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NEW DEVELOPMENTS IN EXIT89

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ABSTRACT

EXIT89 is an evacuation simulation computer model for high-rise and other large buildings that was first written by the author in 1989. Work on the model has continued since that time, and additional features have been added, including the treatment of contra flows (travel against on-coming traffic or other restrictions) and travel both up and down stairs. These features, as well as those added previously, are crucial to the realistic simulation of the evacuation of large numbers of people in large buildings, where people of differing abilities, with varying reaction times, and with or without staff assistance, may encounter crowds or other path obstructions during their escape.

INTRODUCTION

In 1989, EXIT89 was a fairly simple network model, written in BASIC, that could calculate the shortest routes in a large building with a large number of occupants and move people along those routes using travel velocities based on occupant densities along the paths. The effect of the presence of smoke could be modeled, based on smoke output data from FAST, the fire and smoke movement model then incorporated in HAZARD I, or the user could enter smoke blockages manually. Pre-movement times were treated by setting at each location a delay time which applied to all occupants of that location.

At that time it did not include several essential features necessary to make it more useful in real-life applications, such as the presence of disabled occupants, a more random distribution of pre-movement delay times among occupants, the use of travel paths other than shortest routes, travel up stairs from basement levels, and contra flows. Those features have since been added to the model and will be described below. A brief review of the other options will also be covered.

PRE-MOVEMENT TIME

Even in a planned and announced evacuation exercise, movement will not start instantaneously upon activation of an alarm. For EXIT89, the author chose to give pre-movement time explicit attention in the model but through implicit, highly aggregated parameters, combining activities occupants might engage in, such as investigation, alerting others, packing, etc. Time estimates for these parameters can be set using as much proven theory and empirical data as is available.

The user can set pre-movement delays in two ways. The first is to specify the delay that will occur at each occupied node. In this way, the user is able to model situations where, for example, the occupants might have a set of assignments to complete before beginning evacuation, such as shutting down process equipment, or locking away documents or securities. It also allows the user to model situations where an alarm system might be inaudible in certain areas of a building, and occupants in those areas would experience a delay in notification of the need to evacuate.

But that still has occupants within a space acting simultaneously, so the user is also able to set, in addition to the delay times for each node, random delays for the occupants throughout a building. To use this option, the user sets the percentage of occupants who will experience these additional delays, and the minimum and maximum delay times. The model then randomly selects the appropriate number of occupants, and selects delay times along a uniform distribution with the specified minimum and maximum values.

ESCAPE ROUTE OPTIONS

The user can choose between two escape route options. The first is to have the model calculate the shortest route from each location to the outside or other designated location of safety. The other is for the user to specify the routes that occupants will follow. In studies of evacuation behavior, occupants are consistently observed to leave by the exits with which they are familiar, rather than the closest, emergency exits, on which the designers probably relied to achieve the required exit capacity.[1] The familiar routes chosen are often those used on a regular basis, for example, the main entrance into a building.

Other studies have shown that exit choice can be strongly influenced by staff actions or occupant training.[2,3,4] In these incidents, occupants were far more likely to use all available exits, and so reduce the time required to evacuate the building. The shortest route option would be the appropriate choice if the user were confident that occupants could be expected to use, or would be directed by staff to use, the exit closest to their location. If spaces on that floor become blocked by smoke, the model recalculates the network on that floor, assuming that at that point, people would begin to explore their options and would be more likely to find the shortest route.

CALCULATING WALKING SPEEDS

Walking speeds in EXIT89 are calculated as a function of density based on formulas from Predtechenskii and Milinskii.[5] Density is used to calculate the velocity for a stream of people, and people in that stream move at that walking speed. Their formula for the density of a flow or stream of people, D, is:

$$D = Nf/wL \quad (m^2/m^2)$$

where

- N = number of people in the stream
- f = the area of horizontal projection of a person
- w = width of the stream
- L = length of the stream

Their model established a maximum density of 0.92 and developed the following equation for the mean value of velocity for horizontal paths:

$$V \quad = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \quad (\text{m/min}) \qquad \text{for } 0 < D \quad 0.92$$

Other formulas were derived for travel on stairs. Adjustment factors were also derived for travel velocities under emergency situations. The body size data used by Predtechenskii and Milinskii was obtained from Russian subjects. Since different body sizes were calculated for Austrian and American subjects, the choice of body size was added to EXIT89's input.[6,7] The user can also select between normal and emergency walking speeds.

