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Extending the Capabilities of the buildingEXODUS Evacuation Model to Cater for Hospital Evacuations

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ABSTRACT

This paper describes the extension of the buildingEXODUS evacuation model in order to: allow occupants to be assigned a limited set of tasks, display co-operation between occupants, represent muster locations and allow occupants to re-enter the structure. By identifying some of the occupants as "staff" and assigning them with a set of patient preparation and rescue tasks, the model is better suited to simulate evacuations from hospital structures. The modified model is demonstrated through the simulation of the evacuation of a geometry resembling a Nightingale Ward. The simulation is repeated with the presence of fire hazards.

1.0 INTRODUCTION

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of individuals from large complex structures. The EXODUS family of evacuation models currently consists of airEXODUS and buildingEXODUS[1-3]. The buildingEXODUS model has been designed to simulate the evacuation of large populations from complex building environments. However, hospital and care facility evacuation scenarios stand out from conventional building evacuation situations in several key areas. These include,

(i) the majority of the occupants are unlikely to be able to evacuate unassisted,
(ii) the able bodied occupants (staff) are expected to assist occupants unable to evacuate under their own power (non-ambulant patients),
(iii) considerable preparation time may be required to assist certain occupants,
(iv) several people may be required to assist in the preparation of each non-ambulant occupant,
(v) when non-ambulant occupants are in motion, the group of people involved in the motion may be as large as three or four (including non-ambulant patient),
(vi) staff are likely to re-enter the evacuating compartment many times,
(vii) staff have several roles to play during the evacuation process,
(ix) as staff may be required to assist repeatedly in the evacuation of non-ambulant patients, staff fatigue may impact the efficiency of the evacuation process,
(x) outside assistance may arrive to expedite the evacuation,
(xi) non-ambulant patients may need to be evacuated with their bed and medical equipment,
(xii) evacuation may be to a safe refuge rather than to the "outside".

While it is possible to implicitly account for some of these unique requirements with the conventional buildingEXODUS software, it is desirable to build into the software the

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capabilities to explicitly model each of these features. The modular structure of buildingEXODUS and its approach to modelling evacuation (i.e. simulation of individuals and the representation of space by a fine network of nodes) makes it uniquely capable for extension into these areas.

One of the key requirements of the proposed developments is the ability to identify the function or role of different building occupants e.g. staff, non-ambulant patients, rescuers, etc and assign them appropriate tasks. For example a staff member may have a requirement to perform the following tasks; co-operate with several other staff members, prepare patient, assisting patient to a point of safety, returning to help another patient, etc. Similarly, a patient may have the following tasks to perform; remain at current location until assisted, move to muster location and assist staff, etc.

The application demonstrated in this paper is intended to represent the evacuation from a Nightingale type ward. Nightingale wards are representative of old style hospital building stock in the U.K. In these buildings, the modern concept of progressive horizontal evacuation does not apply and so in these cases it is usually necessary to evacuate patients to the outside of the building. This is often difficult due to the need to carry patients down stairs. The procedure for evacuating non-ambulant patients may require two nursing staff to carry the patient using a special bed sheet designed for this purpose. This may require the staff to carry the patients down several flights of stairs.

2.0 buildingEXODUS OVERVIEW

The EXODUS[1-3] software attempts to take into consideration people-people, people-fire and people-structure interactions. The model tracks the trajectory of each individual as they make their way out of the enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The EXODUS software has been written in C++ using Object Orientated techniques and utilises rule base technology to control the simulation. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules. For additional flexibility these rules have been categorised into five interacting submodels, the **OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY** and **HAZARD** submodels (see Figure 1). These submodels operate on a region of space defined by the **GEOMETRY** of the enclosure. Each of these components will be briefly described in turn. In February 1999 buildingEXODUS V2.0[4] was released, this is a 32 bit version of the software.

