Advanced Occupant Behavioural Features of the building-EXODUS Evacuation Model

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ABSTRACT

The purpose of this paper is to describe and demonstrate some of the advanced behavioural features currently being developed for the building-EXODUS evacuation model. These advanced features involve the ability to specify roles for particular individuals during the evacuation. With these enhancements to the Behavioural Submodel of building-EXODUS, it is possible to include a number of procedural and behavioural aspects previously ignored in evacuation simulations. These include the behavioural aspect of group bonding, the procedural aspects involved with the role of the fire warden and rescue operations undertaken by the fire services. The importance of these enhancements are discussed and demonstrated through three simple simulations.

KEYWORDS: evacuation, computer model, human behaviour, rescue, fire warden, group bonding.

INTRODUCTION

The ability to enable the efficient circulation of people in heavily populated enclosures is important to the efficient day to day operation of large commercial buildings such as airport terminals, railway and underground stations, shopping malls and cinemas. More importantly, it is an essential design feature in the event of emergency situations.

As building codes all over the world gradually move towards performance based regulations, building designers increasingly find that the fixed criteria of the traditional prescriptive methods too restrictive. This is due in part to their almost total reliance on configurational considerations such as travel-distance, exit width etc. Furthermore, as these traditional prescriptive methods are insensitive

to human behaviour or likely fire scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency.

Computer based evacuation models have the potential of overcoming these shortfalls, however if they are to make a useful contribution they must address the configurational, environmental, behavioural and procedural aspects of the evacuation process [1].

Configurational considerations are those generally covered by the traditional building codes and involve building layout, number of exits, exit width, travel distance etc. In the event of fire, environmental aspects need to be considered. These include damage to the building structure, the likely debilitating effects on the building occupants of heat, toxic and irritant gases, and the impact of increasing smoke density on travel speeds and wayfinding abilities. Procedural aspects cover the actions of staff, level of evacuation training the occupants may have, occupant knowledge of the enclosure, etc. Finally, and possibly most important, the likely behavioural responses of the occupants must be considered. These include aspects such as the occupants' initial response to the call to evacuate, likely travel speeds, family/group interactions etc.

Traditional analysis techniques tend to concentrate solely on configurational considerations. While a number of evacuation models have been developed over the years [2-8] these tend to concentrate on one or two of these controlling issues. It is also often the case that when several of the defining aspects are considered, they are included in a manner which does not allow interaction. Consider for example the effect of fire hazards upon the behaviour of the occupants. In general, increasing smoke density will result in a decrease of occupant travel speeds [9], it may even force occupants to change their direction of travel. Few evacuation models consider the presence of fire hazards whilst egress is taking place. The EXODUS evacuation model attempts to overcome these shortfalls by addressing all four of the contributory aspects controlling the evacuation process.

EXODUS was originally designed primarily for use with transport systems such as aircraft [10-12]. However, its modular format makes it ideally suited for adaptation to other types of environment, such as buildings. To achieve realistic predictions of building evacuation scenarios, the main component of EXODUS which must be adapted is the Behaviour Submodel.

In addition, EXODUS geometric capabilities required expansion to include multiple floors and staircases, the ability to read and interpret building designs through standard DXF files produced by CAD packages, and the ability to represent obstacles typically found in buildings, such as tables and chairs. These differences have lead to the development of two products, air-EXODUS and building-EXODUS, both of which use the core EXODUS software. The building-EXODUS model has been applied to a number of building geometries including a supermarket/restaurant complex, an aged persons home, a school building and a large concert hall complex (see figure 1). While the first two examples were confined to a single floor, the latter two involved multiple floors.