HANDLING THE PRESENCE OF DISABLED PEOPLE

Any evacuation model used to evaluate an engineered design must be able to realistically handle disabled occupants, regardless of the size of the building. The author modified EXIT89 so that that the user, when describing the number of occupants at each node, can specify how many of them will travel at reduced speeds. Then for each disabled occupant, the user enters a percentage of the calculated speed at which each disabled person will move. A different value can be entered for each person. Any able-bodied person slowed while assisting a mobility-impaired occupant, including parents with small children, can also be described as traveling at the reduced speed.

This option can also be used to model evacuees who for any other reason will travel at speeds different from others around them. This can include occupants who are unusually fast, by using a speed adjustment factor greater than one.

MODELING THE PRESENCE OF SMOKE

EXIT89 can handle the modelling of smoke effects in two different ways -- by the model reading in output data from CFAST or by the user entering smoke blockages manually. (CFAST is the fire and smoke transport model now used in HAZARD I.)

CFAST calculates and writes to a disk file the optical density of the hot upper layer at each node at each time interval and the height from the floor of the cooler lower layer. With this option, EXIT89 reads this file and determines that notification begins throughout the building when the smoke level reaches that defined for smoke detector activation. Evacuation will begin immediately throughout the building, unless delay times are specified at nodes by the user. Room blockages occur when levels reach that defined for untenable conditions.

Using the second option, the user can input the names of nodes that would become blocked by smoke and the times those blockages would occur. This option was created so that results from other fire and smoke transport models could be used, as well as observations from actual fires in order to do incident reconstructions, rather than having to rely only on

CFAST output. By using this option and not specifying any blockages, the user can model the evacuation of a building with no fire.

NEWEST FEATURES OF EXIT89

Contra Flows: There can be times during an evacuation when the available width of travel for escaping occupants will be reduced by, for example, others traveling in the opposite direction, firefighters or firefighting equipment in stairwells, or other obstructions that have built up along the path.[8,9,10]

EXIT89 calculates travel velocities based on the density of occupants at each location. Contra flows have the effect of narrowing the available floor space for occupants, thereby increasing the density of the crowd in that space and decreasing travel velocity of occupants there.

To model the impact of fire service operations in stairwells, for example, the user can determine, based on predictions of fire department response and incident scene activities, the time(s) at which locations along escape routes will be restricted, as well as the degree to which the locations are restricted. If fire department operations are expected to restrict a stairwell by 50 percent eight minutes after the occupants are first notified of the incident, the user incorporates this estimate by selecting the affected stairwell nodes and inputting the degree of restriction and time of occurrence for those nodes. If nodes later open up again, the same method is used for returning the nodes to their original size.

Data is not currently available on the amount of travel space restricted by contra flows, so since the user directly controls the value used, a range of percentages deemed appropriate by the user can be tested.

Travel *Up* Stairs: The original version of EXIT89 assumed that occupants were escaping from the upper floors of a high-rise building to ground level. In reality, many buildings have significant occupant loads below ground level. Also, in a phased evacuation, only the occupants of the floor of fire origin and the two floors above and below that floor need to be evacuated. Occupants above the floor of origin may be directed to move to a higher floor so that they are not required to pass the fire floor. The model was revised to allow movement *up* stairs.

The following simplifying assumptions have been made:

a) either all occupants will travel on horizontal paths or down stairs, or they will all travel on horizontal paths or up stairs.
b) for buildings with levels above and below grade, the model will be run twice -- once for those above grade and traveling down and once for those below grade and traveling up. Occupants on the grade level should be included in both runs, since their travel will impact, and will be impacted by, the presence of those using the stairs.
c) If the results show that the occupants traveling down will interfere with those traveling up when they all reach ground level or any other common travel path, that

is, if the simulations show that the two groups reach common nodes at the same time, another run should be made using the contra flow feature addressed above, restricting each group's travel path at the appropriate points in time.

The addition of this feature of the model allows its application to a more complete simulation of a complex structure. This includes structures that are built entirely below ground, as well as those that have occupied floors above and below grade level. It also allows the simulation of occupant movement in a building where staged evacuations are planned, where people located on floors immediately above the fire will be moved higher in the building, while those immediately below the fire will move downwards.

VERIFICATION EXERCISES

The final step in the development of a simulation model is to verify its usefulness by comparing its predictions to actual experience. The demonstration of satisfactory predictive capability on a wide range of scenarios should build user confidence in the application of a model in the evaluation of new designs for which data would not be available.

