Review of Pedestrian and Evacuation Simulations

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Abstract

Simulating emergency evacuations has grown in popularity since the tragic events of September 11th. Unfortunately there are a large number of modeling, simulation, animation and computer graphics systems available today – many of which are misleading. Models and simulations fall into two main categories: Microscopic and Macroscopic. We highlight the general differences in these approaches outlining the strengths and weaknesses in both approaches. We examine the fundamental principles of pedestrian and evacuation simulations in this paper and guide the reader towards a greater understanding of crowd dynamics and evacuation analysis. A background to modeling and simulations, their purpose and objectives followed by a risk assessment analysis description is presented. We highlight the different type of evacuation scenario that need consideration when choosing a modeling/simulation tool and conclude with a checklist for choosing an evacuation analysis system.

Keywords

Crowd Dynamics; Crowd Safety; Evacuation Analysis; Pedestrian Simulation; Risk assessment, behavioral based safety.

Biography

G. Keith Still has a PhD in "Crowd Dynamics" and has developed a wide range of crowd simulation and modeling techniques for critical infrastructures. Projects include the modeling of the Haj (annual Pilgrimage to Makkah in Saudi Arabia) and the real-time command and control system for multi-building, wide area evacuation at Canary Wharf – UK Financial District. He is a regular visiting speaker at the UK Cabinet Office Emergency Planning College (Easingwold) where he runs workshops on crowd dynamics and crowd safety in the build and complex environment. He has provided testimony for the Committee on House Administration at a televised public hearing (June 9th, 2005) on the "Emergency Preparedness of the House and the Evacuation of May 11th, 2005". His website www.GKStill.com is used by academic and industry based researchers around the world.

1 – Introduction

Modeling evacuation from complex spaces involves a large number of variables, many of which are unknown and potentially unknowable. How a crowd reacts to an incident is not something that can be easily tested as the nature of an evacuation, and its consequences, are impossible to replicate under controlled conditions without endangering the test subjects [1, 2, 3, 4, 5, 6, 7]. However, we can learn from past events [8, 9], study the things that work and those that fail, improve process and understanding – but planning for the unforeseen (such as the tragic events of 9/11) remains an oxymoron.

Simulations help us explore the boundary conditions of a problem. For example the best possible time would it take to evacuate X people from Y floors of a multi-story building [10, 11, 12, 13, 14]. But evacuation is highly dependant on crowd behavior, communication systems and the nature of the threat, the alert status (which can create over-reaction or the opposite, complacency) and many other variables. Extreme caution is advised on taking the results of a simulation as an absolute safe egress value [15, 16, 17, 18, 19, 20, 21, 22].

Models and simulations should be considered to have two main purposes: either proof/ failure of some theoretical value, or to provide some insight to potential problems. Clearly there is a requirement for simulating an emergency evacuation of the built and complex environment. The egress time is a critical factor in understanding and applying the appropriate evacuation strategy.

In general evacuation simulations can be used to explore potential failures in our planning for an emergency or issues that may arise during egress. However, this requires basic and fundamental understanding of the elements of behavioral based safety to be used with any confidence [23, 24].

2 – Modeling techniques

The two main categories of modeling techniques are defined as microscopic and macroscopic [25]. Microscopic modeling used some computer simulated agents capable of decision making in a model of the built or complex environment we wish to test. Macroscopic models include the building codes, general flow and distance calculations and available egress widths demonstrating compliance to the building codes.

A two stage process should be employed in the process of modeling an evacuation. Begin with the macroscopic process – evaluate the travel distances and route capacity. Should questions arise from this analysis then change resolution to the microscopic level of analysis. Use the process of modeling to gain insight to the nature of the problem – a simple example is to run a shortest path test. Take a map or plan of an area and test a number of initial starting positions. Draw a graph of the travel distance against the occupancy levels. How many people may arrive at the same time, to any specific exit, can tell you a lot about the success of an evacuation of a place of public assembly.

