Standing Room Only

Frederick D. Franzwa
Jonathan L. Matthews
James I. Meyer
Rose-Hulman Institute of Technology
Terre Haute, IN 47803

Advisor: Aaron D. Klebanoff

Letter to the Editor

To the Editor:

Recently, the city has decided to review the current public safety ordinances pertaining to the capacity limits on buildings and public areas. Our team has been asked to reconsider the current ordinances and suggest modifications. Our recommendation will be discussed and voted upon at an upcoming city council meeting, which has stimulated public interest and discussion.

We began our review by defining the purpose of such regulations. We felt that the primary purpose is to preserve public safety. Limiting capacity for other reasons is unnecessary and is likely to promote disagreement and repeated requests for exceptions.

Threats to public safety take two forms: emergencies that require evacuation, and incidents within the venue that require access by police or rescue personnel.

Our analysis is based on statistical data taken of crowd motion in public areas. These data were then incorporated into a computer model that allowed us to investigate crowd behavior in the context of many different situations, including general purpose assemblies of various sizes, classrooms, lecture halls, cafes, and banquet halls, as well as outdoor events from small rallies and demonstrations to parades. This investigation was broad enough to encompass nearly every type of public event.

Only two simple regulations are needed to ensure public safety. First, *there must be no more than 40 people for each exit in the facility*. This rule assures that any room in a facility can be evacuated in one minute or less.

The UMAP Journal 20 (3) (1999) 311–320.

The second regulation is that *each person must have at least 5 sq ft of floor space*. This limitation ensures that small groups of individuals can move throughout a crowd in a reasonable time. Even if there are unlimited exits, a high density of people can be very dangerous; in the event of a personal emergency (heart attack or possibly severe allergic reaction), rescue workers must have sufficient access to the area. These problems are compounded in the event of a riot or mob situation. We found that if the amount of space per person is much less than 5 sq ft the difficulty of moving through the crowd increases drastically.

Overall, we feel this change to regulation will be beneficial to everyone. It will maintain a high standard for public safety and is not unduly complicated or cumbersome. We urge anyone with questions or concerns to contact us. We would be happy to share any additional information or details of our analysis.

Sincerely,

The Room Capacity Assessment Team

Reasons for Legal Capacity Limit

Capacity limits must be considered from the standpoint of convenience and comfort. For example, an overcrowded concert hall can diminish the elegance of the facility, and likewise it is very frustrating to be stuck in line to leave a stadium with fewer exits than optimal. However, we feel that the only justification for a capacity limit is public safety, which falls into two basic categories:

- **Emergency evacuation time:** In the event of a fire or other emergency, the room must be able to be completely emptied quickly.
- **Mobility of small groups of individuals:** Any time a large number of people are packed closely together, there is potential for a mob or riot situation. There is also the possibility of medical emergencies occurring in the crowd. Police, security personnel, and rescue workers must be able to reach any location in a timely manner.

We discuss special cases with unique considerations in the **Appendix**.

Qualities of a Good Capacity Limit

A good capacity limit preserves public safety and is fair and defensible. The model must be easy to understand and implement, to reduce confusion and promote fairness. It is very likely that at times an organization will petition for special permission to hold an event, which may require that the regulation be defended in a courtroom, so the model must be well supported.

Overview of the Approach

We created a model of motion of individuals in a crowd and implemented it on a computer. This model was then used to observe the behavior of the crowd and test various capacity-limiting criteria. Test rooms of various sizes and layout were constructed, and for each room several trials were run, each time increasing the density of individuals in the room.

We made two measurements on each room/crowd-density trial. The first measured the time to empty the room completely, while the second counted the number of individuals whom a security guard is likely to encounter when moving from one side of the room to the other.

Assumptions

- We are concerned only with safety factors. Any other factors need to be addressed by the owner but should not be taken into account in deciding if the capacity is "unlawful." Customers of the facility will hold the venue owner responsible for comfort issues.
- The people have perfect knowledge of the state of the room at all times. This is reasonable because people do have a good sense of the state of the room.
- People try to get out of the room in the shortest possible time.
- People act in their own best interests, not necessarily in the best interests of the group.