Those features of the model described in this paper were exercised using the results of five actual evacuations in four different buildings, including:

- two evacuation exercises in a hotel, with a subject population that included several disabled adults;[11]
- a staged evacuation exercise on three floors of a high-rise office building;[4]
- a complete evacuation of another high-rise office building, where some occupants traveled up stairways to reach exits;[12] and
- an unannounced evacuation of a department store while occupied by the public.[2]

The case studies were selected because they both were well-documented and allowed the illustration of the important features of EXIT89.

The two hotel evacuations took place in a two-story hotel with a total of 63 guest rooms and 60 test subjects, including four wheelchair users and one walker user. Daytime and nighttime scenarios were used in these exercises. Video cameras were used to record the subjects' delay times in the hotel rooms and the activities of the subjects while they were in the hotel corridors. The author was able to use the reported delay times in hotel rooms for each occupant and to model the disabled occupants based on their reported travel speeds. The detailed reporting of observations from the drills allowed direct comparison between the observed and predicted evacuation times for each participant. The model slightly overpredicted the evacuation times, but within 21 percent of the observed times, on average.

The staged evacuation exercise involved three floors of a high-rise office building, each occupied by 125-150 people. The occupants were instructed to move to the exit doors when the fire alarm sounded and to wait there for further instructions. In this evacuation exercise, the occupants were directed to leave the building approximately five minutes after the alarm first sounded. The evacuation was modeled in four phases -- the first three involving the evacuation of each floor's occupants to the stairway doors and the four phase involving their movement down the building's four stairwells.

The fourth phase of this exercise highlighted a problem with EXIT89 that will be addressed in the next set of enhancements -- the use of a single uniform distribution from which random delays are selected. The delay times at the stairs that were reported for the drill ranged to approximately 5 minutes, although the delays for the majority of occupants were much shorter. Because the model uses a uniform distribution to select random delays, though, a large number of very long delay times were set in the simulation, with the result that the model's distribution of delay times was vastly different from what was observed. This problem will be overcome by using distributions, such as a beta distribution, which can allow for outliers, but will not allow them to be over-represented in the analysis.

The other office building evacuation exercise allowed the demonstration of the newest features of the model -- the presence of contra flows and travel up stairs. In this evacuation, many of the occupants traveled up stairways to reach the exit closest to the designated meeting point outside. When modeling this evacuation, the contra flow option was used to simulate the impact of the flow of people traveling down the stairs with the flow of people who had traveled up from lower floors. The results of this simulation compared quite well with the actual evacuation exercise, although the total evacuation time was under-predicted by 35 seconds. (The last few evacuees in the drill left the building 66 seconds after the majority of occupants.) The variation in the number of occupants using each route was due to the variability in behavior that real people exhibit (for example, traveling against traffic away from exits, changing direction during their evacuation) that this model does not simulate. The results were very good, however, and demonstrate the effectiveness of EXIT89 in simulating a complex evacuation pattern in a high-rise building.

The last example provided the most interesting challenge to the model, because this single-story department store did not include any corridors or fixed barriers between spaces. There were 495 people in the store at the time of the unannounced drill. The actual evacuation exercise was completed in 2 minutes 45 seconds. The simulated evacuation ended in 1 minute 51 seconds. Because they were well assisted by staff, emergency exits throughout the store were well used. Although the results of this simulation were surprisingly good, EXIT89 works better with a more structured floor plan. The openness of the store layout allowed occupants to travel freely in all directions, while a more compartmented layout would restrict movement along better defined paths.

Although the model was originally written with high-occupancy, large-population applications in mind, the results of these exercises showed that the model can be effectively applied to smaller buildings. While the issues of queuing and crowdedness may not be important in smaller buildings, the evacuation of disabled occupants, the impact of exit choice and the variation in pre-movement times have universal relevance and can all be modeled by EXIT89.

CONCLUSION

EXIT89 is now capable of realistic treatment of:

- a building population with varying mobility capabilities;

- crowdedness that can occur during evacuations;
- the impact of training on efficiency of evacuation;
- obstructions that can impede travel during an evacuation;
- a range of pre-movement times, of whatever cause; and
- complex evacuation scenarios, including travel up stairs, and merging flows from different parts of a building.

EXIT89 remains a model of movement behavior and does not model either pre-movement behaviors or non-movement behaviors during evacuation. The model is available for practical use and additional evaluation in the fire safety engineering community.

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