Using Computer Simulations to Support A Risk-Based Approach For Hospital Evacuation

C.W. Johnson,

Glasgow Accident Analysis Group,
Department of Computing Science, University of Glasgow, Glasgow, United Kingdom, G12 8QQ.
E-mail:johnson@dcs.glasgow.ac.uk http://www.dcs.gla.ac.uk/~johnson

Terrorist actions, such as the attacks on the London Underground and the Madrid train bombings, as well as fires, such as the destruction of the Station Night Club in Rhode Island, have focussed public attention on the evacuation of public buildings. Partly in consequence, there have been a number of recent legislative changes across Europe and the United States. This legislation encourages a risk-based approach to evacuation. Existing risk assessment techniques, including FMECA and fault trees, provide means of reasoning about potential fire hazards. They can also be extended to analyse the risks that occupants may not escape from a damaged building. However, it can be difficult to validate the findings from such analyses because group and individual behaviours have a profound impact on egress times. For instance, it is hard to assess the likelihood and consequence of the flocking behaviours that occur during mass evacuations. Live exercises address these limitations by providing direct insights into the behaviours of building occupants. However, these drills seldom recreate the conditions that hold during real emergencies, especially when occupants know that they are participating in an exercise. Ethical problems also restrict these drills. For example, patients' health can be jeopardised if they are evacuated from centres of care in a hospital. It can also be difficult to hold drills that might disrupt the 24/7 activities of power distribution and financial service companies. This paper, therefore, describes the development of the Glasgow-Hospital Evacuation Simulator (G-HES). G-HES is an interactive, stochastic software system that can be used to simulate the evacuation of large public buildings. It supports a 'risk-based' approach to evacuation and can be calibrated using observations from 'live' evacuation exercises. Managers can use it to explore the consequences of different staffing levels and evacuation procedures. Monte Carlo techniques provide means of calculating mean and worst-case evacuation times under these different conditions. The evacuation of a local general hospital is used as a case study. This decision is justified by the difficulty of performing such evacuations and by the relatively high number of fires that occur in hospital buildings each year[1].

Keywords: accident analysis; evacuation; simulation; human factors.

1. Introduction

Recent terrorist actions, such as the bombing of the London Underground, and the plethora of false alarms that follow such attacks have focused public attention on the evacuation of public buildings. Fires, such as the destruction of the Station Night Club in Rhode Island, have also increased concern. Partly in consequence, there have been considerable changes in the legal and regulatory frameworks that protect building occupants.

1.1 Regulatory Background

The United States provides both local and Federal regulations governing the evacuation of public buildings. Most states have adopted the provisions of the International Building Code, which requires that building records and floor plans show the "construction, size and character of all portions of the means of egress" (NCSBCS 2000, Section 106.1.2). The US Occupational Safety and Health Administration require employers to 'ensure that routes leading to the exits, as well as the areas beyond the exits, are accessible and free from materials or items that would impede individuals from easily and effectively evacuating' (OSHA, 2003). The Code of Federal Regulations, Standard 29, Part 1910, Subpart E requires that employers prepare emergency action plans to address 'fire; toxic chemical releases; hurricanes; tornadoes; blizzards; floods; and others'. Many of these regulations have recently

[1] Thanks are due to F. Ashraf, J. Johnston, C. McAdam, G. Mckinlay and M. Wilson who drove the design and implementation of the simulation software described in the later sections of this paper.

been reviewed. For example, the Senate is urging the Secretary of Homeland Security to promote the National Fire Protection Association standard on Disaster/Emergency Management and Business Continuity. This requires that the owners and managers of public buildings conduct ‘hazard identification and risk assessment’. The aim is to provide the best means of “instructing occupants to evacuate the building or shelter in place”(NFPA, 2005).

European legislation is also intended to ensure the prompt evacuation of public buildings. Directives, 89/391/EEC and 89/654/EEC, describe minimum standards that should be enforced by legislation in each member state. The UK Fire Precautions (Workplace) Regulations were amended in 1999 to meet these directives. All occupants must be alerted and leave buildings safely in the event of a fire. Employers are responsible for the outcome of any adverse event. The focus of the UK amendment was also to introduce a *risk-based approach* to fire regulations. Building owners and managers must demonstrate that any precautions are appropriate to the likelihood and consequences of any hazard. Evacuation measures could be use to demonstrate mitigation of the potential consequences of an adverse event.

This risk-based approach has been adopted within the provisions that guide the use and management of large public buildings within particular domains. For instance, the 2001 Department of Health guidance covering Scots hospitals includes requirements that “NHS Trusts must have an effective fire safety management system which provides for…means of ensuring emergency evacuation procedures for all areas… means of ensuring that procedures are in place to undertake fire risk assessments throughout the Trust and to monitor these on a regular basis”. Individual NHS Trusts must also appoint specialist Fire Officers who can provide technical support and “involvement with estates staff and others, in fire safety audit and fire risk assessments and assisting with reports to management” (NHS, 2001).

Most recent legislation advocates the use of risk assessment to identify the hazards that threaten the safety of public buildings. The development of evacuation plans and the provision of escape routes provide owners and managers with means of mitigating the risk of fire etc. The following sections argue that a risk-based approach should be extended beyond the immediate *causes* of an evacuation to consider the particular hazards that might *prevent* occupants from escaping a building. The evacuation of the World Trade Center has shown us that the owners and managers of large public buildings must consider the possibility that some emergency exits are blocked and damaged whilst others remain open (Johnson, 2005). They must also consider what might happen if it is no longer possible to use the public address systems that are often used to initiate evacuations.

1.3 Overview of the Paper and the Proposed Approach

There is very little practical advice on how to adopt the risk-based approach that has been advocated in Europe and the USA. The owners and operators of large public buildings continue to relay on subjective inspections and walkthroughs both to assess the risks that can lead to an evacuation, such as a fire hazard, and also the integrity of evacuation routes. These informal techniques have been widely criticized in the aftermath of major fires (Johnson, 2005). It can also be difficult to adapt more objective forms of risk assessment to represent and reason about the risks that might complicate the evacuation of large public buildings. Section 2 will show how the gates within a fault tree can be used to identify the conjunctions and disjunctions of basic events to represent the ways in which bottlenecks can arise through poor building design and fire damage or barriers created by temporary structures and partition walls. However, these techniques must be supported by evidence from previous fires and live drills if they are to account for the wide range of human behaviors that have been seen in many evacuations. The lack of national and international databases for evacuation information, especially about the mass of near miss and low severity incidents, restricts the insights that can be obtained from previous incidents. Ethical and practical considerations limit the use of ‘live’ evacuation drills and exercises. For instance, it can be difficult to conduct these drills in institutions such as banks and hospitals that are intended to provide 24/7 services.

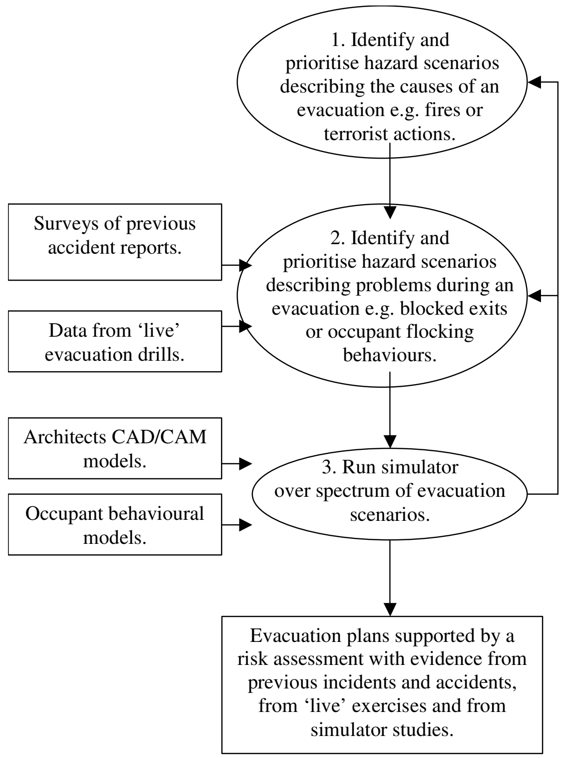

Figure 1: Overview of the Approach and Structure of the Paper

This paper argues that computer-based evacuation simulations can be used to supplement live exercises and more conventional risk-assessment techniques. Figure 1 provides an overview of the proposed approach and also sketches the structure of the argument in this paper. As can be seen, the approach begins with a risk assessment, as recommended by the legislation reviewed in the previous section, into fire and other hazards, such as chemical release, that might cause an evacuation. Part of this process will include some consideration of the ways in which improved evacuation procedures will help to mitigate the risks. The output from such an initial analysis can then be used to inform a risk-based approach to evacuation management.

The second stage of the risk based approach to evacuation management, illustrated in Figure 1, uses existing risk assessment techniques, including Fault Trees and FMECA, to map out the ways in which an evacuation may fail. The intention is to identify the most critical hazards, in terms of consequence and likelihood that could prevent egress from large public buildings. It is important to reiterate the difference between this stage and the previous phase that involves more a conventional assessment of the events that trigger an evacuation. For example, occupants can be forced to leave a building from a fire or from terrorist action. However, their evacuation might be impeded in both cases by the inadequate lighting of internal stairwells or by occupant flocking behaviors. This second stage, evacuation risk assessment must be informed by an analysis of previous situations where occupants have been forced to leave similar buildings using accident and incident reports. The objective of this analysis is to identify critical hazard scenarios that will then be the focus for further investigation using software simulation. The analysis can also be informed by insights from ‘live’ drills, although this may not be possible in new buildings.

