Emergency Planning After Hurricane Katrina: Using Task Analysis with Observational Studies to Simulate Hospital Evacuations

C.W. Johnson,
Glasgow Accident Analysis Group,
Department of Computing Science,
University of Glasgow,
Glasgow G12 9QJ.
http://www.dcs.gla.ac.uk/~johnson,
johnson@dcs.gla.ac.uk

ABSTRACT

Hurricane Katrina forced the closure of at least nine of the twelve major hospitals in the New Orleans area. This triggered a series of mass evacuations that tested emergency plans in ways that had not been foreseen. These procedures are, typically, rehearsed using live drills. However, the financial costs and organizational complexity of such exercises places considerable constraints on the range of scenarios that are considered. Individuals often behave very differently in these exercises than they do during emergencies. Drills also place individuals at risk, especially if they suffer from pre-existing cardiovascular conditions. Many US states, therefore, require that evacuations are only rehearsed once per year and few require direct patient involvement. This paper argues that simulation software can be used to supplement **but not replace** conventional evacuation drills. Many existing simulators borrow ideas from CHI, including user models to represent the cognitive processes and emotional state of building occupants. In the past, these links have been the result of ad hoc collaborations. This paper proposes a more systematic use of CHI techniques in the development of evacuation simulators. Task analysis helps elicit key features from complex evacuation plans. Observational techniques are then used during live 'drills' to calibrate the findings from an initial analysis. Finally, information from previous disasters captures behaviors such as flocking that cannot easily be predicted from analytical models or from 'live' drills. Simulation software for the evacuation of a large general hospital is used as a case study. This is justified by initial reports following hurricane Katrina and precursors, such as the Houston evacuations following tropical storm Alison.

Author Keywords

Task analysis; observational techniques; simulation.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Hurricane Katrina has focused public attention on the preparation for natural disasters. The lack of appropriate evacuation plans forced many individuals to place their own lives at risk. For example, staff from the East Jefferson General Hospital had to perform ad hoc evacuations of elderly patients by wading from the emergency department ramp to an elderly care home that was being inundated. Clinicians and support staff at New Orleans' University Hospital had to carry patients down four flights of stairs to take them to an improvised Intensive Care Unit (ICU) when their generators flooded. The chairman of medicine at Tulane University Hospital was forced to use a colleague's canoe to coordinate with senior staff at New Orleans' University Hospital and Charity Hospital when the phone lines failed. Investigations are continuing into multiple fatalities following the evacuation of the Memorial Medical Center in New Orleans. Patients on the seventh floor had to be carried through the hospital to reach an evacuation point. Many patients had to spend considerable time waiting until a boat was available to transport them to safety. The hospital administrator argued that the deaths were the result of a 'systems failure' and criticized the lack of guidance on how to prepare for such mass evacuations.

Emergency evacuation plans are typically, based around a relatively small number of disaster scenarios. These often suffer from hindsight bias; organizations devote most resources to incidents that have occurred in the immediate past. They can also suffer from a limited horizon;

organizations do not consider the knock-on effects from an initial emergency. For example, many hospitals prepared well for the high winds of hurricane Katrina but few prepared for the subsequent flooding. Emergency plans are gradually refined over time using pre-planned drills. However, these exercises further constrain the range of emergency scenarios. They are expensive and disrupt 24/7 healthcare. There also pose risks for example staff and patients with pre-existing medical conditions [8, 9, 19].

Simulation software is increasingly being used to supplement **but not replace** live evacuation drills [7]. Emergency planners can use these tools to explore a wider range of evacuation scenarios than is possible using conventional exercises. Many of these tools exploit techniques that were originally developed within CHI. For example, simulators have drawn on previous work in user modeling to represent individual intentions and goals as building occupants move towards an exit [9]. Similarly, CSCW research has affected the modeling of group behaviors, for example when teams of co-workers 'flock' towards a common exit [1]. However, last year's conference identified further ways in which CHI techniques might be used to improve evacuation simulation in the light of recommendations made by the 9/11 Commission [13]. Ethnographic and observational studies of fire fighting behavior, including the work of Camp, Hudson, Keldorph, Lewis and Mynatt's at Georgia Tech [3], have not previously informed the development of evacuation software. Similarly, SIGCHI has promoted recent studies into creativity in design [4, 5]. Further work is needed to encourage the 'creativity' that is needed when emergency planners use computer models to predict plausible worst case scenarios. Although these recommendations were made in response to the 9/11 Commission, they are equally valid in the aftermath of Katrina. This natural disaster exposed a lack of 'creativity' in emergency planning and evacuation modeling. For the first time we have had to develop software simulations that consider the evacuation of a US hospital under sniper fire.

Figure 1 shows one way in which CHI techniques can be integrated into the development of evacuation simulations. As can be seen, the approach uses an initial risk assessment to identify probable, high consequence hazards including natural disasters such as Katrina but also the fires and terrorist actions that might trigger an evacuation. These hazards form the focus for the subsequent scenario modeling that must inform both live evacuation drills and software simulations.