3 – Snake oil

The claims of many vendors to “model the range of human behavior” can sound convincing however, in our extensive experience, elements that affect the human behavior such as way finding, demographics, public address and communication systems, dominant personalities (such as a police officer), state of alertness (the evacuation behavior pre- post- 9/11 is very different in tall buildings) can all change the evacuation timings and are not easily modeled. To cut through this maze of conflicting and confusing variables our first criteria for evaluating a modeling system is the vendor’s claim. It is very easy to read the papers written on a modeling technique and these should be readily available. Conference proceedings such as “Human Behavior in Fires” [12, 13], “Pedestrian and Evacuation Dynamics” [14, 15] outline various modeling techniques and provide a good cross reference for the specific simulation. Validation of the vendors claim, third party validation and refereed publication separate most of the problems of good/bad simulations currently available.

An honest vendor will state their claims clearly and in an easy to understand manner,. Beware the “snake oil” pitch of a software vendor and always seek third party validation. Simulating emergency evacuation is a matter of life or death and the garbage in/garbage out principles, fundamental to all computer simulations, should not be underestimated.

4 – Egress time

Evacuation is a two stage process and this must be defined in any model and/or simulation. The two stages are “reaction time” and “evacuation time”. The former of these is the time it takes the crowd to ***start to move***. Clearly if the reaction time is the second the alarm is raised then the evacuation time is a function of the various egress route capacities and travel distances.

However, if the building occupants take time to ***start to move*** then the evacuation time will be a function of both the reaction time ***and*** the travel distance/route capacity. Sime [26] ran a series of tests on the Tyne and Wear Transport system His results are show in the table below.

Evacuation Test	Time to start to move		Time to clear the station	Appropriateness of behavior
	Concourse	Bottom Escalator		
1 Bell Only	08:15	09:00	14:47	Delayed or no evacuation, not all the people leave
2 Staff	02:15	03:00	08:00	Users directed to concourse
3 P.A.	01:15	07:40	10:30	Users stood at bottom escalator
4 Staff + P.A.+	01:15	01:30	06:45	Users evacuated
5 P.A.++	01:30	01:00	05:45	Users evacuated by trains and exits

Table 1 – Results from the Sime evacuation analysis

To summaries his research the reaction of the crowd, the time to start to move, is highly dependant on the crowd communication system. Most modeling software, simulations and evacuation analysis ignores this important element of behavioral based safety. It is how the crowd reacts to the change in the environment coupled with the information system that can dramatically change the evacuation timings. The different timings above are a matter of perception, following the events of May 11th where many of the building occupants were alerted via blackberry communication systems it was noted that several minutes delay could be added to the above while the message to evacuate propagates through the networks.

Clearly evacuation modeling that is travel distance and capacity based has severe limitations in assessing the actual egress time. So one of our first elements to our checklist for a good simulation is the reaction time – does this simulation allow me to test variable initial reaction times?

5 – Egress instructions

Simple instructions, delivered in a clear and concise manner has a dramatic effect on the evacuation process and, again this is often ignored in modeling and simulation of emergency egress. An example of this critical element in modeling evacuation is illustrated in another of Sime's research projects.

Lecture Theatre	% using route		Instructions from lecturer
	Entrance	Fire Exit	
F	55	45	To leave the room (exit unspecified)
R	0	100	To leave the room via the fire exit only
F	62	38	To leave the room (exit unspecified)
R	30	70	To leave the room (exit unspecified)

Table 2 – Results from the Sime Theatre Evacuation Analysis

From Sime [27]

> *The aim of the study was to examine the effects of exit position on the exit chosen and time to evacuate. To do this the simultaneous evacuation of two lecture theatres on the ground floor of a building in Portsmouth Polytechnic was monitored. The "front" (F) lecture theatre had its entrance and fire exit in both back corners. The "rear" (R) lecture theatre had the entrance at one corner at the back and fire exit in a corner at the front.*
>
> *In the F theatre the lecturer decided not to tell his "audience" which exit to leave by. A statistical analysis was conducted on the possible relationship between seat position, travel distance moved, exit used and time taken to leave in the F theatre. Observers at each exit recorded frequencies and evacuation times and gave out a questionnaire to each evacuee, which was used to supplement the other data. Of 56 people in the F theatre 55% left by the entrance, 45% by the fire exit;*

As the above experiment demonstrates Empathy or Authority announcements can dramatically alter the evacuation time in places of public assembly and, again, this element is often ignored in a simulation of emergency egress. During a security alert at the Birmingham Arena the staff had to call an evacuation. The demographics of the crowd (at a rave – a dance event) were youths ages 18 – 24. Initially, the security staff made an announcement using the venue public address system to evacuate the area immediately.