In earlier publications [1,13,14] the behavioural and environmental capabilities of what is now known as building-EXODUS were demonstrated through evacuation simulations involving hundreds of occupants with mixed abilities from a supermarket/restaurant complex under a variety of conditions, including fire, smoke and toxic gases. A range of scenarios were considered in which the population and enclosure configuration characteristics as well as the fire atmosphere composition were varied. These simulations highlighted the profound impact that variations in

individual travel speeds, occupant response times, obstacles (such as shopping trolleys) and smoke concentration have in determining the overall evacuation performance.
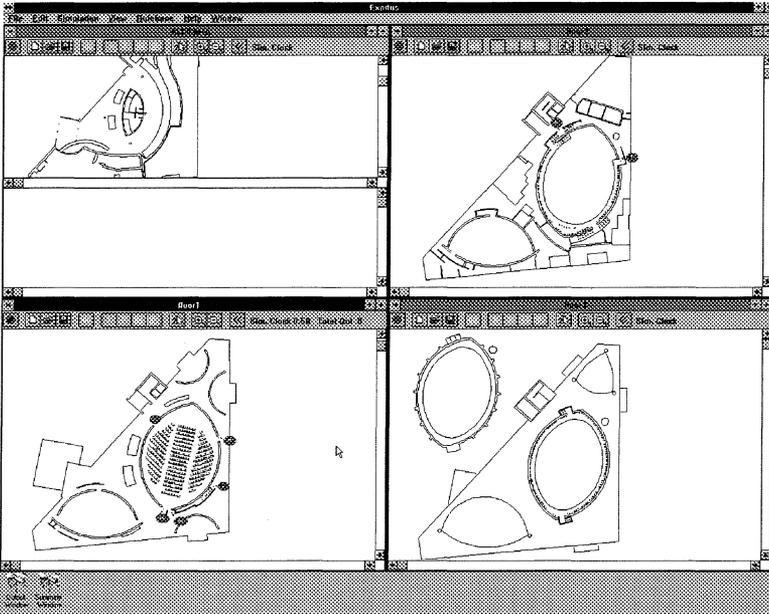
Figure 1: Multi-floor concert hall under investigation in building-EXODUS.

In this paper, new procedural and behavioural aspects of the building-EXODUS model currently under development are demonstrated. In particular, the ability of the building-EXODUS model to represent people with specific roles such as safety officers and rescuers is demonstrated. In performing these functions it is further necessary to demonstrate the ability to cater for contra-flows and allow redirection of evacuees.

building-EXODUS MODEL DESCRIPTION

A brief description of the nature and structure of building-EXODUS follows, a more detailed description can be found in other publications[e.g. reference 1].

The EXODUS suite of software is written using C++ and is portable across platform types from PC to workstation running the WINDOWS or MOTIF environments. The minimum computer requirements necessary to run any of the EXODUS software comprises a 33 MHz 486 PC with 16 Mbytes of memory. The EXODUS suite of software is available from the University of Greenwich.

building-EXODUS is an egress model designed to simulate the evacuation of large numbers of individuals from large multi-floor buildings. The model tracks the trajectory of each individual as they make their way out of the building, or are overcome by fire hazards such as heat and

toxic gases. The building-EXODUS model comprises five core interacting submodels, these are the OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD submodels. The software describing these submodels is expert system based, the progressive motion and behaviour of each individual being determined by a set of heuristics or rules.

The spatial and temporal dimensions within building-EXODUS are spanned by a two-dimensional spatial grid and a simulation clock (SC). The spatial grid maps out the geometry of the building, locating exits, internal compartments, obstacles, etc. Geometries with multiple floors can be made up of multiple grids connected by stair nodes. Within the WINDOWS environment of building-EXODUS, each floor is allocated a window which can be displayed individually or several together on a single screen (see figure 1).

The building layout can be specified either through a standard DXF file produced by a CAD package or constructed interactively using the tools provided. Geometries can be stored in a geometry library for later use. The grid is made up of nodes and arcs, individuals travel from node to node along the arcs. The node-arc structure within building-EXODUS will allow any number of arcs to emanate from a node. In building-EXODUS, nodes are typically separated by 0.5 m and generally possess eight arcs separated by 45°. Nodes which have distinguishing features may be assigned to special node classes. For example, nodes which correspond to stairs, obstacles or clear floor space share certain terrain features and so make up three different classes. The Movement Submodel identifies the type of node being traversed and flags the Occupant Submodel for the appropriate travel speed - of which there are six. These represent the maximum unhindered speed the occupant can attain under a variety of conditions. The different speeds represent the rates at which occupants run, walk, crawl, leap, travel stairs-up and travel stairs-down.