Crowd Escape Model

Description

We simulated people leaving a room. We created rooms in an Excel spreadsheet and then imported the data into a program written in Visual C++. We represented the room as a grid of 1-ft squares, where every spot on the grid was an open space, an immovable object, or an exit. A specified number of people were placed into the room in random locations, with each person occupying a single 1-ft square.

In the simulation, people exit the room according to the Personal Movement Algorithm described below. The algorithm is executed for each person in the room then repeated. Each iteration allows a person to move 1 ft. We measured average walking speed to be approximately 3 ft/s, so each iteration represents 1/3 s.

Personal Movement Algorithm

- Find the best exit and move toward it, taking into account the size of the crowd waiting to use that exit and the distance to the exit.
- If your path is blocked, move in the next best direction. If no moves get you closer to the door, stay in place.

This algorithm is an appropriate model of people exiting a room. People in the model initially head for an exit close to them; but if that exit becomes too congested and another exit clears up, they may head for the less busy exit (much like switching checkout lines at the grocery store). The second rule is reasonable because this is the best way for a person to minimize the time in line. There are two additional restrictions on moves:

- No person can move onto a square that was occupied by another person in the previous time step.
- Flow through the each exit is limited to one person every 1.33 seconds.

To gain a qualitative sense of crowd behavior, we collected data by observing people leaving a movie at a local theater. We recorded how many people traveled through a double door per second and the density of the crowd passing through the door, as well as the speed and density in an open area. This information motivated the additional restrictions.

Without the first restriction, the model is unrealistic because people get much too close to one another. Our observations indicate that the density is much less than 1 person/ft^2 when people are moving; otherwise people would be walking on the heels of the person in front of them.

At the theater, we also noticed that people tend to move more slowly going through a doorway than in an open area. This necessitated the introduction of the second restriction to ensure a realistic flow rate through each exit.

Description of Test Rooms

After defining how people leave the room, we constructed a set of test rooms. The characteristics of the room that could influence the exit time can be grouped into four basic categories (**Table 1**) or a special case.

For each category, we constructed rooms of various sizes, composed of immovable objects (walls, desks, etc.), open space, and exits (**Table 2**).

Exits

One exit represents an opening large enough for one person to walk through at a time. Single doors are represented by one exit. Though three people can walk abreast through a set of double doors, our research at the movie theater shows that a crowd will move through such a doorway two at a time; so we model double doors as two adjacent single doors.

Table 1.
Room classification.

Category	Example
Limited exits	Parties, conventions, concerts, many indoor assemblies
Rows and aisles	Auditoriums, lecture halls, movie theaters, stadiums, inside sporting events
Unlimited exits	Outside sporting events, rallies, demonstrations, parades, air shows, some outdoor concerts
Movable objects	Banquets, cafeterias, restaurants

Table 2.
Test Rooms—Escape Model.

Category	Name	Size (ft^2)	Description
Limited Exits	Small room	144	1 exit
	Medium room	800	3 exits
	Large room	3,000	9 exits
	End exit	800	3 exits all at one end
Rows and aisles	G220 (classroom)	380	2 exits with rows of tables
	E104 (lecture hall)	1182	4 exits with rows of seats
Unlimited exits	Soapbox speech	229	Small outside assembly
	Parade	931	Large outside assembly
Movable objects	Small cafe	411	1 exit with tables and chairs
	Banquet hall	1498	3 exits with tables and chairs
Special cases	Airplane (normal deboarding)	286	1 exit with rows and aisle
	Airplane (crash)	286	6 exits with rows and aisle

Movable Objects

An object small enough to be stepped over should not be considered in the model. Other objects that can impede flow can be treated as immovable. For example, if a chair is in your way in a very crowded room, there is no place to move the chair because of the high density of people. On the other hand, if the density of people is low enough to allow the chair to be moved, you could instead simply use that space to move around the chair. Either way, you are delayed, either by changing your path to move around the chair or by pushing it out of the way. Therefore, our model assumes that people move around movable objects.