The second stage focuses more narrowly on the human response to the evacuation and involves the integration of both task analysis and observational techniques. This combination is slightly unusual and there are tensions between these two different approaches [18]. An initial task analysis is critical to the development of human behavioral simulations because, as we shall see, evacuation procedures can be extremely complicated. For example, the evacuation plans for a major general hospital can now run to more than 500 pages providing high-level guidelines for the deployment of several hundred employees. However, human behavior often deviates from pre-scripted rules and procedures. It is, therefore, important that simulations are informed by direct 'observations' from evacuation exercises. These insights help to ensure that simulations capture the effects of uncertainty and confusion that can characterize real evacuations.

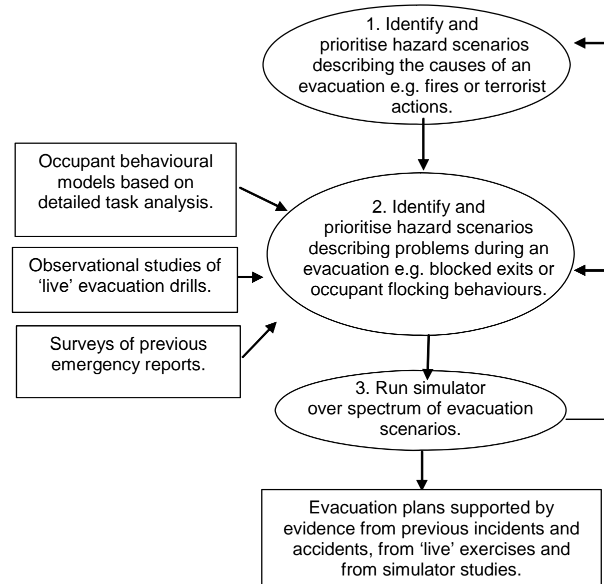

Figure 1: Integrating CHI Techniques into Emergency Planning

BEHAVIORAL MODELS AND TASK ANALYSIS

Evacuation software, typically, relies upon models of human behavior to drive the simulation. For example, building occupants often try to establish the credibility of an alarm before starting to move away from a potential hazard [2]. Simulations can mimic these findings by introducing a fixed delay into each run. More elaborate occupant models also 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 for simulation software to consider the social and team factors that have been shown to influence evacuation times in 'live' hospital exercises. The Federal Emergency Management Agency has 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. However, these social and cognitive characteristics cannot be viewed in isolation; a panicking group is more likely to travel at greater speed than a person who is calm [13]. Simulators have accounted for these behaviors by extending previous user modeling research to represent occupants' emotional state. For example, our simulators have based individual behavior around user models that exploit Murray's variables of personality [15] and Wu and Clark's [23] more recent work on aggression.

Behavioral models must be tailored to the population who use particular buildings. Most evacuation simulators focus on office blocks and entertainment complexes, such as sports stadiums. Hurricane Katrina has shown that this is a significant omission. Prior warning of the approaching storm ensured that office buildings, theatres and stadiums were successfully evacuated before the hurricane struck. In contrast, the need to continue providing healthcare left the hospitals crowded and exposed to the after-effects of Katrina. Events in New Orleans have also exposed the difficulty in extending human behavioral models from other public buildings to simulate healthcare evacuations. For instance, many building occupants will delay an evacuation by up to sixty seconds after an alarm depending on their level of preoccupation with the task at hand . This is very different from the evacuation of a hospital where nurses must continue to provide healthcare services as patients are being moved. Similarly, patients often only begin to evacuate when they are supervised by staff. In contrast, the occupants of other types of building show greater initiative during evacuations [9].

The need to coordinate the provision of continued care during an evacuation partly explains why hospitals draft complex contingency plans. Command hierarchies and roles are, typically, reinforced through drills and exercises. In consequence, the development of hospital simulations must focus more on the modeling of plans and procedures than on the impact of individual assertiveness or on the emergent behaviors of large crowds. It is for this reason that Figure 1 introduces task analytic techniques into an integrated approach for the development of interactive simulations. For isolated emergencies in primary healthcare, such as doctors' surgeries, these procedures can be relatively straightforward. In such cases, informal techniques such as Hierarchical Task Analysis are sufficient. For example, 'issuing the alarm' can be broken down into 'triggering the building alarms', 'contacting 911' and 'informing local fire wardens' as they would be in any other building. Tasks like 'evacuating the patients' may simply involve 'identifying the source of the hazard', 'collect together all patients' and 'lead them away from the hazard'. Each of these sub-goals in the emergency procedures provides objectives for the behavioral models that are associated with the software 'agents' in an evacuation simulator.