The third stage is to develop and run interactive simulations for the building and occupant population being considered. Subsequent sections of this paper will describe a suite of tools that automatically derive these simulations from the CAD/CAM files used by architects. This reduces the costs associated with simulation and also opens the potential to run evacuation simulations before a building is constructed. This simulation stage also relies upon behavioral models for the building occupants.

Young and assertive individuals will often respond quite differently to, for example, large family groups during emergency evacuations.

Figure 1 describes an iterative approach to evacuation management. Simulations can be shown to many different stakeholders, including building occupants and emergency personnel. These consultations often yield large numbers of additional hazards and evacuation scenarios that must be integrated with any existing risk assessments conducted in the first and second stages. Similarly, annual or monthly evacuation exercises can yield further insights that must be incorporated into the evacuation planning process.

The evacuation of a large, general hospital will be used to illustrate the application of the techniques summarized in Figure 1. The number of fires that occur in hospitals each year justifies this decision. For instance, there are approximately 2,500 major fires in Scots hospitals alone. In the United States, there are 3,500-4,000 fires involving multiple fatalities in nursing and assisted living homes per annum. No accurate records are kept for the number of incidents that lead to the deaths of single individuals. The focus on hospital evacuations is also justified by public concern following particular incidents. The Seacliff Mental Hospital Fire in New Zealand continues to have an impact on the planning of healthcare institutions in that country and remains one of the worst single incidents in their history with thirty-seven deaths. In 2003, 30 patients died in a hospital fire in Belarus while another 10 died in a fire at the Greenwood Health Care Center in Cennecticut, USA. The January 2004 Rosepark Care Home fire in Uddingston killed ten patients and sparked a national debate on the safety of healthcare institutions in the UK. As I write this paper, news has arrived of 17 deaths in a hospital fire in Costa Rica. Public concern is justified even when there are no direct fatalities. For example, a recent arson attack on London's University College Hospital cut off oxygen and power supplies and forced a partial evacuation that placed patients and staff at risk. These events motivated a roundtable into Healthcare Fire Safety, held by the International Association of Fire Chiefs (IAFC, 2004).

Risk-based approaches to evacuation planning pose significant challenges for large hospitals. Many of these institutions rely on a mixture of legacy buildings together with more modern facilities. Further complexity stems from the diversity of patients who are treated in many healthcare facilities. These can include ambulatory outpatients as well as individuals who rely on wheel chairs. It also includes patients who cannot be moved from their beds or who can be moved but only after their care has been transferred to a complex array of mobile monitoring and treatment devices. Complexity also arises from the range of detailed procedures that hospital staff use to ensure that patients are evacuated away from a hazard as soon as possible.

2. Identifying and Prioritizing Evacuation Scenarios

At present most managers and owners identify the hazards that might lead to an evacuation or prevent it from being completed by informal walkthroughs with designated Fire Safety Officers. Paper-based forms provide check boxes to note the presence of particular hazards within a building. For example, these are often used to indicate the obstruction of fire escape routes by non-permanent objects or to indicate the need for additional fire extinguishers. Informal 'walk throughs' are far from ideal. Confirmation bias occurs when inspectors consistently identify the presence of particular hazards but also consistently miss other hazards when they work together. Organizational bias occurs when the managers and operators of a building act to influence the outcome of a walkthrough by promising actions, such as the removal of obstacles, before a report is published. Individual bias occurs when inspectors promote particular concerns beyond the level that might otherwise be justified for a particular hazard. Many of these problems remain hidden until an evacuation occurs because the judgments made during a fire inspection are not usually supported by detailed evidence from previous fires or evacuation exercises. The gradual introduction of the risk-based approach has also created a situation in the UK and in the US where managers have introduced rolling-plans of inspection across large portfolios of buildings. Changes in building occupancy create a continual need to go back and re-inspect areas that were considered only a short time before. This can lead to further disagreement where practices that were safe in a previous inspection may no longer be acceptable under new operating conditions.

A number of groups have advocated risk assessment to counter the perceived weaknesses of unstructured, techniques for analysing fire hazards in public buildings (Chamberlain, Modarres, Mowrer 2002, US National Fire Protection Association, 2004). However, most previous research focuses on subjective risk assessment for the events that trigger evacuations, such as fires or terrorist action. There is little quantitative work on assessing the risk of different evacuation scenarios. Existing techniques, such as FMECA or Fault Trees, could be used. Table 1 illustrates the FMECA approach using column headings based on those in US Military Standard Mil-Std-1629A. As can be seen, analysts must identify the various sub-systems that support an evacuation. They must then identify the causes of the various failures that can affect these systems. For example, a sprinkler system can help evacuations by reducing smoke levels and can buy additional time for an evacuation by limiting the growth of a fire. Such support can be jeopardized if the aprinklers' water supply blocked.

Evacuation of Area 1: Treatment Rooms							
Ref	System/ Equipment Failure	Cause	Effect	Detection	Mitigation/ Compensation/ Safeguards	Overall assessment	Overall criticality
1A	Sprinkler system	1. Blocked	Water cannot be discharged through system.	Pressure diagnostic tests.	Clean system using steam/pressure. Possibly consider redundancy.	Sprinkler system failure from evacuation perspective may prevent clearing of smoke and decrease time available for evacuation.	B.
2A	Evacuation corridor	1. Bottleneck caused by trip or fall.	Stampede and possible crush injuries.	Fire officers monitor egress of personnel and patients from all areas.	Review evacuation routes. Ensure supervision of egress at key points offering assistance to some occupants.	Critical in areas where many occupants meet at same time, eg stairwells & landings.	A.

Table 1: Example FMECA for a Hospital Evacuation

Table 1 also illustrates some of the changes that must be made if FMECA is to be used to consider the wider hazards that can arise during an evacuation. The final row considers the problem of a bottleneck in an evacuation corridor that can be caused when occupants stumble and fall during an emergency. It would be unusual to consider a corridor as a 'system' within other forms of FMECA. However, the application of the approach to building evacuations forces the analyst to consider the layout and operation of such escape routes as a primary concern. A number of issues remain. For instance, Table 1 also includes a criticality assessment. The product of likelihood and consequence determines this in the usual manner. However, any assessment of these two factors depends upon a large range of different environmental and contextual factors. The likelihood would depend upon the number of people in the building. It would also depend upon their distribution and their average speed. These issues, in turn, determine whether large numbers of people will reach any particular bottleneck at the same time. The severity of any consequences depend on a similar broad range of factors such as the age and physiological condition of the occupants, the speed they were travelling, whether they were panicking, whether there was smoke etc. One approach would be to associate the most plausible worst-case criticality with each row in an FMECA evacuation table. In order for this approach to contribute to future evacuations it is important to identify those locations in a building where the 'plausible worst-case scenarios' are likely to occur. This would then enable managers and occupiers to re-design the layout of evacuation routes or, for instance, to deploy additional fire officers.

Fault Trees can be used to focus more on the likelihood of evacuation hazards. Each of the causal factors in Table 1 could be considered within the disjunctions and conjunctions of such diagrams. This approach offers a number of advantages because inspectors can use the resulting diagrams to explain the reasons why they are concerned about particular hazards during an evacuation. Figure 1 illustrates an evacuation Fault Tree. As can be seen, crush injuries can occur given that a building occupant falls to the floor and they are in an 'at risk' group, such as the elderly. Such falls can occur if an evacuation route is obstructed or the visibility is poor. Fault tree diagrams can also be used to identify appropriate mitigation techniques for each of the factors that contribute to the likelihood of an evacuation hazard. Building managers might provide additional emergency lighting, luminous handrails and step indicators in areas where smoke accumulates. Additional fire officers might also be recruited to guide 'at risk' residents to appropriate exits.

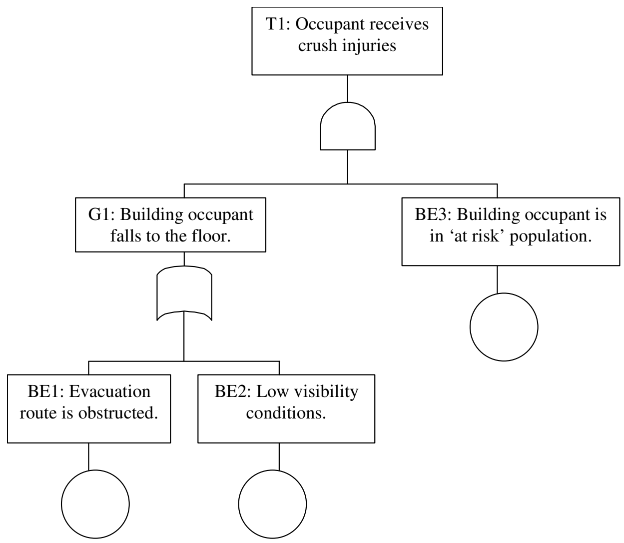

Figure 1: Example of an Evacuation Fault Tree

The application of Fault Trees to support a risk-based approach to the evacuation of public buildings raises a host of further questions. For example, many of the most powerful applications of Fault Tree analysis rely on the propagation of failure probabilities through the tree to help calculate the likelihood of a top-level adverse event. This can be fairly straightforward for some events. For instance, building investigators can survey the population of occupants to determine the likelihood of an individual being 'at risk' of severe injuries during a fall. Previous studies of different fires can also be used together with an analysis of building contents to estimate the likelihood that a fire might result in low visibility conditions. However, it is unclear how to calculate the likelihood of an 'evacuation route being obstructed' within a hospital given that such obstructions continue to occur even though regular inspections are conducted and procedures are drafted to avoid such hazards. Many of the organisational and individual biases that affect ad hoc walkthroughs will also influence attempts to obtain evidence for the likelihood estimates in evacuation Fault Trees.