Test Room Results

Each test room was simulated with 10 trials, each trial increasing the number of individuals in the room, from 20 ft^2/person to 2 ft^2/person:

- **Limited Exits:** As expected, increasing the number of people in the room also increased the escape time. There was not a noticeable change when the exits were all placed on one end.

- **Rows and Aisles:** Rows and aisles did not seem to have a significant impact on the escape time. Like the open-room tests, people simply crowded up around the exits.

- **Unlimited Exits:** Escape time seemed to be limited by how far the individuals had to move.

- **Movable Objects:** Movable objects did not seem to have a significant impact.

- **Special Cases:** When exiting an aircraft, the use of emergency exit doors greatly expedites the evacuation process.

Overall, we found that

The ratio of persons to exits determines escape time.

Variations in the data can be explained by several factors. First, the size of the room does play a role. In large rooms, the exit time is slightly longer than for a small room, mainly because even if there are few people in the room, it is large enough that the exits are underutilized while people initially start moving towards them. This effect is best shown in the large room at low densities.

Also, the presence of additional objects does seem to slow progress slightly, as in the airplane example, where the number of available paths is very limited.

Weaknesses

- **Parameter values are debatable:** We based our packing and flow rate constants on a restricted data set. Our observations from the movie theater give us a handle on the situation, but more information is desirable.

- **People don't slow for obstacles:** When a person has to change path to avoid a chair, person, or other obstruction, the person does not slow down. This would only become a major concern when the limiting factor for room escape is the time to reach the exit, as in a large sparsely populated area.

- **People move too much:** In real life, people realize that moving left and right will not get them any closer to the exit. In the model, people always try to get closer to the exit by making extraneous movements. These extra movements help to keep people spread out so that the crowd density doesn't get too high, but do not seem to affect exit utilization.

- **Abnormal rooms:** There are certain room setups where the Personal Movement Algorithm will not lead all persons to exits. For example, people will never move away from an exit to navigate around large obstacles. This can result in people becoming stuck within the room. This problem can be avoided by creating submodels. If a room contains an area in which people can become stuck, then that portion can be modeled separately from the rest of the room. In this way, we can handle any possible room configuration.

Strengths

- **Movement models observed data:** Our model is grounded with data from a situation very similar to the ones we are modeling. This gives a higher confidence in the conclusions and promotes better applicability to actual situations.
- **Movement looks realistic:** The path of a single individual in the simulation follows the path that we would expect of a real person.
- **Adaptable and robust:** Our algorithm works on a large number of rooms and venues. Nearly any given room can be modeled.
- **Expandable:** It would be easy to incorporate more data into the model.

Group Mobility Model

Description

The group mobility model is used to determine the critical factors that predict the ability of a person (e.g., security guard) to get to a specific location in a crowd. This model is a modified version of the crowd escape model. Five guards start on one side of a room filled with people who are moving in random directions, and the guards move across the room to the other side.

Instead of measuring the time required to cross the room, we count the number of people whom the guards encounter along the trip. An encounter is when any person occupies a grid location directly adjacent to the guard's path. "Encounters per foot traveled" measures how much the crowd impedes travel through the room.

Description of Mobility Test Rooms

With these modifications to the computer simulation, we tried to correlate mobility with the size, shape, number of people, number of obstacles and the density of people in the room. This gave rise to the test rooms of **Table 3**.

Table 3.
Test rooms—Group Mobility Model.

Room name	Description
Small room	144 ft^2
Medium room	800 ft^2
Large room	3,000 ft^2
Cafe	800 ft^2 with tables and chairs

Results of Mobility Test Rooms

For each room, we ran the simulation 50 times, 5 times each for 10 different densities. We counted the total number of encounters that the 5 guards made while crossing the room. The distance that the guards traveled (as the crow flies) was divided by the total number of encounters.

The data suggest that

The number of encounters per foot is inversely proportional to density.