As you may expect the crowd did not react to this announcement. A few minutes later the DJ made an announcement that began the evacuation process. Same message but difference was using an empathy figure instead of an authority figure to deliver the message. How the message is delivered is vital to reducing the ***start to move*** time.

6 – Boundary conditions

Modeling and simulation help us understand the lower limits (fastest possible time) and the user is advised to restricted modeling and simulation to the analysis of travel distance, availability and location of exits with respect to the general population, direction and capacity for optimal egress. We call this process a ***spatio-temporal analysis*** in which the boundary conditions are explored [28, 29, 30].

To illustrate this given a specific occupancy limit, a number of exits how long would it take for the occupants to reach a place of safety. We can test some or all of the available exits under a range of initial start to move assumptions and explore the environment. One project, for an international bank, involves 4 stairwells in a 32 story building. We used a commercial simulation to test the what-if scenarios of all exits available and all combinations of 1, 2 or 3 exits (16 tests in total). This uncovered a problem at the South-East exit in which the security system would create a bottleneck if the occupants had to ***ALL*** leave by this exit. Modeling egress using different scenarios under the same assumptions (zero reaction time, all occupants to the same exit) allows the user to explore the potential problems. This application of modeling is firmly in the "insight" domain as it throws up a potential problem in relative terms and not as an ***absolute*** egress time. As we have illustrated ***absolute*** egress times need to be treated with the appropriate understanding of the evacuation process and communication system deployed [31, 32].

7 – Behavioral based safety

Modeling human behavior is, as we've stated above, a complex business and there are many unknown variables such the communication message and delivery [33, 34]. This can have a dramatic affect on the egress rate and we need to include this in our analysis to understand emergency behavior and the evacuation time.

Where the simulations are useful are in defining the lower (best) evacuation. We can simulate to define the lower boundary conditions, this may prove useful in defining building code compliance and our simulation process begins to take shape as providing ***insight***. We can digitize and environment, measure the travel distances, calculate the capacity using the narrowest point along the route limits [35, 36, 37], and estimate using both a rough cut capacity analysis of flow and density (see table below) and estimating the additional start to move time depending on our communication systems and methods.

	Density	Space	Space	Flow Rate	Flow Rate	Av. Speed	Av. Speed
LoS	**(ped/m^2)**	**(m^2/ped)**	**(ft^2/ped)**	**(ped/min/m)**	**(ped/min/ft)**	**(m/s)**	**(ft/min)**
LoS A	**≤ 0.27**	**≥ 3.24**	**≥ 35**	**≤ 23**	**≤7**	**≥ 1.3**	**260**
LoS B	**0.43 to 0.31**	**2.32 to 3.24**	**25 to 35**	**23 to 33**	**7 to 10**	**1.27**	**250**
LoS C	**0.72 to 0.43**	**1.39 to 2.32**	**15 to 25**	**33 to 49**	**10 to 15**	**1.22**	**240**
LoS D	**1.08 to 0.72**	**0.93 to 1.39**	**10 to 15**	**49 to 66**	**13 to 20**	**1.14**	**225**
LoS E	**2.17 to 1.08**	**0.46 to 1.39**	**5 to 10**	**66 to 82**	**20 to 25**	**0.76**	**150**
LoS F	**> 2.17**	**≤ 0.46**	**< 5**	**variable**	**variable**	**≤ 0.76**	**≤ 150**

Table 3 – Highways Capacity Data – the speed/density/flow relationships [38]

At a fundamental level the travel distance is just one function of egress time and, in that respect, capable of modeling and design optimization. Modeling techniques that are based on the travel distance and involve assessing the capacity of routes and optimization of the egress rates serve our general evacuation needs very well – but do NOT provide the actual time to egress and hence we should NOT treat these as absolute values.