The OCCUPANT submodel defines each individual as a collection of 20+ attributes which broadly fall into four categories, physical (such as age, weight, gender, agility etc), psychological (such as patience, drive etc.), positional (such as distance travelled, Personal Elapsed Time (PET) etc.) and hazard effects (such as Fractional Incapacitating dose of Narcotic gases (FIN) etc.). These attributes have the dual purpose of defining each occupant as an individual and allowing their progress through the enclosure to be tracked. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels. Populations are easily created either by accepting the in-built defaults (e.g. set to recommended values as set out in national codes), specifying a range of values for each variable or selecting pre-defined populations from the population library.

Associated with each node is a set of attributes which define the state of the node. These are, temperature (°C), HCN (ppm), CO (ppm), CO_2 (%), oxygen depletion (%) and smoke concentration. For each of these variables two values are stored, representing the value at head height and near floor level. These state attributes are assigned and updated by the hazard submodel and used by the FED based toxicity submodel [15]. EXODUS does not include a component for predicting the generation and spread of fire hazards but simply distributes the hazards generated by other models such as field and zone models.

On the basis of an individual's personal attributes - specified in the Occupant Submodel, the Behaviour Submodel determines his or her response to the current prevailing situation, and passes its decision on to the Movement Submodel. The Behaviour Submodel functions on two levels, the first is concerned with the occupants' global response to the emergency. This

involves implementing an escape strategy which may lead an occupant to exit via their nearest serviceable exit or most familiar exit. The second level concerns the occupants' response to local situations. This includes such behaviour as determining the occupants initial response to the call to evacuate i.e. will the occupant react immediately or after a short period of time or display behavioural inaction, conflict resolution, overtaking and the selection of possible detouring routes. As certain behaviour rules (e.g. conflict resolution) are probabilistic in nature, the model will not produce identical results if a simulation is repeated. A fully animated demonstration of building-EXODUS is available on the world wide web [16].

ENHANCEMENTS TO THE BEHAVIOURAL SUBMODEL.

Three enhancements to the Behavioural Submodel currently under development will be discussed and demonstrated in the remainder of this paper. These enhancements involve the ability to specify roles for particular individuals during the evacuation. For instance, a particular occupant may have to perform several pre-defined duties before evacuating. The primary duty may be to search a series of rooms and upon completion of this task to proceed with his secondary duty of positioning himself at a predetermined location and direct the flow of the remaining occupants.

With this enhancement to the Behavioural Submodel of building-EXODUS it is possible to include a number of procedural and behavioural aspects previously ignored in evacuation simulations. The first to be considered is rescue.

Rescue

During an evacuation, building occupants or external individuals such as firemen, may be tasked with performing search and rescue operations. In the case of occupants, certain individuals may have a primary role to check particular rooms in their care before evacuating. The techniques developed to model this behaviour, could also be applied to allow certain individuals to re-enter the building in an attempt to locate lost associates or possessions.

In the case of firemen, they may be tasked with entering the premises while the evacuation is underway and perform a search and rescue operation. This may result in contra-flow situations where building occupants are attempting to leave the premises while firemen are attempting to enter. A set of procedures - which are an extension of the conflict resolution and overtaking procedures - have been developed to cater for these contra-flow situations. If the path of a rescuer is blocked by a mass of oncoming people, he will attempt to side-step the blockage, effectively going around the obstacle. If there is insufficient space to allow this action he will attempt to 'squeeze' by the oncoming mass of people, essentially swapping their location with the nearest blocking individual in their path. This squeezing action is slow and results in a considerably reduced effective forward travel speed. In the present implementation this has been arbitrarily set to 50% of the normal forward travel speed.