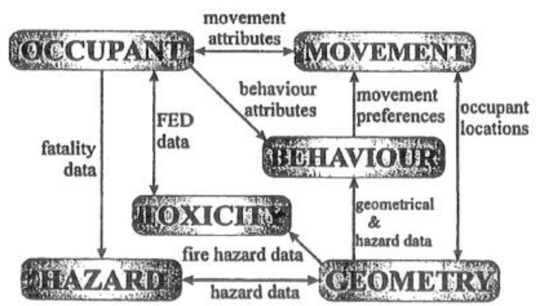


Figure 1: EXODUS Submodel interaction

The **GEOMETRY** of the enclosure can be defined in several ways. It can be (i) read from a geometry library, (ii) constructed interactively using the tools provided or (iii) read from a CAD drawing using the DXF format. Internally the entire space of the geometry is covered in a mesh of nodes that are typically spaced at 0.5m intervals. The nodes are then linked by a system of arcs. Each node represents a region of space that may be occupied by a single occupant.

The **MOVEMENT SUBMODEL** controls the physical movement of individual occupants from their current position to the most suitable neighbouring location, or supervises the waiting period if a suitable location does not exist. The movement may involve such behaviour as overtaking, side stepping, or other evasive actions.

The **BEHAVIOUR SUBMODEL** determines an individual's response to the current prevailing situation on the basis of his or her personal attributes, and passes its decision on to the movement submodel. The behaviour submodel functions on two levels, global and local. The local behaviour determines an individual's response to the local situation while the global behaviour represents the overall strategy employed by the individual. This may include such behaviour as, exiting via the nearest serviceable exit, exiting via most familiar exit or phased evacuation.

The **OCCUPANT SUBMODEL** describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered running speed, maximum unhindered walking speed, response time, agility, etc. Some of the attributes are fixed throughout the simulation while others are dynamic, changing as a result of inputs from the other submodels. Occupants with disabilities may be represented either by limiting these attributes (e.g. travel speeds) to appropriate levels or through the use of the mobility attribute.

The **HAZARD SUBMODEL** controls the atmospheric and physical environment. It distributes pre-determined fire hazards such as heat, smoke and toxic products (namely, CO, CO_2, HCN and low O_2) throughout the enclosure at two heights (head height and near floor height) and controls the opening and closing of exits.

The **TOXICITY SUBMODEL** determines the effects on an individual exposed to toxic products distributed by the hazard submodel. The model determines the debilitating effects of the narcotic fire gases using a Fractional Effective Dose (FED) model[4,7], exposure to convective heat using the Purser FED approach[4,7] and the reduction in travel speed resulting from the obscuration effects of smoke using the data of Jin[4,8]. These effects are communicated to the behaviour submodel which, in turn, feeds through to the movement of the individual.

3.0 DESCRIPTION OF NEW FEATURES FOR HOSPITAL APPLICATIONS

The additional modelling functionality described in this paper is intended to cater for the special requirements of hospital evacuaitons identified as (i) to (vii) in section 1.0. The new modelling features described in this paper are still undergoing development and evaluation. While they have been implemented in a prototype format, they are not available in the general release version of the buildingEXODUS software. To cater for the new functionality five new software features were required. The new software features involve the representation of; target nodes, patient identity, staff identity, patient recognition and group movement. Each of the new software features will be described in turn and an explanation provided as to how these new features enable the required new functionality.

3.1 Target nodes.

Physical space within EXODUS is discretised into a vast collection of nodes. Essentially each node represents a small area of space ($0.5m^2$). Within EXODUS, occupants move from node to node until they reach an exit. As such occupants have exits as their target destination. The software has been modified to allow the user to identify specific nodes manually selected by the user as a ***TARGET NODE***. In this way occupants could be assigned target destinations that do not correspond simply to exits.

3.2 Patient Identity.

Certain occupants may be identified as patients requiring assistance. These occupants are intended to be the non-ambulant patients. These are generated in the usual manner, except that their response time is manually assigned the value of –1. This value overrides the normal response time parameter and indicates that the patient will not be able to move until assisted. In addition, the travel speed of the patient is set to the value that is likely to be achieved when assisted by staff.