For example, how a crowd may react to a specific event (such as the Cessna incident on May 11th in Washington DC) can depend on the time of day, nature of the information (blackberry information and rate of communication – reports of several minutes delay to transmit, receive, understanding, time to react) all add significantly to the overall evacuation time [39, 40, 41, 42, 43, 44].

One element of evacuation is the ***cry wolf*** element too many false alarms and the effective evacuation time would ***increase*** for the next evacuation alert. Again this element of evacuation simulation is often neglected with obvious consequences.

8 – Scenario planning

Prior to 9/11 the majority of evacuation considerations was joking referred to as the GTFOT principle. In the event of an emergency (typically a fire) then the occupants were advised to **G**et **O**ut of **T**he building as quickly as possible. Sadly human behavior in fire is often complex and confusing. Given the rate of the incident may develop in seconds the initial reaction time is critical to life safety.

Post 9/11 we need to take into consideration the possibility of chemical, biological or nuclear/radiological threats. This leads to a very different type of scenario planning and one in which modeling and simulation can serve a useful purpose. There are four main categories of evacuation which can be served by a variety of the modeling/simulation/animation techniques.

.1 Total

This is the process in which all occupants leave by the nearest available exit and assemble at a place of safety. We need to consider the location of a place of safety as, unlike fire, simply being away from the threat is a function of the nature of the threat. The assembly points may be in a danger zone in the event of a bomb threat.

.2 Directed

This is the range of scenarios in which is becomes necessary to evacuate a building or place of public assembly in a specific direction. So again assessing the place of safety, this may be a cordon, a range away from a threatened area or upwind from some contaminant (natural or terrorist activity).

.3 Phased

The problems of internal contamination, such as anthrax, in which most of the building can be evacuated but certain areas need to be contained until decontamination procedures are implemented. Also in the event of fire in tall buildings the floors immediately above and below the seat of the fire will be evacuated BEFORE the other floors. This is the typical process and procedures where sufficient fire suppressing systems are functional. The policy of phased evacuation has come under criticism as, again, human behavior and therefore behavioral based safety may conflict with the building design, operation and evacuation strategy.

.4 Stay Put

Events during the bombing in London from the IRA have demonstrated, in numerous cases, that the policy of "stay put" can be very effective in life preservation. The building can absorb the blast while the occupants are contained in a place of relative safety inside the structure. Consider a simple thought experiment in the recent Cessna incident (May 11th). Were the building occupants at greater risk running through the streets or within the building? Clearly this depends on what payload the plane was carrying and its intended target. To consider an effective evacuation strategy you must model the risk assessment to the people.

4 – Risk Assessment for places of public assembly

There are a number of risk assessment techniques available and we have a selection of these on our website [45]. The basic principle is to create a table of the likelihood against the consequences. We illustrate this below.

	Consequence				
Likelihood	Minor	Medium	Major	Critical	Extreme
Almost Certain	*Moderate*	*Substantial*	*Substantial*	*Intolerable*	*Intolerable*
Likely	*Tolerable*	*Moderate*	*Substantial*	*Substantial*	*Intolerable*
Possible	*Tolerable*	*Tolerable*	*Moderate*	*Substantial*	*Substantial*
Unlikely	*Trivial*	*Tolerable*	*Tolerable*	*Moderate*	*Substantial*
Rare	*Trivial*	*Trivial*	*Tolerable*	*Tolerable*	*Moderate*

Table 4 – Risk Analysis Matrix (Likelihood vs Consequences)

.1 Using a matrix for risk assessment

Risk assessment for an evacuation can be assessed considering the target and the payload of a small aircraft – therefore if the target was people and the people were on the streets then the consequences would be extreme. This is a simple application of a game theory model to assess relative risk and develop a strategy that is appropriate for the scenarios.

By comparison of the numerical values of likelihood and consequences we can develop a site specific threat scenario analysis and appropriate evacuation strategy. We use a colour coded method to make these tables easier to read – you can download the excel spreadsheet from the website (www.crowddynamics.com).