Each rescuer can be programmed with the procedures he has been instructed to carry out. Thus, if the adopted technique requires two firemen to enter each room and execute a search pattern which follows the compartment walls in a anti-clockwise direction, then this procedure can be adopted in the simulation.

The following example, run in building-EXODUS, consists of a long corridor with a total of six rooms, three to either side of the corridor. The physical layout is similar to a typical corridor in a hotel. A total of 29 occupants are located throughout the corridor and associated rooms. The occupants escape from their rooms and head towards the main exit located at the lower end of the corridor (see figure 2). As this is occurring, two firemen enter the corridor against the flow of oncoming evacuees. Each rescuer is assigned a set of rooms, one taking the rooms on the left while the other takes the rooms on the right. Their search procedures require that they first move to the far end of the corridor and work back down towards the main exit, entering each room in turn, using an anti-clockwise search pattern. On entering a room with a casualty, the rescuer immediately moves to the casualty and carries him to safety. During this process the physical capabilities of the rescuer are reduced. For the purposes of this paper, one casualty only is placed inside room 3, as indicated in figure 2.
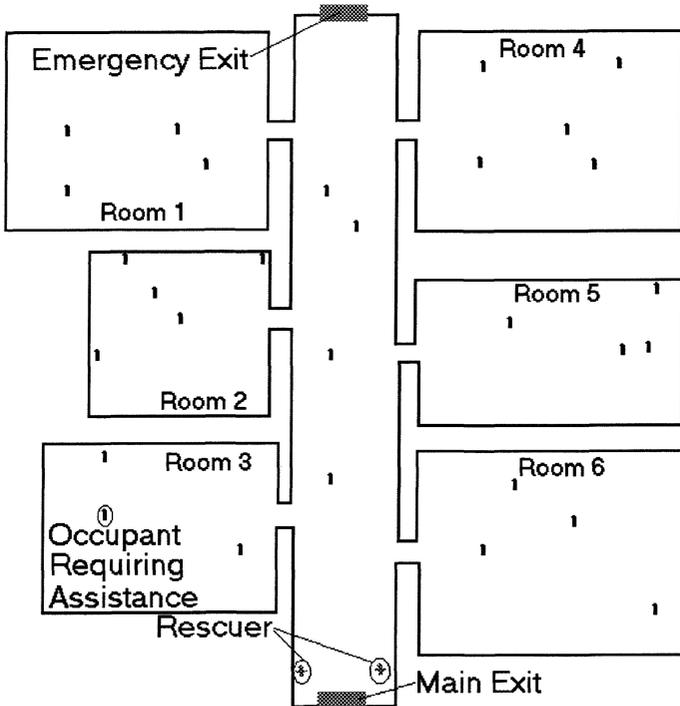
Figure 2 Geometry layout and initial starting locations of occupants for rescue simulations.

Two screen grabs from the building-EXODUS simulation are displayed in figure 3. They depict the situation at two stages during the evacuation. Figure 3a displays the situation after the rescuers have entered the corridor and most of the occupants have successfully evacuated or are in the process of evacuating. One of the rescuers (rescuer 2) has managed to pass a number of fleeing occupants and made his way into room 4 where his search is almost complete. The other rescuer (rescuer 1) has encountered a heavier load of oncoming occupants

resulting in him being slowed down significantly. As a result he has not entered or searched the first room. In

(a)