3.3 Staff Identity.

In addition to identifying the patients requiring assistance it is necessary to identify the occupants that will provide the assistance. The occupants providing assistance may not simply be staff but may be other patients, visitors, rescue personnel etc. While such occupants are referred to as staff within buildingEXODUS it is understood that they may be anyone lending assistance. The role of the STAFF is to assist the non-ambulant patients to evacuate to a place of safety. This may be to a place of relative safety or outside the building Once the occupant has been assigned "staff member" status, it is then possible to assign them a role. In the current prototype version, the role of the staff member is simply to visit a list of target nodes. It is also possible to assign the staff member a delay time at the target node. This can be used to represent the time required to prepare the non-ambulant patient. This additional attribute represents a further advance over earlier attempts at modelling this type of scenario[5]. Thus the role is specified through the specification of a list of target nodes. If required, the staff member will re-enter the structure and continue visiting the specified target nodes.

3.4 Patient Recognition.

When a staff member with a target node list reaches their next target node, should a patient requiring aid be at that node, then the patient *inherits* the staff members next target node. After the user-specified delay time has elapsed, the staff member then proceeds to the next target node, with the patient closely following. In the current prototype version, each patient requires the assistance of two staff members before the patient will actually move. However, the delay time commences when the first staff member arrives at the patient location.

3.5 Group Movement.

Non-ambulant patients require two staff members to assist in the preparation and movement of the patient. If only one staff member has arrived at the patients side, the pair will wait until another staff member arrives to provide assistance. The patient and staff combination will only be able to begin to move once the preparation time (i.e. delay time) has elapsed. The group then moves to the next target node. If the drop-off target node is an exit, the patient is deemed to have evacuated and the staff members may re-enter the structure if they have further target nodes or simply evacuate themselves. Patients may also be left in safe refuges and be deemed to be "safe".

4.0 DEMONSTRATION OF NEW CAPABILITIES.

To demonstrate the new features of the buildingEXODUS model, a segment of a hypothetical Nightingale type ward will be used. Two scenarios will be considered, both involving four nursing staff. One scenario will involve the simulation of a "drill" evacuation and the second scenario will be a repeat of the first but will include an evolving fire atmosphere. The demonstration scenarios presented in this paper is similar to the earlier buildingEXODUS simulations[5] and so are intended to loosely follow those of exercise 2 of the Hackney experiment[6], thus they represent an ordinary acute ward circa 1978.

4.1 The Geometry.

The geometry consists of a segment of a Nightingale type ward[5,6] (see Figure 2). The ward segment is separated into two regions, one containing the patients and beds and the other which is screened-off leading to the fire escape stairs. The region containing the beds is 17m long by 7m wide.

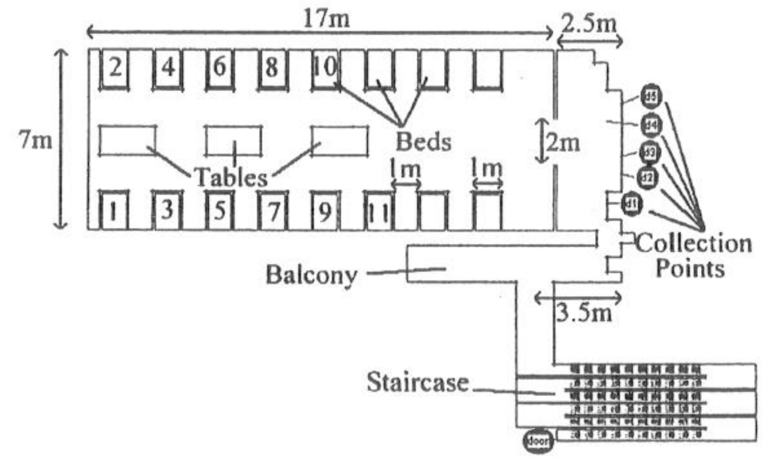


Figure 2: Layout of ward and means of escape used in both scenarios.

The screened-off region measures 2.5m in length and 7m in width. The screened-off region is irregular in shape and the screen contains a 2m wide opening which is centrally located. Leading from the screened-off region is a 1.5m wide balcony. Travelling a distance of 3.5m along the balcony from the screened-off end, a right angle corner is encountered leading to a 3.5m long approach to the top of the fire escape. The ward is located three floors above ground level and the fire escape consists of six flights of stairs and five landings. Each landing is 2.2m long and 1.3m wide and each flight consists of 10 risers measuring 0.17m in height and 0.27m in depth. The maximum travel distance to the stairs is 29.7m and the total maximum travel distance is 54.1m.