The key issue here is that most existing risk assessment techniques provide a high-level structure or template for arguments about the risks associated with particular hazards. They do not provide a panacea for the host of more detailed problems that arise when conducting a risk-based approach to evacuation. These techniques are useful because they provide analysts with a high-level means of identifying important hazards, including obstructions and reduced visibility. They cannot easily be used to assess the likelihood and consequences of relatively small changes to the geometry or functions conducted in areas within complex public spaces.

2.1 Insights from Previous Accident and Incident Reports

It is important that the managers and operators of large public buildings learn as much as possible from previous adverse events. For example, it is relatively uncommon to witness panic. Disbelief is a more frequent response to an initial warning about an adverse event. Occupants often attempt to establish the credibility of a warning by asking colleagues or members of staff (Bryan, 1982). There is also a tendency to ignore any warning if there is conflict or ambiguity. For example, building occupants will delay an evacuation if an audible alarm is not located within their immediate vicinity. Such general findings can be confirmed by specific investigations into previous hospital fires. Edelman et al (1980) analyzed the evacuation of a nursing home and stressed the impact that previous false alarms had upon occupant behavior. The alarms were ignored until several patients began to shout 'fire'. Only one psychiatric patient showed symptoms of panic during the evacuation. There are further common factors between hospital evacuations and emergency response in other buildings. Proulx (2001) describes how many people ignored fire exit signs and rushed back in the direction that they had used entered a terminal at Munich Airport. Similarly, two people were killed in the evacuation of the Lowenbrauskeller when the majority of occupants walked part 8 emergency exits to reach the main entrance. The 2003 fire in Rhode Island's Station nightclub provides a further example. Most of the 300 customers retraced their steps back to the main exit. Those who reached this area had to force their way through a bottleneck created by a ticket booth leading to numerous crush injuries. Edleman et al (1980) describe a similar evacuation strategy for the staff in the care home fire. 95% (85) of the patients on the affected floor were led down a single staircase even though three others were available. This staircase was the normal route used by staff and patients between the two floors. The other three were evacuation routes and were fitted with entry alarms, hence there was a reluctance to use them even when the fire justified this. In consequence, the evacuation took longer than expected by the building designer and by the Fire Officers who were involved in the certification of the building.

Reports into the causes of hospital evacuation are published in two formats; aggregated information about minor incidents and detailed reports into major investigations of single adverse events. A recent US Food and Drugs Administration report into fires involving electrically powered hospital beds can illustrate aggregated information. The likelihood of any individual hospital experiencing one of these fires is relatively low. However, regulatory agencies such as the FDA collect this information in order to ensure that lessons learned in one organization can be passed to others. Their records revealed that this hazard accounted for over 100 fires in less than ten years. Approximately 25% of the reports failed to identify any particular cause for the smoke or flames that were observed. The remaining 75% were due to motors overheating, overheating of bed capacitors, arcing at the plug and wall plate due to poor fit, plug damage etc.

Aggregate studies of previous incidents are useful because they provide insights into trends that can only be detected as a regional or national level. However, they are typically targeted at the causes of fires and rarely yield specific insights into particular evacuation procedures. This information is, typically, easier to extract for more detailed reports into individual adverse events. For example, the US National Fire Protection Association (1993) has published a summary report into a hospital fire in Booklyn. This illustrates the evacuation problems that arise when fires are triggered by causes similar to those described in the FDA aggregate report, cited above. In this case, a fire quickly ruptured the oxygen hoses that were being used to treat a patient. The hoses were directly attached to wall outlets and the resulting free-flow of oxygen fed the resulting fire. Large amounts of smoke were forced into the hall and throughout the patient floor. A relatively small fire, therefore, escalated far more quickly than might otherwise have been the case. It also forced the evacuation of larger numbers of people than might have been expected in a residential setting given the close proximity of large numbers of bed-bound patients within the hospital wards.

This example illustrates the complex nature of hospital evacuations that force managers and staff to make detailed plans for the various scenarios that have been mentioned in previous sections. Nurses and Fire Officers may have to delay the evacuation of patients in order to find the time necessary to prevent a fire from spreading. In this case, staff may be diverted from evacuations to close the pipeline zone valves that control oxygen enriched treatments. The level of detail that is necessary in evacuation scenarios can also be illustrated by this example. Nursing staff must consider the consequences if they close the valves that control the oxygen flow to patient's rooms. Such actions will reduce the amount of oxygen feeding a fire; it will also cut off the oxygen supply to other patients within the affected zone. Residual pressure in the pipeline will often allow a short interval before a patient's treatment will stop completely. This provides nursing staff with the opportunity to make alternate arrangements, for instance using bottled oxygen supplies. However, these also create hazards if they are stored on floors where a fire has been detected.

A similar fire caused by smoking materials in a patient's bed led to the deaths of five patients in a Virginia hospital (NFPA, 1994). This incident is typical of many in well-prepared hospitals. The building itself was constructed from fire-resistive materials. Hospital staff had also been well trained to respond to such emergencies. However, smoke spread into concealed spaces about the ceilings of the patients' rooms and several factors combined to prevent a prompt evacuation. These can be summarised as follows:

- Delayed fire discovery. Staffing levels drop at night and this can increase delays in detection. Staff also will often be preoccupied with other tasks. Many hospitals, especially in legacy buildings have areas in which fires can break out, such as linen closets and equipment stores. Many of these areas cannot easily be covered by accurate fire detection technology and are not easily inspected by busy clinical staff.

- Delayed communication with emergency services. The system connecting the hospital alarm to the local fire department had been taken out of service. Such equipment problems are typical in many health related organisations where direct patient care is often seen as the primary objective and issues such as fire safety are paradoxically seen as having a secondary importance.

- Oxygen enriched environment. The severity of the fire when it was discovered and the rapid development of untenable conditions. The Virginia hospital fire is typical in that many hospital fires rapidly develop to threaten the safety of large numbers of patients. The role of oxygen and other volatile gases has been mentioned above. In addition, many of the doors that connect patient rooms and wards to corridors are deliberately left open. This can occur even for fire doors. Wedges can be used to help patients call for attention from busy nursing staff. Open doors assist ventilation in legacy buildings. Door can also be wedged open by busy staff as they clean rooms or distribute equipment and supplies.

- Complex building design. Hidden areas between individual rooms helped to propagate fire and smoke. Again, this is typical of many legacy buildings where, for example, false ceilings have been introduced into Victorian hospitals. Ventilation and cabling ducts can also introduce hidden transmission routes. It is important not to underestimate the impact of such passageways. In this Virginia fire, one patient died far away from the seat of the fire while many others survived. Such 'hidden' transmission routes may also force staff to consider evacuating areas that are well beyond the immediate vicinity of a fire.

- Lack of sprinkler system. Finally, the report into this incident criticised the lack of a sprinkler system in the room where the fire began. Such systems delay propagation and buy extra time during an evacuation. However, as with many other aspects of hospital evacuation, there are cost-benefit trade-offs if a sprinkler system is used when patients rely on sensitive electrical equipment to provide vital support.

The Virginia incident illustrates how reports into previous hospital fires can be used to guide the identification of evacuation scenario that other hospitals use during drills and exercises. These reports can also be used to identify the likely consequences and hence provide direct evidence in support of particular risk assessments. However, hospitals are extremely complex buildings. The hazards vary according to the layout and function of different areas. It is, therefore, critical that Fire Officers consider a broad range of reports rather than attempting to generalise too widely from a narrow range of examples such as the Virginia and Uddingston incidents. For example, it is far easier to initiate the evacuation of patients from their rooms and wards than it is to respond to fires in an operating theatre. The US Joint Commission on Accreditation of Healthcare Organizations (2003) estimates that there are 100-200 of these fires in the US each year. The risks of fire again include an oxygen-enriched environment with a wide range of possible ignition sources including lasers and cautery units. However, evacuation can be hazardous both for staff and for patients who typically require intensive care whilst under sedation. Specialist training is required in order to use hand-held fire extinguishers and fire blankets in sterile environments.

The way in which the JCAHO have to estimate the number of surgical fires in the US raises another important issue; there are no national or Federal registers that provide a central record for most of these events. In Scotland, for example, it is a requirement that all National Health Service organisations report fires involving death or serious injury to the Health and Safety Executive. They must also report fires involving death, serious injury or damage on a large scale, to the Department of Health. This focus on relatively serious incidents limits feedback on less serious events that can provide insights into successful evacuation techniques. Between 1994-2001 only 6 reports were made. 5 involved patients smoking and 1 involved 'willful' fire raising (NHS, 2001). It can also be difficult to access information about more serious events; which are often subject to litigation. In consequence, Fire Officers rely on 'war stories' and informal anecdotes that are passed by word of mouth during periodic meetings and evacuation training sessions. This contrasts strongly with the legal reporting requirements that govern the failure of the devices that cause fires in healthcare settings.

2.2 Insights from Evacuation Drills

Many evacuations in response to minor incidents and false alarms are never reported. In the absence of suitable national and international exchange mechanisms, analysts must rely on live drills and exercises to provide insights into their evacuation strategies. These exercises also play an important training role by providing staff with an opportunity to rehearse and coordinate their response to an adverse event. This creates a circular problem. Drills are used to identify potential problems in an evacuation. However, it is important to anticipate potential problems that can arise during an evacuation so that they are scripted in such a way that staff are challenged to respond to these problems. In consequence, many organizations with a strong safety culture will use evacuation drills in an iterative manner. Subsequent exercises are designed to test weaknesses that have been exposed in previous drills (Johnson, 2005).