(b)
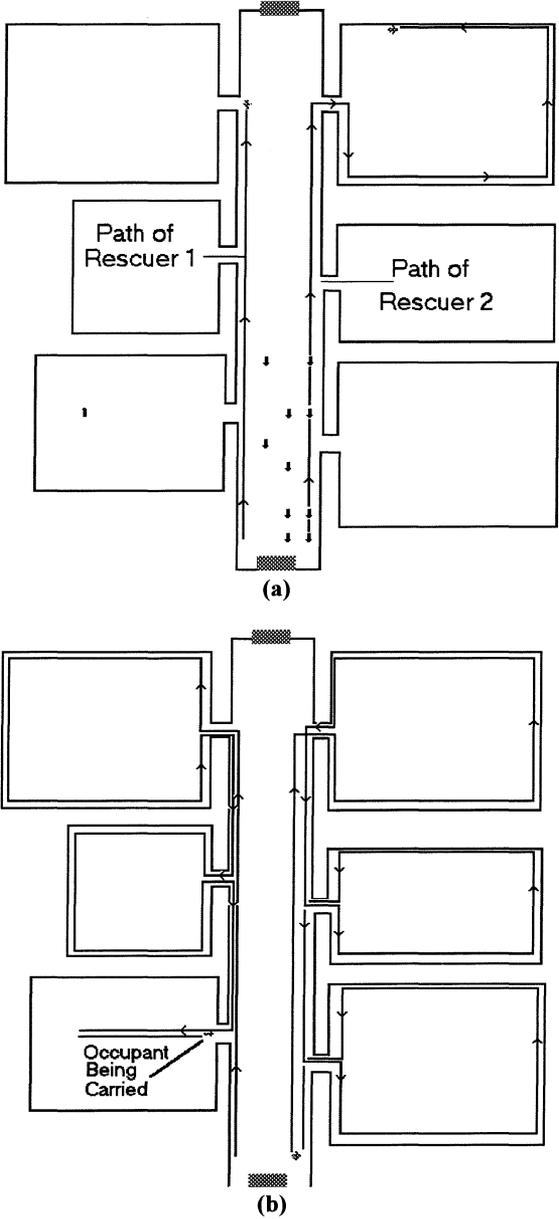
Figure 3 Paths taken by the rescuers (a) mid-way through simulation and (b) near end of simulation.

figure 3b, rescuer 1 has entered the last room, found a casualty and is carrying him out of the room. During this process the movement capabilities of the rescuer are reduced, reflecting the encumbrance of carrying the casualty. Rescuer 2 is about to exit the corridor having found no occupants requiring assistance.

Group Bonding

Building populations are often made up of groupings of people. The groupings may be associated by a number of different links, for example emotionally i.e. family groups or socially i.e. friends. Populations made up of such groups will behave differently to an identically sized population made up of unattached individuals [17]. For instance, a population comprising family groups made up of two parents and two children will exhibit different flow dynamics to an identical size group of unattached adults. The population involving family groups will generally attempt to reunite and evacuate as a group whereas the population made up of individuals will attempt to evacuate separately [17]. Thus it is important to include the ability to represent group bonding within evacuation models.

Using the ability within building-EXODUS to define roles for various occupants, a group such as a family can be defined. A family group may involve for example, a parent and two children. The role of the parent can be defined as follows, primary role: locate and gather children, secondary role: guide family group to exit. The role of the children may be dependent on the age of the child and the particular scenario which is being considered. For instance, the role of the child may be defined as follows, primary role: remain stationary until found by parent, secondary role: follow parent to exit. Conversely, the primary role of the child may be to find the parent in which case, both parent and child will attempt to locate each other. Once the group is reunited they head towards the exit. In these circumstances, the model selects the travel speed of the group to be the speed of the slowest individual within the group. building-EXODUS can also permit such behaviour under hazardous conditions involving smoke, toxic gases and heat. Under these conditions the search may continue either until the parent is overcome by the fire hazards or the parent may abandon the search when conditions become excessive. These options are scenario specific and may be selected by the user.

Such behaviour may have many negative effects on the outcome of the evacuation. The effective evacuation response time of the individuals involved is greatly increased as evacuation actions do not commence until the family is reunited. Furthermore, the search activities of group members may interfere with the flow of the other occupants and once reunited, the group movement may also impede the effective flow of other occupants. Clearly, group behaviour is an important factor which must be included in evacuation models.