4.2 The Population.

The simulations consist of 28 patients and four staff. Of the 28 patients, 17 are ambulant and 11 are non-ambulant. The patients are located in beds and at several tables. Eight beds are located along each wall and each bed is separated by 1.0m. The remaining 12 patients are by the tables located at the opposite end of the ward to the screen. All patients positioned beside tables are considered ambulant.

The population used in these simulations are identified by a number indicating their location. The numbering commences in sequence from the end of the ward opposite the screened-off section. Odd numbered patients are on the balcony side of the ward and even numbers on the opposite side. Patients numbered from 17 to 28 are seated around the tables. For the purposes of this demonstration, the exact specification of the patients attributes are not important. However, the travel speeds for the ambulant patients reflect the fact that they are unassisted and capable of achieving normal travel speeds. The response times for the ambulant patients were assigned according to a random distribution with limits of 0 seconds to 50 seconds.

The non-ambulant patients are not expected to move on their own. They are allocated a travel speed for traversing open space that is randomly distributed between 0.5 to 1.5 m/s and for travel on stairs that is randomly distributed between 0.19 to 0.36 m/s. This is necessary as when the staff/non-ambulant grouping move, the group will inherent the speed of the slowest member of the group. Thus the speed assigned to the non-ambulant patient is intended to represent the speed of the patient/staff grouping. As described previously, all non-ambulant patients must wait for two staff members to prepare them. Preparation times are randomly assigned to each non-ambulant patient between 90 seconds and 200 seconds.

4.3 Description of Evacuation Scenarios.

It is assumed that ambulant patients play no part in the evacuation apart from evacuating themselves. Four occupants are identified as staff for the purposes of this demonstration. The role of the staff can be described as follows:

1. The staff work in two groups of two, one working the left side of the ward (patients 1,3,5, etc), the other working the right side (patients 2,4,6 etc).
2. The patients are visited in a rigorous order, starting first with the patients furthest from the exit screen, and working back to the screen.
3. The patients are moved into the vestibule area behind the screen.
4. Once all the patients have been moved to the vestibule area they are moved one at a time to the second staging area at the head of the stairs (identified as balcony in Figure 2).
5. Once all the patients have been moved to the balcony area they are carried down the stairs and deposited outside of the building.
6. Each movement phase requires two staff members to move the patient. Patients cannot be moved until a delay time equivalent to the assigned preparation time has elapsed. This time is measured from the time that the first staff member arrives at the bedside.

7. In evacuations involving fire, staff members will not attempt to rescue patients if the FED of the staff member exceeds a user defined critical value (arbitrarily set at 0.89 in this demonstration) or temperatures in the vicinity of the target patient exceed a user defined critical value (arbitrarily set at 80°C in this demonstration).

For the scenario with the developing fire atmosphere, an arbitrary set of evolving fire hazards is defined. In this scenario, the screened-off region is considered a place of relative safety, the fire atmosphere being less severe than that developing in the ward area. In this case it is assumed that some of the fire hazards are leaking into the screened-off region.

While buildingEXODUS allows the user to specify quite complex fire development relationships, for the purpose of this demonstration only a relatively simple fire scenario will be presented. In particular,

(i) fire hazard concentrations at head height only will be specified,
(ii) occupants do not drop to the floor and crawl at any time,
(iii) the obscuring effects of smoke are excluded from these simulations,
(iv) a simple linear rate law is used to express increases in hazard values,
(v) all hazards assume identical rate laws,
(vi) the extent of the physical region over which the hazards operate do not change with time.

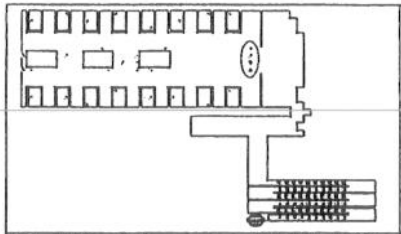
The fire scenario is made up of two fire hazard zones, the ward and the screened-off region. The fire atmosphere within the ward develops at a rapid rate while that in the screened-off region progresses at a slower rate. The conditions within each zone grow linearly, attaining the maximum values depicted in table 1 at the end of the time span identified. The fire is assumed to have started in the region furthest removed from the screened-off region. At the end of the growth period, the fire hazards remain constant at these values for the remainder of the simulation (see table 1).