It is important to illustrate the scale and complexity of evacuation exercises in hospitals. For example, a US hospital recently conducted 3 mock fire drills during a 6-week period. One scenario started when the tip of an electrosurgical pencil that had not been placed in a holster ignited a drape or cover (McCarthy and Gaucher, 2004). Staff members rapidly removed the cover from the patient by throwing it on the floor and using a fire extinguisher. Other colleagues were informed of the fire. At this point, however, the staff running the simulation intervened to inform them that the fire had spread. A senior nurse began to coordinate the evacuation of operating room staff. There was initial confusion about the best way to transport the patients to a triage point. Partly as a result of this several adjacent rooms were evacuated at the same time causing temporary gridlock in the corridors. This evacuation drill simulated the movement of intubated patients using the operating room bed with a bag-valve mask. The exercise also required staff to move individuals with open incisions. Wounds were packed with sterile, saline-soaked laparotomy sponges and then covered with sterile drapes. The evacuation scenarios were also scripted to determine whether staff knew which items of equipment needed to be evacuated with their patients. They had to collect enough instruments to close the incision even though the evacuation plans provided for sterile equipment to be available in the triage area. Staff were also supposed to know that it was not necessary to transport the anaesthesia machine with the patient.

Debriefing sessions were held after each exercise and enabled staff to provide additional information about a wide range of problems. Evacuations did not always proceed in an orderly fashion. Some staff were unsure about how to use a check sheet describing the key tasks for coordinating an emergency response. There were delays in calling for backup when both the patient and the anaesthetist were 'injured' during the exercise. Debrief sessions also helped to identify problems that were not always visible to the organisers. For instance, one anaesthetist said that they would have evacuated a patient using the back door of the operating theatre. This exit opened onto a steep incline above a busy road. The hospital was then able to respond by posting additional guidance to staff in that area, including signs on the doors that discouraged their use as an evacuation route.

These exercises also provided information on more ‘systemic’ problems. For example, the hospital paging system played a central role in coordinating the emergency response. During the exercises, it emerged that many announcements could not be heard. Staff then had to either contact the desk issuing the calls or leave their posts to seek further clarification. It also emerged that no one was sure what would happen if it were to be damaged. As a result of these exercises, changes were made in the way that messages were sent around the hospital. A messenger position was opened and plans were made to distribute walkie-talkies in case the existing communications infrastructure was compromised during an adverse event.

Evacuation Procedures in the Case Study Hospital
These exercises provide staff with the opportunity to practice complex evacuation procedures. For example, the hospital that forms the case study in this paper exploits ‘horizontal evacuation’. Staff move patients from a hazardous area to a place of safety on the same floor, for instance behind fire resistant doors and walls. Only if the situation worsens significantly will they consider moving patients to other floors and eventually out of the building entirely. The evacuation follows a predetermined plan in which staff must first locate the source of any hazard and then ensure that the proposed destination will keep them free from any immediate danger until the emergency services can arrive. This implies that the destination must be more secure that the area from which a patient is being moved. It is also important to continue to ensure that there is a protected route from the place of safety to an exit from the building. Different classes of occupant raise different concerns during an evacuation. Patients in immediate danger must be moved first. Some assessment may have to be made about whether the risk of moving the patient is greater than the risk posed by the fire or other hazard. Non-ambulatory patients can, typically, be considered before ambulatory patients and visitors. Wheel chair patients are grouped together and then taken to a place of safety by teams of nursing staff. Staff can lead groups of more mobile patients to safety in a single journey. Patients must be taken to a place of safety that does not impede the ingress of emergency personnel. This is important because there is a danger of injury as equipment and people move in to tackle a fire or similar hazard.

Even this superficial description should illustrate the additional complexity that such evacuations can pose beyond the normal workplace drills that most people will be familiar with. However, these drills can be vital in gathering information about the time that is required in order to complete an evacuation. For example, each ward in the hospital appoints one person to coordinate the evacuation. Their performance can vary widely according to the level of staffing and the mix of patients they have to care for. Drills have shown that it takes three people around five minutes to disconnect patients from fixed equipment and reconnect them to mobile monitoring units etc. It can take up to fifteen minutes to transfer a conscious patient from a bed into a wheelchair. Once patients are ready to be moved, drills provide further information about the time required to evacuate them to a place of safety. For example, in most floors in our case study hospital it is possible to find refuge within approximately twenty meters of each patient’s room. On average it takes staff seventy seconds to move a patient from various locations within their room to a place of safety. It takes a further thirty seconds for staff to return to the patient’s room to collect someone else. This would occur if several wheelchair patients have been grouped together for evacuation.

Previous sections have argued that there is a great need for healthcare institutions to share insights provided from previous evacuations. However, the utility of this information is limited because evacuation procedures vary between healthcare institutions. In particular, different patient profiles will influence the evacuation techniques that are used. For example, Wisconsin like many other US states urges staff not to use the ‘horizontal’ evacuation techniques described for the case study hospital when evacuating ‘Intermediate Care Facilities serving persons with Mental Retardation’. Evacuations should move all patients outside the building; ‘this is required, regardless of building construction certification’ and such a facility ‘may not use defend in place methodologies’ even during evacuation drills.

Limitations of Live Drills and Exercises
As mentioned, ‘live’ evacuation drills serve a double purpose. They can be used to establish that minimum evacuation times continue to be met. This is important because fire exits can be inadvertently

locked or obstructed. Fire drills can also be used to ensure that occupants are familiar with necessary evacuation procedures and routes. Hence, in many countries it is a requirement that these drills be performed on a regular basis even after it has been demonstrated that a building meets the initial regulatory requirements, described in the previous sections. For example, many US hospitals conduct exercises in key departments at least once every three months in order to meet insurance requirements. This creates a host of practical problems. For instance, most exercises are conducted during the day. However, it is equally important to provide night staff with an opportunity to practice their skills and also to observe the impact that evacuation procedures have at such times. The results of these night drills can often be very different compared to the same patient population during the day. Many more patients require assistance after being roused from sleep, especially if they are under sedation. Staffing levels are often reduced at night and so coordination can become far more problematic. Many hospitals rely on a greater proportion of agency and part-time staff at night. It can be difficult to ensure that these temporary staff members are familiar with evacuation procedures. Some of these issues persuaded the Department of Health in Scotland to change its regulations and "reduce the need for annual fire safety training for all staff where a full risk assessment has been carried out" (NHS, 2001). However, NHS Trusts must ensure that "procedures are in place within the Trust to provide regular fire safety training for all staff, appropriate to the duties of the staff and their place of work" and provide "means of ensuring that appropriate training exercises are undertaken at least annually for the fire response teams and other staff who are involved in patient evacuation". There are, however, a number of limitations that affect the utility of 'live' fire drills as a means of assessing occupant's ability to escape from large public buildings, such as hospitals:

1. **Sustained Costs.** For many employees, fire drills are little more than a nuisance every month. However, there are considerable costs associated with evacuation drills in hospitals. They can have knock-on effects that disrupt complex healthcare schedules, including surgical lists. It is for this reason that the Scots regulations, cited above, advocate that a risk assessment be used to determine those personnel who must be involved in an annual evacuation drill.

2. **Limited Accuracy.** It can be hard to use fire drills to simulate a range of potential hazards. There is a tendency to simply ensure that everyone in the building knows where the nearest exits are located. Few drills determine the impact of forcing occupants to find alternate forms of egress should these become blocked during an incident. Previous studies of evacuations within other healthcare institutions, including long term residential care, have shown that periodic drills only have a limited effect in persuading staff and patients to use fire exits rather than the main entrances for a building. Similarly, many exercises do not involve the participation of external agencies who may be required to enter the building to complete an evacuation.

3. **Short 'Shelf Life'.** Changes in building use affect the results from 'live' simulations, especially for hospitals that rely on annual drills. In the meantime, large items of furniture such as filing cabinets and beds, as well as other items of clinical equipment can accumulate in areas that obstruct horizontal evacuation procedures. Given the day to day demands on many healthcare institutions it can be difficult for staff to remember that they may have to move several beds and wheel chairs down smoke filled corridors within a short interval after an evacuation has been ordered. In consequence, a successful drill in the immediate past can provide only limited assurance of a successful evacuation in the future. The limited 'shelf life' of evacuation drills is also affected by the rotation systems that govern the operation of many healthcare organizations. For example, anesthetists may work in many different departments across several different hospitals. Operating theatre staff work in rotation. Hence, fire drills that involve specific teams may have to be repeated to involve a broad cross-section of the individuals who may be called upon to act together in an emergency.

4. **Lack of Design Focus**. It is difficult to use the insights from evacuation drills to inform the design of large public buildings. For example, the UK NHS has been involved in the construction of several large, centralized hospitals such as the New Gloucestershire Royal Hospital. This must satisfy design criteria that bring conflicts of interest in terms of acoustic

performance, ventilation and comfort whilst also meeting evacuation provisions in the national Fire Codes. Drills cannot easily be conducted to provide insights into evacuation times for buildings that do not yet exist. Instead, architects and managers must focus on a narrow set of 'static' factors such as the size and location of emergency exits. They cannot easily account for the distribution of semi-permanent obstacles or even the detailed staffing levels throughout the working day that have a profound impact on an evacuation. It would be useful to have a system that designers might use on an iterative basis to assess the effects that changes might have as they revise the layout and structure of a potential building.

5. **Danger.** Several firefighters die in evacuation exercises each year, either form 'workplace accidents' or from existing medical conditions. In consequence, extreme care must be combined with appropriate risk assessments before such trials can be attempted. There are additional ethical and legal complications when subjects may be drawn from the potential occupants of a building. In consequence, restrictions can be placed upon a healthcare organization's ability to involve patients in these exercises. Informed consent is a prerequisite. It can be difficult to obtain sufficient support from patients whose primary concerns do not focus on their involvement in a drill. Many US states follow the Pennsylvania code in letting healthcare institutions decide whether or not to involve patients;

6. **Poor Reliability.** If the same exercise is performed on several different occasions within a limited period of time then the outcomes can be very different. Contextual factors have a profound impact upon evacuation rates. For instance, if an individual begins a prompt evacuation then their peers will often follow shortly behind. However, if individuals delay their initial evacuation to complete particular tasks, such as closing down a computer workstation, then others in the group will often feel the need to do the same before beginning to egress from the building. Such dynamics of group interaction reduce the reliability of results obtained from specific evacuation drills. In hospitals, evacuations must often be coordinated by a small number of key individuals. If those individuals forget to alert all of their colleagues or skip necessary steps in an evacuation plan then the outcomes can be significantly affected, as illustrated by the drills mentioned in previous paragraphs.