None of the other four factors is a significant contributor. The number of people and size of room cannot be factors, since the four rooms (when they have the same density) all show the same flow impedance even though they are different sizes and have different numbers of people in them. The four rooms are not the same shape yet exhibit the same behavior under similar densities. Finally, the café has many small obstacles but follows the same trend. (Note: The density in the café was calculated as the number of people divided by the amount of open space.)

Weaknesses

This model exhibits many of the same strengths and weaknesses as the previous model, with some additional characteristics.

- **People move for guards:** Usually, when people see a security guard coming, they tend to move out of the way. Our simulation assumes that people never move out of the way—a worst-case scenario. However, the simulation does represent how easy it is for an ordinary person to get out of the room in case of an allergic reaction or other pressing issue.

- **Densities vary throughout crowds:** Chances are that people will not be evenly spread out. They could be clumped around the place the guard needs to go, creating further difficulty. Our model does not attempt to simulate this sort of behavior.

Strengths

The strengths of this model that pertain solely to the changes we made to the basic model are:

- **Multiple runs:** We ran each simulation 5 times with randomized starting positions for the people and came up with data that were highly correlated. This implies that our model is not sensitive to small changes.

- **Stability:** Our model is not sensitive to relatively large changes in any aspect except the density of people in the room.

Proposal and Conclusion

We feel two limitations should be placed on the number of people in a particular room:

- **Persons per exit:** The overwhelming limitation to the escape time is the number of people per exit. If the maximum escape time is to be 1 min, then there should be no more than 40 people per exit. This requirement will ensure that the room can be evacuated in a reasonable of time.

- **Area per person:** To maintain good accessibility by security personnel, each person should have at least 5 ft^2 of floor space; tables, chairs, and other obstructions must be subtracted from the gross floor space of the room.

Based on our conclusions, we present this formal proposal:

> *The Maximum Occupancy for said room shall hereby be determined as the lesser of the two following quantities: the number of existing exits multiplied by a factor of 40, and the entire square footage of the room that is deemed usable for walking divided by a factor of 5.*

This requirement possesses all the qualities of a good model as specified in the introduction. It ensures public safety by being based on both a maximum time to clear the room and a maximum resistance that people will have trying to traverse through the crowd. It also is simple, requiring only two easy calculations, and defensible, since we have shown above that any other consideration for deciding maximum capacity is negligible.

The specific values for persons per exit and area per person might need to be adjusted depending on the particular situation. For example, if a room is deep within a building, it may need to be evacuated in 30 sec to ensure that the occupants get outside quickly enough. Also, if there is a known hazard in the room, the occupants may need to be able to evacuate the room even faster. The safe density of people could be different for a room depending on whether it is used for rock concerts or for basketball games.

An additional desirable restriction would be that every spot in a room should be within a certain number of feet of an exit. This restriction is especially relevant in large rooms where the capacity is low, since neither of the limitations we recommend takes this situation into account.

Appendix: Special Cases

Elevators

There would be few evacuation problems with a well-functioning elevator due to the small size of an elevator and the close proximity of all spaces in the elevator to the door. The primary safety consideration with an elevator due to capacity would be exceeding the weight limit of the elevator. Access of emergency personnel wouldn't present a problem, either, because the entire elevator could be quickly evacuated to make room for the personnel.

Because of the safety measures in modern elevators, a broken elevator is rather stable. When an elevator is stuck between floors, the primary time concern for evacuating the elevator would be accessing the elevator compartment rather than removing individuals from the elevator once the elevator has been accessed. There would probably be very little difference in removing one person from a stopped elevator than there would be for removing many.

Pools

The two models can be made to apply to pools by applying them first to the pool itself with different speed information than for walking individuals. The standard model would then be applied to the outer rim area with the actual pool area treated as an immovable object.

A pool has other considerations that should be regulated. The maximum occupancy of a pool with lifeguards on duty should be limited with proportion to the number of lifeguards on duty.

Acknowledgment

Special thanks to the General Manager of the local Keresotes Theaters for permitting access to theaters to collect data on the motion of patrons.