Table 1: Description of conditions in fire scenario.

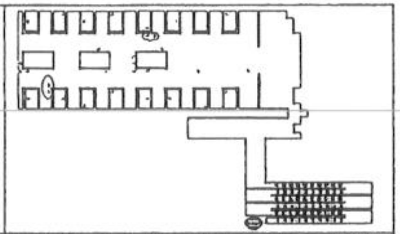
Area	Time Span (mins)	CO (ppm)	CO2 (%)	O2 (%)	HCN (ppm)	Temp (°C)
Ward	0 - 2	0	0	21	0	20
Ward	2 - 12	3500	4	18	100	100
Ward	12 - 20	1500	2	21	50	60
Screened Area	0 - 12	0	0	21	0	20
Screened Area	12 - 32	1500	2	21	50	60

5.0 SIMULATION RESULTS.

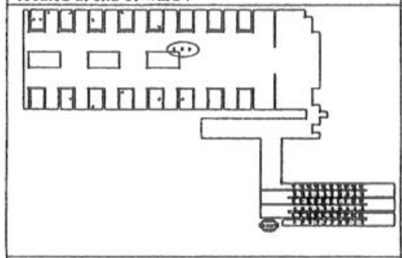
The results for the two scenarios are presented below and depicted in figures 3 to 5.



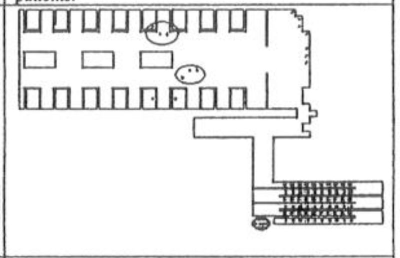
(a) t=0.0s. Staff members (circled) initially located at end of ward .



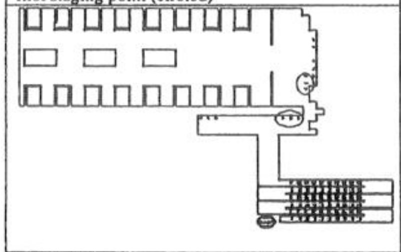
(b) t=12s. Staff (Circled) proceed to assist first patients.



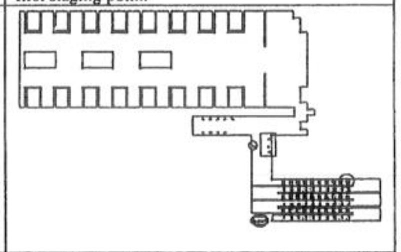
(c) t=130s. Staff starting to escort patients to the first staging point (circled)



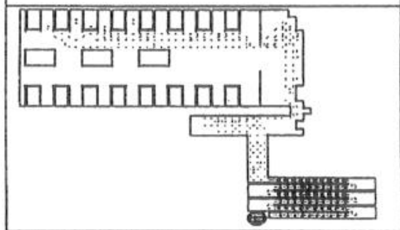
(d) t=797s. Staff have moved most patients to the first staging point.



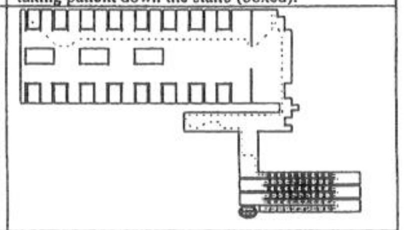
(e) t=1138s. All non-ambulant patients have been moved to first staging point. Staff (circled) are moving patients to the second staging point.



(f) t=1511s. Staff proceeding to take patients down the stairs. Some staff are returning to pick up another patient (circled), while others are taking patient down the stairs (boxed).



(g) t=2574s. Evacuation is complete. The path taken by one of the staff members during the evacuation is highlighted.



(h) Path taken by one of the non-ambulant patients during the evacuation.

Figure 3: buildingEXODUS predicted evacuation sequence for scenario 1.

