figure 6) are, by design, difficult to break and will impede emergency egress by occupants or ingress by first responders into a facility. Without planning and training for such contingencies, an unsuspecting person may panic and be trapped in a dangerous situation.

Figure 6. Woman unsuccessfully attempting to pass through a hardened window system by using office furniture (computer) as egress tools.

References

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