

Many public facilities are assigned a “maximum legal occupancy” which limits the number of people who can be in that facility at any given time. Assuming typical facilities in a city or town, we consider personal space, evacuation time, and ventilation to determine this number. We present several models of evacuation and flow of people in general to determine how quickly a given number of people can leave a room or complex of rooms in case of an emergency. We give estimates for the time it takes for a room to become dangerous to inhabit when toxins are leaking into the atmosphere, including the carbon dioxide produced by human respiration and by a fire. In addition to an emergency situation, we investigated how the ventilation through a room might limit its maximum occupancy.

In general, we expect people to need 0.5-1 square meters of personal space in a building. For an elevator or a concert in which close contact is not considered uncomfortable, smaller values may be used. For a swimming pool where people need more room to maneuver, we recommend more.

We used three models of flow of people out of a room with a door. One assumes the flow rate is constant, the second bounds it by a linear function of the density of people (people per unit area) in the room, and the third bounds it by a concave-down quadratic function of the density of people. In each case, the rate at which people exit is roughly proportional to the combined flow rates of all the doors. A room with a lot of small furniture turns out to be very similar, since people are not heavily restricted in direction of travel. The space taken up by furniture must be subtracted from the whole when calculating capacity based on personal space. A room with large furniture which severely restricts motion is better considered as a complex of connected rooms.

Any series of rooms may be represented as a graph where nodes represent rooms and edges, marked with a flow rate, represent doors. In the case of constant flow rate, the Ford-Fulkerson algorithm can calculate the maximum flow through the room which gives an estimate of the time it would take any given number of people to evacuate. For the constant and quadratic bound models, a computer simulation was written which gave consistent results for a complicated cafeteria on campus. Unless there is a bottleneck somewhere inside, the limiting factor on the evacuation rate seems to be the flow rates of the doors.

Once the time it takes to evacuate  $n$  people is known, we can back solve to determine the maximum number of people that can evacuate in time  $t$ . The problem is determining how much time to give an evacuation. Based on a quick computation of the combustion of wood, we estimate that the sample cafeteria would take 2.5 minutes to evacuate, but 2.5 hours to fill with carbon dioxide in case of a fire.

There is a simple formula for determining how quickly a toxin flowing into a room reaches fatal levels. Humans generate carbon dioxide as they breathe, which may limit capacities in small, enclosed spaces. A crowded, 27 cubic foot elevator may reach the fatal level of 8% CO<sub>2</sub> in 2 hours or so. However, they are likely to be rescued before then, so this constraint is generally not important.

For elevators, a more important constraint is weight, which is specified by the manufacturer.

Our evacuation models are flexible, in good agreement with each other for the sample buildings we came up with, and give reasonable times for evacuation. The ventilation model is likewise reasonable and flexible. Unfortunately, many of the actual numbers used in the models, such as parameters to the quadratic bound and physical data about buildings, had to be guessed. We were able to design some experiments that would determine these constants. Furthermore, the estimate of time until fatality for a fire was extremely rough and should be refined.

We recommend that in the case of a room, personal space be used for a first estimate of the capacity. The evacuation models should then be applied to the building to be sure that there are no bottlenecks. The ventilation system should be examined to ensure that enough fresh air comes into the building and that it dissipates heat quickly enough. We also recommend that the room be able to dissipate the heat generated by human bodies (100 Watts per person) so that the temperature does not climb.