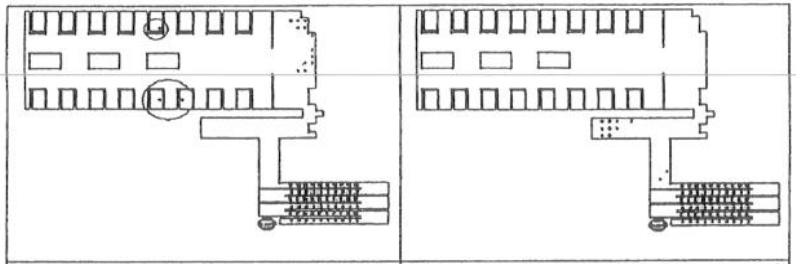
5.1 Results for Scenario 1.

The first scenario considered the evacuation of the ward without the presence of fire hazards. The results are depicted in figure 3a to 3h. The starting location of patients and staff are depicted in figure 3a. In the first 12 seconds of the evacuation the staff have moved off to assist the non-ambulant patients while the ambulant patients with short response times are already leaving the ward (see figure 3b). Within 40 seconds, the first of the ambulant patients have successfully evacuated, while the last of the ambulant patients have evacuated within 95 seconds. It should be recalled that the ambulant patients were arbitrarily given "normal" travel speed parameters. In a more realistic simulation, these patients while ambulant, may be prescribed reduced travel speed parameters.

After 2 minutes and 12 seconds (figure 3c), the first non-ambulant patient is being carried to the first staging area behind the screened-off region. By the time seven patients have been moved to the first staging area some 13 minutes and 17 seconds have elapsed (see figure 3d). The staff have successfully moved three patients to the second staging area within 18 minutes and 58 seconds and by 24 minutes and 39 seconds, the staff have successfully evacuated the first of the non-ambulant patients. At 25 minutes and 11 seconds the second of the non-ambulant patients is about to begin the descent down the stairs while one of the other staff has returned to pick up the next patient. However, he must await the return of his partner who is still ascending the stairs (see figure 3f). The evacuation is completed after 42 minutes 54 seconds, with the staff covering an average distance of 580 m during the evacuation! The path taken by one of the staff during the evacuation is depicted in figure 3g, while the path of one of the non-ambulant patients is depicted in figure 3h.

5.2 Results for Scenario 2.

The second scenario considered the evacuation of the ward in the presence of fire hazards. With the exception of the inclusion of the fire hazards, all other specifications in scenario 2 are identical to those in scenario 1. The results are depicted in figure 4a and 4b. In the early part of the scenario, the situation is similar to that in the previous scenario. The first of the ambulant patients evacuates within 40 seconds and the last of the ambulant patients exits after 95 seconds. This is within the first two minutes of the evacuation in which the conditions within the ward have not begun to deteriorate. The scenario continues in this manner for the first 11 minutes. While the situation begins to rapidly deteriorate in the ward, conditions in the screened-off region are much more survivable. Most of the non-ambulant patients have been successfully moved to the screened-off region in this time. However, by 11 minutes and 43 seconds, the conditions in the ward are considered too hazardous by the staff (conditions have reached the user defined critical values). At this point three patients remain in the ward and cannot be rescued by the staff (see figure 4a). At 13 minutes and 36 seconds, the three abandoned patients are predicted to perish due to over exposure of narcotic fire gases. After 16 minutes and 49 seconds, the staff are evacuating the patients down the stairs (see figure 4b). The evacuation is completed in 33 minutes and 45 seconds. The non-ambulant patients have FEDs ranging from 0.16 up to 0.79, while the staff have FEDs of 0.81 to 0.85. An FED of 1.0 results in incapacitation and death. Depicted in figure 5 is a comparison of the cumulative evacuation graphs for scenarios 1 and 2.



(a) t=703s. Three patients (circled) have been abandoned due to untenable conditions in ward.

(b) t=1009s. Patients are being evacuated down the staircase.

Figure 4: buildingEXODUS predicted evacuation sequence for scenario 2.