Computer-based simulation tools address some of the limitations of 'live' exercises. For example, it is possible to explore what might happen by altering the layout of a building before it is constructed. Managers can simulate the effects of different staffing levels on average evacuation times. Similarly, they can explore the effects of increasing patient numbers or altering the mix of patient conditions being treated within a particular area of the hospital. It is possible to interactive block escape routes as the simulation progresses. This software has a variety of potential end users from architects through to Fire Safety Officers. Regulatory agencies, certification bodies or the emergency services can use them during the approval process that is required before a building can be opened for operation or approved for construction. Occupiers can also use these tools to examine the potential impact of changes in the architecture or operation of a structure. The results from previous exercises can be used to calibrate the findings from these models, which also avoid many of the costs and risks associated with exercises involving real patients. The following section, therefore, introduces some of the design challenges that arise during the development of such software simulations.

3. Simulating a Spectrum of Evacuation Scenarios

There have been a number of previous attempts to develop computer-based simulations of evacuation behavior from large public buildings. For instance, the UK Atomic Energy Authority (2002) has developed the Egress simulator. This tool enables users to draw a simple floor plan of the building under investigation. Hexagonal cells are then used to segment the area. Different types of cell are used to distinguish between internal walls, between areas that are already occupied by people and movable obstacles such as tables and chairs. The Fire Research Service adopts a more elaborate approach (BRE, 2004). CRISP users can associate behaviours with each occupant. These are described in terms of actions, which may be abandoned, and substituted by new ones in response to changes in their environment. Individuals can also investigate, warn others etc. before starting their evacuation. In contrast to Egress and CRISP, the EXODUS system has also been adapted for use in the aviation and maritime industries (Owen, Galea and Lawrence, 1996). Key attributes of the behavioural modelling include the ability to dynamically insert individuals during a simulation. The EXODUS tool provides important facilities in terms of signage annotations so the end-users can simulate the impact of providing additional warning and information notices. Dynamic behaviours can be altered so that individuals will automatically seek alternatives if they see that a particular exit is already congested.

Evacuation software, typically, relies upon models of human behaviour to drive their simulations. For example, we have already mentioned previous incidents in which occupants have first tried to establish the credibility of an alarm before starting to move away from a potential hazard and towards a place of safety (Bryan, 1982). Simulations can mimic these findings by introducing a fixed delay into each run. However, more elaborate models can also be developed to consider a range of more detailed factors that can influence this delay before evacuation. These include the perceived threat posed by the alarm, the degree of preoccupation with the task to hand, familiarity with evacuation procedures from previous drills etc. It is also important to consider the social and team factors that have been shown to influence evacuation times in 'live' hospital exercises. The Federal Emergency Management Agencies have argued that the stronger the bond between group members, the more likely it is that one member will put their own life at risk to protect another group member. Tong and Carter (1985) describe a further form of social behaviour that occurs as crowds grow and groups converge. "Flocking" can attract more people into areas that are already crowded. This form of behaviour can act as a catalyst to flight. Personality traits such as assertiveness have been shown to influence decision-making and behaviour under stress. For example, the Transport Canada Personality Profile 2 (TCPP2) identifies 13 characteristics that influence behaviour during evacuations. Projections based on the results of their experimental studies suggest that 20% of people are 'highly assertive' or 'goal directed'. These individuals can have evacuation times that are up to 25% faster than the 15-18% of people who are classified as being in less goal-oriented groups (Latman, 2004).

Not only must evacuation simulators consider social and cognitive characteristics, they must also account for different physiologies. Age and physical limitations determine the speeds at which people will travel through the building during an evacuation. However, these characteristics cannot be viewed in isolation; a panicking individual is more likely to travel at greater speed than a person who is calm. In the GES tool, each person is assigned an initial speed. The medium speed is set to be 1.4 ms^{-1} (Thompson and Marchant, 1995). The low and high-speed groups are set to have a pace that is 80 and 120 percent of this respectively. These values can be set by the user to calibrate their system. However, these initial values are based on empirical observations that take into account individual pace under different crowd densities. This preferred walking speed of evacuation is sustained unless they cannot make any further progress because one or more people in front of them blocks their path.

We have developed the Glasgow Evacuation Simulator (GES). This tool relies on Monte Carlo techniques to introduce non-deterministic behaviour into scenarios. Random numbers are generated and then compared against probability distributions to help simulate individual and group behaviours. This ensures that building occupants do not always follow the same course of action during each run of the simulation. They are, however, more likely to perform those actions that are considered to be most probable during an evacuation. The probability of particular behaviours can be directly informed by previous incident reports and by the observations derived from evacuation exercises. In consequence, it supports the iterative approach to fire and evacuation risk assessment illustrated in Figure 1. It is informed by rather than being a substitute for 'live' drills. One innovative feature of the GES is that it uses the 3D models that can be obtained from architects' design tools. Unlike many other simulators, there is no need to build specialized models for the evacuation simulator. This reduces costs and allows a tight integration between the simulator and the design of such structures. As shown in Figure 1, the ability to derive simulations from the files of tools such as AutoCAD enables us to simulate buildings that have yet to be constructed.

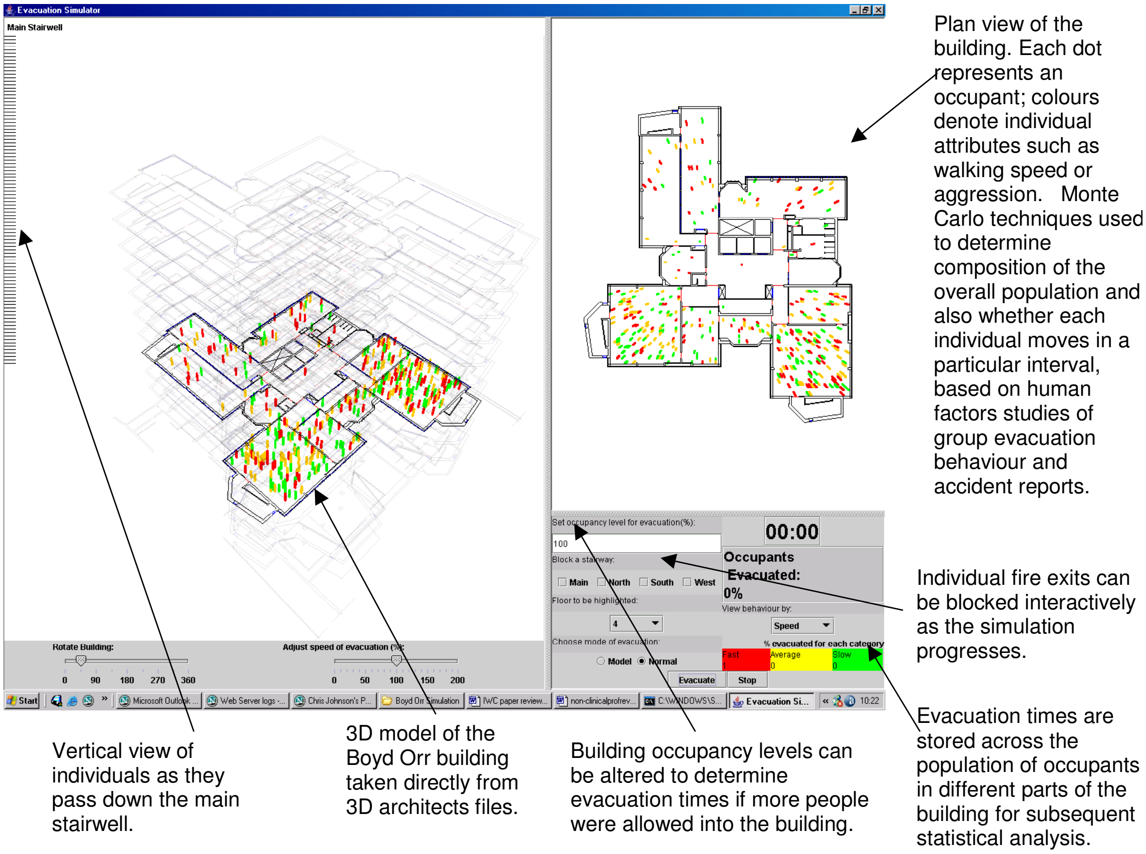

Figure 3: User Interface to the Glasgow Evacuation Simulator (GES)

Figure 3 illustrates the application of the GES to model evacuations from a large auditorium complex within the Boyd Orr building in Glasgow. As can be seen, the interface enables users to vary the occupancy levels in the building. Users can also interactively open and close emergency exits as a simulation progresses to model the effects of damage to the building or intervention from the emergency services. It is also possible to specify whether users will follow a 'model behaviour' in which they are likely to use the nearest available emergency exit or a more expected behaviour in which most users retrace their steps back towards the main entrance for the building. Figure 4 illustrates an application of the GES tool by analysing evacuation times when one of the emergency stairwells is blocked. The top line shows mean evacuation times under different occupancy levels when occupants are likely to retrace their route into the building. The lower line provides the same information for 'model' evacuations in which each occupant attempts to exit by the nearest available route. The difference between the 'model' and 'normal' mean evacuation times is much greater than for any other emergency stairwells. Hence, considerable efforts should be made to ensure that building occupants use this route rather than retracing their steps if they are to benefit from the timesavings indicated in Figure 4.