Level of Risk	Defined
1	*Trivial*
2	*Tolerable*
3	*Moderate*
4	*Substantial*
5	*Intolerable*

Table 5 – Level of Risk - Numerical definitions

Each threat scenario, likelihood against consequences and tabulated provides a relative measure of threat/risk assessment. To expand on this theme we can assign actions to the various threat levels as follows:

Trivial	No further action and no record required
Tolerable	A risk that has been reduced to a level that can be endured
Moderate	The risk needs to be evaluated carefully and reduced to being a 'tolerable risk'.
Substantial	A high level of monitoring and record keeping will be required, until the risk is reduced or eliminated.
Intolerable	This level is not acceptable and change is required until the risk has been reduced to one of the above

Table 6 – Risk Action Planning Matrix

Finally we can apply an action list to the above and develop an approach to both modeling the threat and developing a strategy.

Elimination of the risk, if possible. Specialists should possibly be used to carry out assessment profiles and suggest risk reduction methods. This would include security and screening processes to eliminate the potential of a security alert (bomb threat).

Reducing the risk, if possible, Organizations should adapt processes to suit the situation or circumstances, take protective measures that cater for everyone in the area, improve controls and procedures, manage the care and safety of the occupants and maintain procedures to the required standards. Fortification falls into this category of risk mitigation.

Manage the risk. If risks cannot be eliminated or reduced sufficiently, personnel need to be deployed to minimize the risk. During evacuation the deployment of security staff, assignment and designation of places of safe assembly can be a dynamic process and effective crowd management is often the practical solution.

Planning around the risk. Emergency procedures should be explained and practiced so that everybody knows what to do. Alarm systems and indicators should be thoroughly tested on a regular basis and should take into account any special needs, noisy environments etc.

5 - Conclusions

Presently, there is a growing concern about the use of modeling and simulation. We have been running education and awareness, training and application workshops around the world for the last decade and the problems of misuse, misunderstanding and ***snake-oil*** salesmanship are all too common. In life critical application we need to be cautious of computer simulation and their limitations. We can make the following general observations about the simulation approach to decision making.

1. Simulation is most appropriate when the problem is too complex or difficult to solve using another method.

2. A model must be developed to represent the various relationships existing in the problem situation.

3. A process such as random-number procedures must be employed to generate values for the probabilistic components of the model.

4. A bookkeeping procedure must be developed to keep track of what is happening in the simulation process.

5. The simulation process must be conducted for many periods in order to establish the long-run averages for the decision alternatives or other changes in the system. Ergodic analysis (long term averages) should be the purpose of the simulation system.

6. Local transient effects can skew simulation results - as can bad model building - it is essential that simulation builders be scrutinized in the same way one would scrutinize the simulation system.

7. A decision support simulation needs to be validated and open to scrutiny. Good third party validation is essential to be confident of any simulation system.

To summarize the situation you should go through the following checklist with the vendor (and consultant) who proposes a simulation system for evacuation strategies.

1. What third party validation do you offer?

2. Is this a black-box or an open source model?

3. How long does it take to build a model?

4. How can we test/validate the underlying assumptions in the model?

5. How brittle is the model - if I make a small change to my basic assumptions how long does it take to change the model?

6. What is the cost of building and modifying a model – both in time to change and training required to make these changes?

The potential user of pedestrian or evacuation model should also pay specific attention to the appropriateness of the model to the application. For example an agent based model with multiple parameters is probably not the best way to model 100,000 people in a mass gathering. Similarly a flow model (macroscopic) is not going to provide accurate results for a complex space involving many turns and congestion points.

These questions are easily answered by asking the vendor specific issues relating to previous use and applications of their software, tools, models or simulations. Ask about validation; ask about the safety factors built into their models and the types of outputs. If the system produces a single value as an output (say 8 ½ minutes for evacuation) rather than a mean time with a standard distribution and a statement about the assumptions used, then be suspicious of the models quality. Ask about the assumptions built into the ***start to move*** process and how that affects the overall results.

If you are not satisfied with the answers to the above questions then - ***caveat emptor*** – buyer beware. In general GOOD simulation systems follow four simple principles. Simulations should be:

1. Simple to build
2. Simple to modify
3. Simple to understand
4. Simple to communicate its output

At all times a model should adhere to the ***BATNEEC*** principle – best available technology not entailing excessive cost.

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[45] You can download both a spreadsheet risk assessment template and the associated descriptions from www.GKStill.com