The next example uses the geometry described in the previous example. However, only two rooms are utilised in this simulation, rooms 3 and 6 (see figures 2 and 4). In this scenario a total of 17 occupants are used, four in room 3 and 13 in room 6. A family group, consisting of one adult and two children is split between the two rooms, with the parent and one child in room 3 and the other child in room 6 (see figure 4a). The set procedure the parent will attempt to adopt involves him picking up the nearest child and locating the other child before heading towards the exit. The child in the company of the adult is simply carried by the adult, while the missing child remains stationary until found by the parent. Screen grabs from the building-

EXODUS simulation for this scenario are displayed in figures 4b and 4c. In figure 4b the path taken by the parent/child combination is depicted. The parent has located the first child, picked him up and carried him across the corridor to room 6 where the remaining child awaits. On attempting to enter room 6, the parent/child combination encounters fleeing occupants resulting in a contra-flow situation at the doorway. This contra-flow situation has an adverse effect on the overall evacuation as a number of occupants are slowed down significantly.

(a)   (b)

(c)
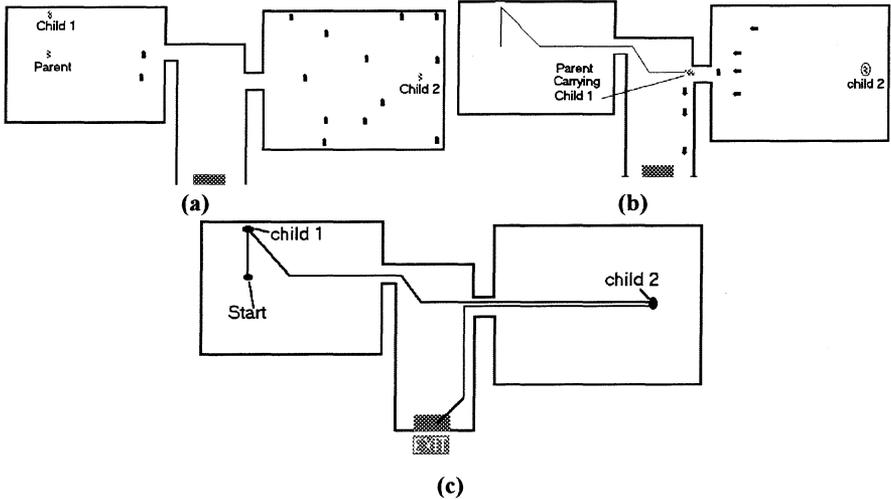
Figure 4 (a) initial starting locations of the occupants, (b) Contra-flow developing at doorway mid-simulation and (c) evacuation path taken by family group

The final path taken by the reunited family is depicted in figure 4c. Once the parent/child combination is reunited with child 2, the group make their way to the exit. Child 2 simply follows the parent/child combination out of the compartment. The travel speed of the combined group is again reduced to be that of the speed of the slowest member of the group.

Fire Wardens and Redirection

The final behavioural enhancement to be considered concerns procedural aspects associated with real evacuations. In many cases within large buildings, certain staff - designated as fire wardens - may have a range of duties to perform during an evacuation. For example, they may issue directional instructions to direct occupants away from an inoperative exit or a region of potential entrapment, instruct occupants to leave encumbering belongings behind, or move to a designated station in order to assist the evacuation. Within building-EXODUS, such functions may be assigned to the fire-wardens through the role specification capability described above.

The last example makes use of the corridor geometry described in the first example (see figure 2) to demonstrate the redirection capabilities within building-EXODUS. In this example, a fire warden is assigned a location which is in the vicinity of an emergency exit not used in the previous two examples. In the previous examples the occupants did not use the emergency exit

because they were not familiar with its location. All occupants used the main corridor exit. In this simulation, the role of the fire-warden is to open the exit as soon as possible, and attract as many of the 64 occupants as possible to the exit. Within building-EXODUS, a parameter measuring the zone of influence of a fire warden is used to indicate the extent of his redirection capabilities. The zone of influence is affected by geometrical and environmental considerations such as physical unobstructed path lengths, level of noise, light level, obscuration level and whether the fire warden has any equipment such as a loud hailer.