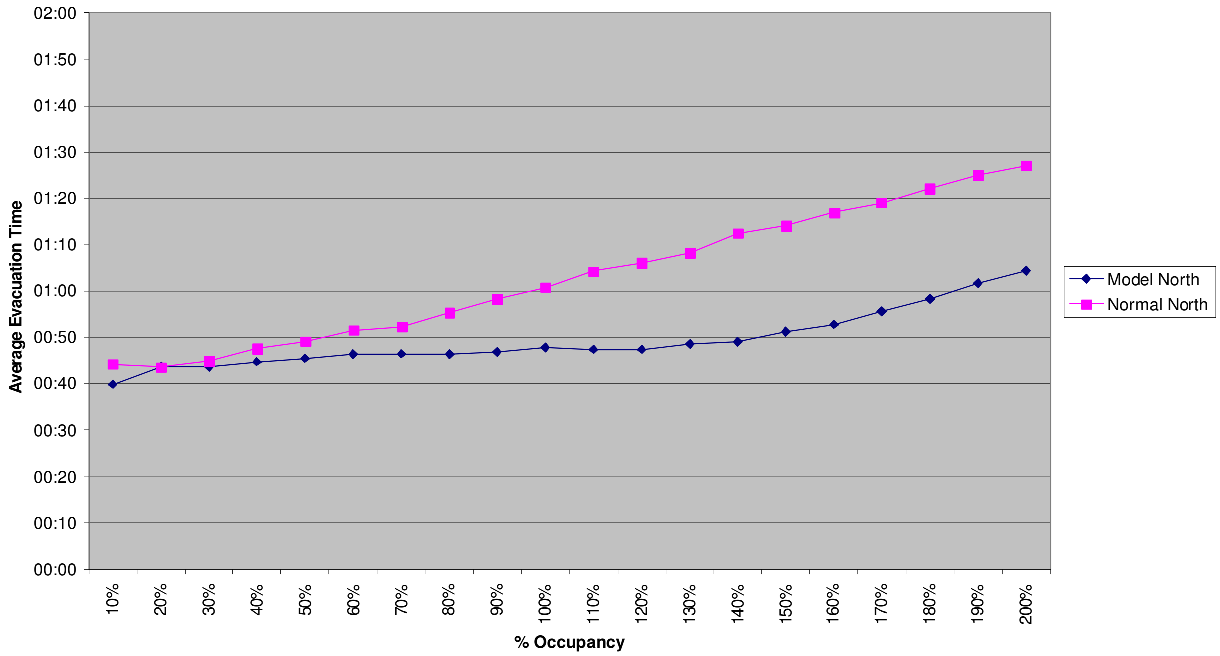

Figure 4: Graphing Mean Evacuation Times when the North Exit Route is Closed

Most existing simulation tools are tailored for the evacuation of large office blocks or entertainment complexes, including cinemas and sports stadiums. Others have been designed for trains, boats and airplanes. Some tools have been extended to support the simulated evacuation of healthcare institutions. For instance, Gwynne et al (2003) contrast the gathering of evacuation data and model development for a University and a Hospital Outpatient Facility. They argue that these two facilities 'employ relatively similar procedures: members of staff sweep areas to encourage individuals to evacuate'. However, the authors also identify numerous differences. Patients only began to leave once a member of the nursing staff instructed them to evacuate. Students were less dependent upon the actions of the staff. This study focused on outpatients. The differences in occupant behaviour between hospitals and other types of institution are more significant for simulations that consider in-patient care. For instance, flocking behaviours are often included in behavioural models for large public buildings. Occupants coalesce into larger groups and will tend to respond to an evacuation in similar ways. This emergent behaviour tends to be less of a feature in hospital evacuations where smaller numbers of patients and visitors may be directed to follow the horizontal evacuation procedures mentioned in previous paragraphs. Similarly, the models of individual behaviour are less important within this context. Individual assertiveness can be a significant factor when modelling the undirected response of individuals within an evacuation. However, it has far less of a role to play in hospital evacuations where staff have been trained to respond in a coordinated manner. Command hierarchies and roles are, typically, determined well before an evacuation through the preparation of detailed plans. They are reinforced through drills and exercises. In consequence, the development of hospital simulations must focus more on the modelling of plans and procedures than on the impact of individual assertiveness or on the emergent behaviours of large crowds. The GES, like most of the other tools mentioned above, was not specifically developed to simulate hospital evacuations. The following sections, therefore, describe the design and implementation of the Glasgow-Hospital Evacuation Simulator (G-HES) tool that is specifically intended to support the evacuation of hospital buildings.

3. The Glasgow-Hospital Evacuation Simulator (G-HES)

As mentioned, most simulators have been designed to model evacuations that are very different from the techniques that we have described for hospitals. There are some exceptions. For instance, Takenaka have developed the 'Assisted Evacuation Simulation System' (Jafari, Bakhadyrov and Maher, 2003). This is designed to simulate assisted evacuations across a range of environments and provides different occupant models for people are not capable of evacuating themselves. The tool enables users to vary the number of patients and helpers. It also simulates a range of evacuation methods including stretchers, wheelchairs and evacuation by helpers' supporting patients on both sides. Although this system provides sophisticated support for modeling the assisted evacuation of patients, it can be difficult to simulate some of the more detailed task allocations that are made in the complex evacuation plans of the case study. For example, one nurse is charged with exhaustively searching for the source of any alarm while colleagues use a whiteboard to coordinate other aspects of the evacuation. It is for this reason that the following pages describe the design and evaluation of an evacuation system that simulates a range of behaviors both for patients and staff.

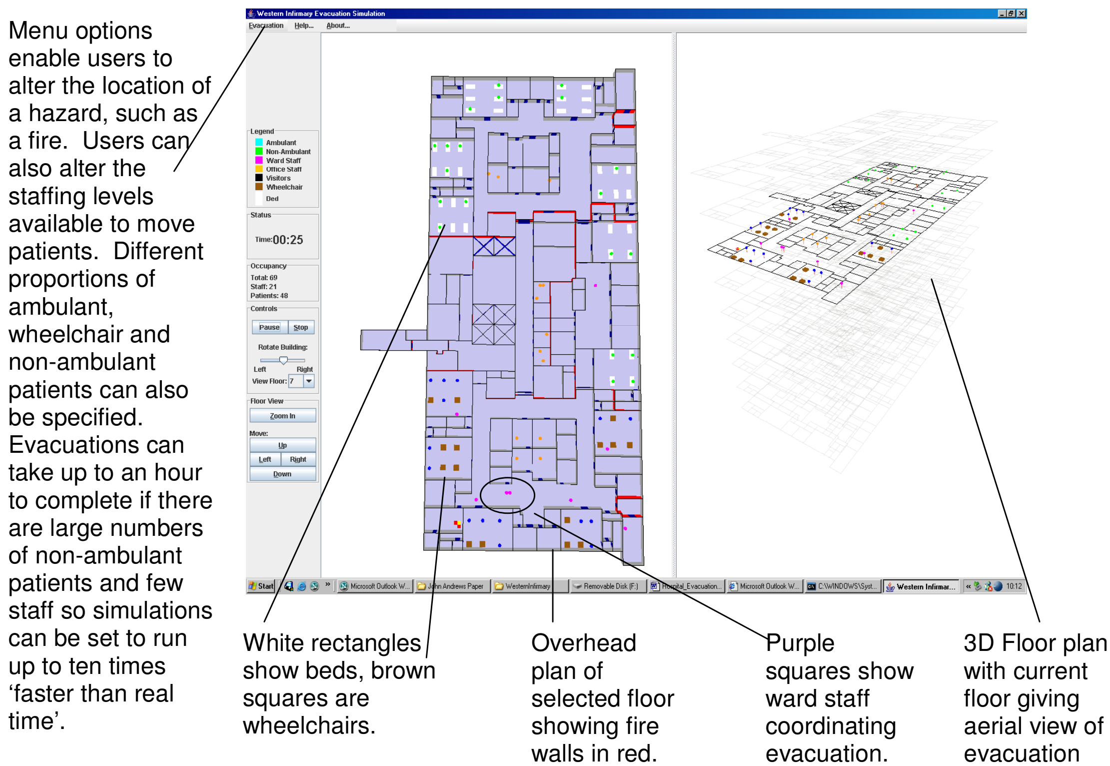

Figure 5: The User Interface to the Glasgow-Hospital Evacuation Simulator (G-HES)

The project began by developing the 3D building model that is used in most evacuation simulators. This is especially important for hospitals where horizontal evacuation will lead to vertical evacuation when fires and other hazards jeopardize the safety of individual floors. Previous sections have mentioned that many public buildings now have electronic plans stemming from the increasing use of AutoCAD and similar products by architects. Tools, such as the GES, can semi-automatically read these during the construction of a simulation. Unfortunately, these plans are not always readily available for legacy buildings. They can also provide unreliable information given that the original infrastructure can be heavily modified as occupants remodel a building to support different activities. Semi-permanent structures and partition walls may not always appear of the plans that are supplied. For these reasons, the model illustrated in Figure 5 was developed by hand from paper plans that were then validated and cross-references through site visits that made use of digital photography for later off-site comparisons. We were particularly interested in the firewalls, illustrated in red on the previous image, because these denoted the boundaries for potential refuges where patients might be relocated during an emergency. We also had to model the difference between smoke resistant doors and doors that also provided protection against a spreading fire.