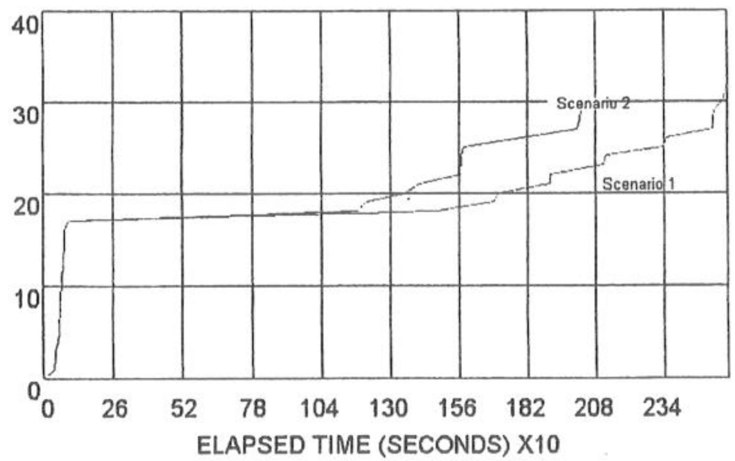


Figure 5: Cumulative evacuation curves for scenarios 1 and 2 (number of people out vs elapsed time (secs)).

6.0 DISCUSSION.

The simulation results (see figure 5) suggest that this evacuation would require approximately 45 minutes. It should be noted that this simulation was not intended to produce a realistic evacuation time. Its purpose was to demonstrate the functionality of the new features

implemented within the buildingEXODUS model. In particular, the simulation did not include a realistic representation of the preparation time required for each of the non-ambulant patients, reliable data concerning transport speeds for the staff-patient combinations, staff fatigue functions, etc. Perhaps the most important of these omissions is that of staff fatigue. In the current implementation, the staff experience no fatigue irrespective of their level of physical exertion.

In reality, an evacuation under the conditions imposed in scenario 1 would probably require a significantly longer period of time as the staff would soon become exhausted, or at the very least require brief periods of rest between trips up and down the stairs. In addition, in a real evacuation, it is likely that additional staff or assistance from outside rescue workers would be present to assist in the evacuation.

As a result of these omissions, the above time should be considered at best as a lower limit to possible evacuation times for this ward in situations where four staff are used. It is interesting to note that the Hackney experiment on which this simulation was based[6] involved five staff members and while the experiment was not run to completion, it was terminated after 25 minutes.

The second evacuation scenario was undertaken in the presence of fire hazards. Once again, this simulation is intended for demonstration purposes only as in addition to the limitations previously mentioned, the composition and evolution of the fire atmosphere is purely hypothetical. In this case the evacuation is completed in 34 minutes. This is some 11 minutes quicker than the previous simulation. This difference is due to several important factors. Firstly, as three patients perish, there are three less patients for the staff to contend with. This obviously speeds up the evacuation of the remaining patients. Secondly, the reduction in travel speeds resulting from the loss of visibility due to smoke obscuration, while possible in buildingEXODUS, was not included in this simulation. If activated, this would have severely slowed down the evacuation of the patients from the ward to the screened-off area. Finally, the staff would have experienced a deterioration in their abilities as a result of the inhalation of the narcotic fire gases. While there is a mechanism for including this in buildingEXODUS simulations, this was not activated during this simulation.

7.0 CONCLUSIONS

The work presented here represents the first phase in adapting the buildingEXODUS model to better simulate the evacuation of hospitals. With these expanded capabilities it is now possible to identify staff members that have the capability to assist patients and to identify patients that require assistance to evacuate. Furthermore, it is possible to have staff re-enter the hospital to continue rescue operations. While the new capabilities have been demonstrated using a Nightingale ward layout, these developments are not restricted to these environments. They may be implemented within any hospital environment such as those utilising the concept of progressive horizontal evacuation. Simulations of this type can be used to demonstrate and test procedures for evacuating wards, investigate the number of staff required to evacuate a ward within preset times and identify possible pinch points leading to congestion. In addition, it is possible to assess the impact that an actual fire may have on the patients, staff and the likelihood of achieving a successful evacuation. It is however essential to collect data concerning patient response times, preparation times required by non-ambulant patients, and movement rates for patient/staff groupings.

Work on the hospital version of EXODUS is continuing with the planned development of a capability to allow staff to prioritise the selection of patients requiring evacuation assistance, the introduction of fatigue functions for staff, the ability to allow additional rescuers to assist in the evacuation, and the ability to represent the spatial dimensions and movement capabilities of obstacle objects such as beds on coasters.

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LARGE FIRES