Two simulations were run using building-EXODUS. The first involved all 64 occupants using the main exit. In the second simulation, the fire warden, originally located in room 1 (see figure 2), makes his way to the emergency exit, opens it and attempts to attract the occupants. For the purposes of these simulations, the occupant travel speeds have been arbitrarily set and both the main exit and emergency exit are in excess of 2m wide. It should also be noted that the potential map [1, 10-14] in each of the simulations is identical, i.e. NO attempt has been made to bias the 'attractiveness' of the exits.

The evacuation curves for these two simulations are displayed in figure 5. Figure 5 suggests that the peak flow-rate (gradient of curve) for simulation 1 is lower than in simulation 2 and the total evacuation time is higher. As both exits are being utilised during the evacuation, the result appears obvious. The important feature is how this was achieved. The intervention of a staff member in opening an exit and attracting the occupants to the exit has resulted in a more efficient evacuation. Had the staff member not been able to reach the exit, or been delayed in reaching the exit due to congestion, the results would be very different. This approach could be used to investigate the likely success or efficiency of proposed safety procedures. The effect of the redirection is further demonstrated in table 1.
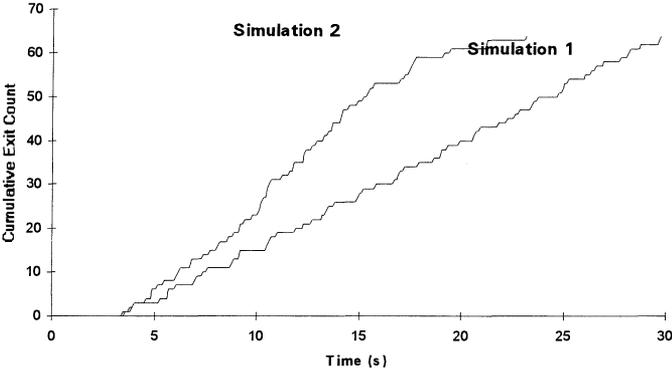
Figure 5 Evacuation curves for redirection simulations

It can clearly be seen from table 1 that there is a benefit in using both exits in the geometry. The total evacuation time (TET) decreases as does the average personal elapse times (PET). As the occupants from rooms 1 and 4 utilise their closest exit, a corresponding decrease in the average distance travelled can be seen. It is also interesting to note that the average CWT (Cummulative Wait Time: total time occupant remained stationary) parameter also decreases.

This reflects the fact that less crowding and queuing occurs when both exits are made available.

Table 1. Evacuation performance parameters obtained from simulations 1 and 2.

	TET (s)	Avg PET (s)	Avg Distance (m)	Avg CWT(s)
Simulation 1	29.7	16.8	9.3	2.7
Simulation 2	23.1	11.6	6.3	1.6

CONCLUSIONS

While the simulations demonstrated here are for purely hypothetical situations they serve to demonstrate the importance of procedural and behavioural aspects of group bonding, redirection and rescue. Furthermore, it should be emphasised that the ability to define and assign roles within building-EXODUS is not simply limited to one or two people in the population. The entire population may be assigned different roles. Considerable effort is still required to obtain representative values for the parameters used to define these features within the building-EXODUS framework. These advanced behavioural features not only allow the evacuation to be more realistically represented but also potentially allow building-EXODUS to be used as a training tool for fire fighters and as a tool to aid in the development of effective evacuation procedures for building systems.

Finally, work on the EXODUS suite of software is continuing with enhancements to the Behaviour Model such as advanced route planning capabilities and the gathering of data for validation studies. Furthermore, in order to enhance the visualisation of EXODUS evacuations, a virtual reality graphical interface is currently being developed. This is intended to aid in the training role of EXODUS.

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