The initial stages in developing the G-HES involved analyzing the more general requirements that have been mentioned in previous sections. In particular, we conducted a number of focus groups with the Fire Officers and clinical staff who were to be the primary user group for the resulting application. Many of these discussions focused on the 'prototypes' that would be used to characterize the patients in each of the floors of the hospital. We began with four basic groups: 1) immobile patients who could not be moved from their beds; 2) Immobile patients who could be moved from their beds but only with considerable difficulty and an associated delay; 3) Immobile patients who could be moved with relative ease given the assistance of one or more members of staff; 4) Mobile patients able to move on their own with some staff directions. It can be difficult to predict precisely the distribution of patients within categories 1 to 4. Initial versions of the prototype simplified this taxonomy to consider ambulant and non-ambulant patients. However, future versions will return to these more elaborate distinctions. Similarly, it is possible to identify a number of categories within the nursing and clinical staff who are available to support an evacuation. The 'lead' nurse coordinates each evacuation. They will use a number of resources, such as a central whiteboard, to keep track of patient locations. The lead nurse can then dispatch their colleagues to initiate patient evacuation.

In addition to the more obvious occupant categories of patients and clinical staff the G-HES had to account for a number of other groups. For instance, many areas of the hospital are staffed by administrators and managers who would not normally be directly involved in the evacuation of patients. They would. However, receive annual training in evacuation and fire fighting procedures. They would also be familiar with the main emergency exits. However, as we have seen in the analysis of previous evacuations, it cannot be assumed that everyone in this category would choose to use these fire exits in preference to the main entrance routes into their areas within the hospital complex. As with all categories of staff, the level of administrative support varies considerably over the working day. Hence any simulation software must help its users differentiate between 'office hours' and other periods when less of these staff will be available.

There are significant numbers of visitors to some of the floors. However, these relatives and friends must, typically, restrict their visits to particular times. As development progressed, however, we quickly realized that the procedures and practice varies between different units. It is, therefore, possible for users of the simulator to specify how many visitors there will be on a particular floor prior to running the simulator. Similarly, it is possible to vary the occupants in floor that house out-patient's clinics by altering the distribution between mobile patients, who represent frequent visitors to the clinic, and visitors, who can be used to represent individuals who are new to the clinic and hence may not be familiar with the building layout.

As mentioned, there is an ordering that helps to determine evacuation priority. There is an expectation that office staff will require minimal supervision during an evacuation. All patients in immediate danger are moved first. Next ambulatory patients and visitors are moved. Wheelchair patients may be groups together and then moved gradually to a place of safety. Finally, non-ambulatory patients will be moved typically with moving those who can be transferred most easily before those who require significant additional preparation. The implicit objective at each stage is to maximize the number of people who can be moved to safety in the shortest available period of time. In addition to modeling these task priorities, it is important for the simulation to consider the timing delays associated with each of these evacuations. Firstly there is a preparation overhead in helping a patient to evacuate. Approximate timings are provided in Table 2. In computational terms, these delays are represented as probability distributions and Monte Carlo techniques can help to determine the real-time duration of any delay. These distributions can be assessed using experimental techniques. They can also be validated using a form of task analysis with staff focus groups given the difficulty of moving critically ill patients in a simulated exercise.

	Patient Category	Minimum delay (Seconds)	Maximum delay (Seconds)
1	Immobile patients who could not be moved from their beds (depending on associated instrumentation).	180	900
2	Immobile patients who could be moved from their beds but only with considerable difficulty and an associated delay (eg to a wheelchair)	180	900
3	Immobile patients who could be moved with relative ease given the assistance of one or more members of staff.	60	180
4	Mobile patients able to move on their own with some staff directions (accounting for telling them what is about to happen).	30	90

Table 2: Initial Preparation Times for Patient Evacuation

Once staff have initiated the evacuation of a patient, it is important for the simulator to determine their average walking speed. There have been many studies into average walking speeds during evacuations (Johnson, 2005). This work has, for example, looked at the manner in which we will slow down to accommodate different crowd densities. There has been relatively little research into the impact of walking speed on hospital evacuations. This creates several important problems. In particular, the relative age and physiological capacity of nursing staff is important given the problems of fatigue and of working in smoke filled environments performing tasks that involve considerable effort to complete. The initial simulations assumed a walking speed of between 2 and 0.04 meters per second. Again, Monte Carlo techniques can be used to assign particular speeds. Table 3 illustrates the results from a number of simple empirical tests to determine how these initial speeds should be modified depending on whether nursing staff were on their own or assisting in the movement of a wheelchair or a bed.

All timings are approximate for 10 meter distance.	Slow (seconds)	Medium (seconds)	Fast (seconds)
Nurse alone	16	12	8
Nurse with Wheelchair	20	16	12
Nurse with Bed	35	25	20

Table 3: Approximate Timings for Patient Evacuation over a Ten-Meter Distance

At present, the G-HES tools do not account for fatigue effects. However, the existing software could easily be enhanced to include a clock-based modifier to slow the speed of each nurse the longer that they participate in an evacuation. It is also important to emphasize the approximate nature of these timings. They depend upon the layout of the route being traveled. In this case we assumed that there were no obstacles and, in particular, the movement of the bed did not require any complex rotations to clear sharp corners. Similarly, the timings given above reflect the equipment available to staff on a particular floor of a particular hospital. The ease with which beds can be moved, in particular, depends on the particular model and degree of maintenance provided. For instance, the beds in our case study measured approximately 1 meter (38 inches) by 2.2 metres (86 inches). Wheelchairs were approximately 0.75 metres (30 inches) by 0.75 metres (30 inches). However, there were several different models. Some wheelchairs were heavily upholstered and more similar to a moveable armchair. Others were based around more conventional metal frames. Initial observations showed considerable variation both in the time to move patients between beds and the wheel chairs and to negotiate potential obstacles under ideal conditions; without smoke etc.

One of the most difficult problems for any simulation is to determine how human behavior will change over time as events unfold during an evacuation. In large group systems, such as the Boyd Orr auditorium system illustrated in Figure 3, individuals alter their behavior in response to changes in direction and speed within the crowd. It is for this reason that the GES uses Monte Carlo techniques where the likelihood that an individual will move in a particular interval is determined amongst other things by the speed and proximity of their neighbors. Such issues are less important in the simulation of hospital evacuations; crowds are less likely to occur except for bottlenecks close to common evacuation routes during visiting hours or in outpatient clinics. In contrast, it is important to account for the ways in which nursing staff will alter their response to an emergency within the constraints provided by 'horizontal evacuation' procedures and related hospital policies. For instance, many healthcare institutions are deliberately designed around a grid-structure where wards and rooms can be accessed from two different directions along common corridors. Nursing staff, therefore often have to choose between several alternate routes between a patient's room and a place of safety. Any simulation should account for those factors that are likely to influence the nurses' decision to use a particular corridor. For example, they should not normally lead patients along corridors that pass the seat of a fire. It must also account for the occasional situations when nursing staff select a more dangerous or slower route, either because they lack critical information or because they make a mistake. Additional complexity is introduced by a requirement that staff should continue to make intelligent decisions about where to move patients as a fire progresses and more routes become blocked.

The implementation of the nursing staff that drives the evacuation of the hospital is based around autonomous threads. The program creates an independent process for each individual. These processes can communicate through a form of message passing; the 'actions' that each nurse performs are implemented based on the represented state of the environment. A form of reactive route finding is implemented for each nurse using the A* algorithm that was first developed within the field of Artificial Intelligence. This assumes that the simulated nurse can identify each of the possible moves that they can make from their current location. They rank each of these moves and then only go on to consider the next set of available moves from the top ranked adjacent position. In this way, their planned route gradually grows as they always pick the best next step for further consideration. If a potential route becomes blocked then it may be necessary to consider the second route in the list of preferences. The success of the algorithm depends upon the choice of an appropriate heuristic. Euclidian distance can be used. Alternatively, more detailed information about the layout of the hospital can also be used to guide the evacuation movements. Recall that an independent thread represents each nurse. Each nurse will also be employing his or her own independent navigation strategy. It is, therefore, possible that contention will occur if, for example, two nurses attempt to move two beds along the same narrow corridor. This is entirely to be expected and specialist negotiation algorithms must then be used to resolve the bottleneck that is also a feature of 'live' evacuation drills. Brevity prevents a full introduction to the range of programming techniques that were used and the interested reader is directed to (Ashraf et al, 2003).

Figure 6 illustrates two key features of the hospital evacuation simulator. The image on the left shows a single panel from the G-HES configuration manager. Users can either alter the total number of staff and patients in different categories or they can alter a ratio of the current maximum occupancy and staffing levels. This interface can also be used to determine the anticipated number of people in the building for simulation runs at particular times of day. The other options available through the tabs on the left-hand image help the user to control the location of the fire. The 'General' option controls the speed of the simulation and allows a certain degree of lower level control over the procedures and route finding algorithms employed by the staff during an evacuation. In contrast, the image on the right of Figure 6 illustrates the output from a single run of the simulation. As can be seen, this run took a total of 17 minutes and 23 seconds to move all of the patients to a place of safety. This illustrates the importance of the option to run simulations at up to ten times their normal speed in order to assess a range of different non-deterministic evacuation behaviors in a particular configuration. The termination of an evacuation run in the context of a hospital evacuation raises a number of questions that do not arise in more conventional simulators. For example, in an auditorium or office block a run can be terminated when all of the occupants have safely exited from a building. In a hospital, however, this is not the case. Horizontal evacuation techniques rely upon the movement of patients to compartments that have a safe exit and that are protected by fire resistant walls and doors. It follows that the safety of patients and staff can be undermined even when this has been achieved. A fire or other hazard may gradually spread into areas that are immediately adjacent to this temporary place of safety. The users of the hospital evacuation simulator, therefore, have the option to restart an evacuation with the fire located in a different position in the building. Staff must then move their patients again. In practice, however, there is an assumption that emergency help will have arrived before such a 'last resort' action would ever be needed.

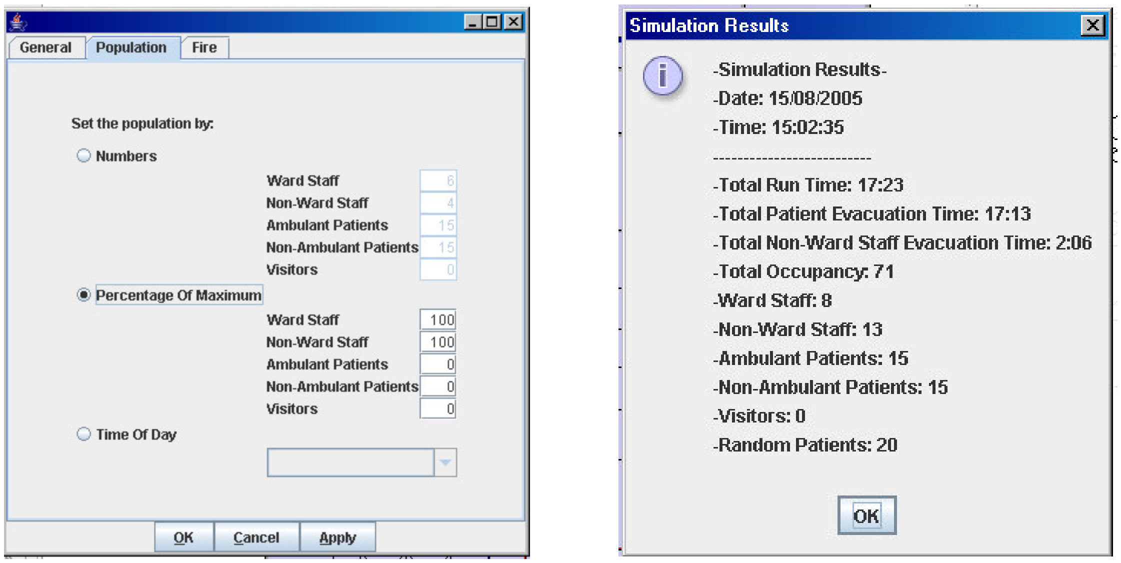

Figure 6: Option Panel and Results Dialogue from the Glasgow-Hospital Evacuation Simulator

The resulting simulator can be used in a range of ways. One immediate application was to explore what might happen to evacuation times with different profiles of ambulant and non-ambulant patients under the given staffing regime within particular areas of the hospital. As mentioned previously, simulator allows for non-determinism both in the patient profile and in the concurrent interaction between staff as they plan the best evacuation routes for a particular hazard. We, therefore, began to apply the tool by examining ten separate runs for the current staffing level of six nurses faced with different proportions of ambulant and non-ambulant patients. The results are shown in table 4.

Number of Non-Ambulant Patients	**Number of Ambulant Patients**	**Mean Evacuation time in seconds (Min:Sec)**	**Standard Deviation in seconds (Min:Sec)**
30	0	2643 (44:03)	257 (4:17)
25	5	1749 (29:09)	205 (3:25)
20	10	1439 (23:59)	189 (3:09)
15	15	1105 (18:25)	86 (1:26)
10	20	801 (13:21)	75 (1:15)
5	25	707 (11:47)	64 (1:04)
0	30	470 (7:50)	54 (0:54)

Table 4: Evacuation Times for Day Staff of 6 Nurses with 10 Runs for Each Patient Distribution

Table 5 continues the analysis showing the same means and standard deviations for different combinations of ambulant and non-ambulant patients. In contrast to Table 4, this illustrates the increased evacuation times associated with the reduced staffing levels that typically hold at night. It should be stressed that these figures are illustrative. As mentioned previously, agency staff are used more frequently to fill these shifts. The simulations do not currently take into account any additional overheads associated with reduced levels of staff training. Similarly, they do not consider the additional complexity of rousing ambulant patients from sleep when they may be under additional sedation. Finally as mentioned previously, we do not explicitly take into account the additional fatigue that may be expected if a small number of staff are involved in an evacuations that would require almost an hour to complete. The programming of these additional factors would be relatively straightforward compared to the synchronization techniques needed to implement nursing staff as a parallel processes. There are several reasons why these factors have not been explicitly modeled. Unlike the figures for daylight evacuations it is far harder to conduct nighttime validation exercises through live drills. It is unclear whether it would ever be possible or ethical to obtain staff participation to assess fatigue in an exercise involving non-ambulant patients where simulation results indicate it might take an hour or more.

Number of Non-Ambulant Patients	**Number of Ambulant Patients**	**Mean Evacuation Time in seconds (Min:Sec)**	**Standard Deviation in seconds (Min:Sec)**
30	0	3445 (57:25)	363 (6:03)
25	5	2976 (49:36)	279 (4:39)
20	10	2703 (45:03)	253 (4:13)
15	15	2357 (39:17)	234 (3:54)
10	20	1991 (33:11)	226 (3:46)
5	25	1723 (28:43)	244 (4:04)
0	30	1343 (22:23)	227 (3:47)

Table 5: Evacuation Times for Night Staff of 3 Nurses with 10 Runs for Each Patient Distribution

In spite of the caveats raised in the previous paragraphs, the results from the evacuation simulator provided important information to hospital administrators and managers as they assessed the risks associated with current staffing levels given different combinations of ambulant and non-ambulant patients. Given the difficulties of conducting 'live' drills and validation exercises, the greatest contribution of this type of tool need not lie in the accurate prediction of evacuation times as an outcome in itself. In contrast, our experience has shown that it can provide the greatest benefits in promoting a risk-based approach to the planning of evacuation exercises. Our preliminary figures for the night-time evacuation showed that there was an urgent need to determine whether current wards with, for example a mix of 10 ambulant to 20 non-ambulant patients, could be evacuated safely given the range of hazard scenarios considered in the emergency evacuation plans. Hence the use of the simulator drove another round of risk assessment that included the need to run night-time live 'drills' to validate the initial findings.

4. Conclusions and Further Work

The safety of large public buildings has become a pressing concern following recent and terrorist actions in Europe and the United States. This has led many regulatory and governmental agencies to advocate a risk-based approach to evacuation. The owners and operators of these buildings must demonstrate that they have taken actions to mitigate the most serious hazards that could prevent a successful evacuation. Unfortunately, it can be difficult to apply existing risk assessment techniques in this domain. Fault trees and FMECA can be used to represent and reason about potential problems. However, it is hard to assess the criticality or even the consequences of hazards, such as a fire exit becoming blocked or of a fire occurring during times of day with an increased occupancy or reduced staffing level. Some of these problems stem from the difficulty of conducting a program of 'live' evacuation exercises. Many buildings are now occupied by thousands of staff. Evacuation drills can endanger those occupants with pre-existing cardio-vascular conditions. They can also prove to be particularly disruptive to the financial and healthcare industries that must provide 24/7 support to their clients.

This paper has described how simulation software can be integrated into a risk-based approach to the evacuation of large public buildings. These tools can be programmed with models that are informed by an analysis of evacuation procedures and also be observations of human behaviour during both 'real' evacuations as well as drills. For example, timings taken from an evacuation exercise can be used to 'fine tune' the predictions made by the simulator. This is an iterative process because the results from a simulation can then also be used to focus subsequent 'live' evacuation exercises. The results of this process can then provide evidence for risk assessments that are structured using more conventional techniques, such as Fault Tree Analysis. The likelihood of particular combinations of hazardous events can be demonstrated by reference to previous accident reports and to live exercises. Where this information is partial or cannot ethically be obtained then computer-based simulations can be used.

Although this 'risk-based' approach to evacuation does not seem to have been explicitly written-up before, it shares much in common with the use of simulation in other engineering disciplines. We have, therefore, chosen to apply the technique in an innovative way by developing the Glasgow-Hospital Evacuation Simulator (G-HES) that is explicitly intended to model the evacuation of a large hospital building. This decision justified by the ethical and practical problems associated with 'live' exercises involving patients. These institutions also pose a considerable risk in terms of the relatively high frequency of fires and also the high potential consequences illustrated by several recent accidents. In many ways, these buildings pose extreme challenges. Occupant models must reflect the complex movement strategies that are devised to ensure that as many patients are moved as quickly as possible to a place of safety. The simulations must also consider the behaviour of other occupants including visitors and administrative staff. Finally, it is important to consider the impact of ambulant and non-ambulant patients where staff may be forced to first prepare patients to be evacuated and then move them using beds and wheelchairs.

We have implemented the G-HES using concurrent programming techniques to model nursing staff as they implement a horizontal evacuation strategy. This technique has been combined with independent route finding algorithms so that staff will automatically alter their actions to 'work around' their colleagues' activities. It is still possible, however, for contention to occur if colleagues try to move several patients along the same corridor. These algorithms also account for changes in strategy as fires spread to block previous evacuation routes. Again, however, the non-determinism in the application can capture periodic mistakes in which staff expose both themselves and patients to unnecessary risks, for instance, by moving down corridors that had previously been safe to navigate. G-HES can also be extended to use Monte Carlo techniques to determine the precise delays that are incurred as staff prepare patients to be moved and then move them away from a hazard. The rate of movement is non-deterministically assessed using speed distributions obtained by empirical studies of staff in the case study institution. Finally, the completed simulator has been applied to assess the amount of time that would be required to evacuate a mixed profile of ambulant and non-ambulant patients given the typical staffing levels both on day shifts and during the night. The results of this study illustrate the need for an iterative approach by motivating further 'live' evacuation drills to confirm the predicted results for nighttime evacuations. The insights obtained from the simulation proved to be crucial in justifying drills that might otherwise have been dismissed as unjustified given the ethical concerns over such exercises. Hence the simulators not only support a risk-based approach to evacuation planning, they also help to inform a risk-based approach to the planning of evacuation exercises.

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