Unfortunately, hurricane Katrina forced healthcare staff to rely on more elaborate evacuation plans. The complexity and integration of a full-scale evacuation from an Intensive Care Unit (ICU) requires more sustained consideration of the different aims, methods and procedures that individuals will adopt under different contingencies. For example, we have assumed in the previous example that all primary healthcare patients can be 'led away from the hazard'. In contrast, ICU patients must be sedated. Teams of nurses must work together in order to coordinate their evacuation whilst maintaining their breathing etc. Hurricane Katrina added further levels of complexity to this already difficult task. The loss of generators from flooding and the scarce supply of battery power left some clinicians counting the drops from intravenous lines to ensure that patients received the correct dosage before they were moved. In the past we have used Concurrent Task Tree analysis developed by Paterno [16] and others in the CHI community to represent and reason about team based tasks during large-scale emergencies. This technique captures the synchronization of particular subtasks using operators such as '[]>>' (enabling with information passing) to represent the way in which clinical triage personnel can order the evacuation of high priority patients. Similarly, the '[>' (disabling) operator can represent the way in which some procedures have to be abandoned when teams are denied particular exit routes. The key point here is not to advocate particular approaches to task analysis but to argue that CHI techniques have a wider role in planning emergency procedures and, in particular, to support the behavioral modeling in evacuation simulators. The need for such analytical techniques can be illustrated by the complexity of existing contingency plans.

Horizontal and Vertical Evacuation Procedures

Most healthcare institutions use 'horizontal evacuation'. Patients are moved 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 staff consider vertical evacuation. As the term suggests, this involves moving patients to other floors and eventually out of the building. Sharon Howard, assistant secretary for Louisiana's state Office of Public Health, therefore made a significant statement when she first announced that the Charity, Chalmette, Lindy Boggs and Methodist hospitals were moving to vertical evacuation in the hours after Katrina's initial impact.

Horizontal and vertical evacuation procedures follow 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 arrive. This implies that the destination must be more secure than the area from which a patient is being moved. It is also important to continue to ensure that there is a protected path from the place of safety to an alternate evacuation route. 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 floods, fires or other hazards.

In most hospitals, an evacuation coordinator is appointed for each ward or center of care. Their performance can vary widely according to the level of staffing and the mix of patients they have to look after. Some assessment must be made about whether the risk of moving the patient is greater than the risk posed by the flood or other hazard. This assessment must continually be revised. For example,

many patients were not evacuated before Katrina struck. The hospitals had independent power sources and considerable supplies. In consequence, by the time that the storm was reaching its peak around 2am on the 29th August, six mothers had given birth in New Orleans' University Hospital. Two had undergone Caesarian sections. However, by the evening of the 30th August flooding had damaged the emergency generators. The internal daytime temperatures exceeded 100 degrees and the rooms were dark. Under such circumstances, evacuation had to be reconsidered.

Patients require different types of care and, hence, raise different concerns during an evacuation. This leads to a form of triage. Patients in immediate danger must be moved first. If a situation suddenly worsens, it is usually possible to lead more mobile patients away from the hazard. This is more difficult for patients who are confined to bed. Hence, non-ambulatory patients are usually considered before ambulatory patients and visitors. Wheel chair patients are grouped together and then taken to a place of safety by teams of nurses. Staff can lead groups of more mobile patients to safety in a single journey. 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. These triage procedures help to guide the immediate evacuation of particular areas within a hospital. As we have seen, however, Kartrina forced the evacuation of entire healthcare institutions. This led to a further form of triage where patients were moved from the hospitals to the city search and rescue base of operations (SARBOs). These acted as staging points for the boat and helicopter operations that eventually ferried them to the temporary medical-operation staging areas.

Task analysis provides a useful framework for representing and reasoning about the complex procedures that govern such evacuations. At present we have applied this technique to identify strengths and weaknesses in the emergency plans prepared by individual healthcare organizations. Katrina has taught that we need to consider extending the scope of this analysis to consider the interactions that occur when multiple agencies must cooperate during an evacuation. For example, greater care is needed to identify situations when decisions by one agency to evacuate large numbers of more mobile patients contradict the priorities of another agency to focus on bed-bound patients first [12].

Using Task Analysis to Benchmark Evacuation Times

Task analysis not only provides high-level tools for representing and reasoning about complex emergency procedures, it can also be used to derive benchmark estimates of evacuation times. For example, emergency planners can use a simplified form of the predictive task modeling advocated by Bonnie John and others [11]. These predictions can, in turn, be used to simulate the time needed to implement particular evacuation scenarios. For example, the physical task of moving a conscious but bed-bound patient to a refuge area on the same floor can take over twenty minutes. This high-level goal relies upon a number of sub-tasks that include disconnecting associated monitoring equipment (5 minutes), transfer to a wheel chair (12 minutes), moving the patient and the wheelchair to a place of safety (20 seconds) and then return to collect the next patient (15 seconds). These timings are based on assumptions about team-based performance. The time of five minutes that is given for disconnecting monitoring equipment is based on exercises in which three nurses work together to complete the task. However, events in the aftermath of hurricane Katrina showed that evacuations often had to be performed by ad hoc teams who had never worked together before. Existing groups of co-workers had to be split up to cover more pressing requirements in different areas of the hospital. Some members of staff had already been evacuated with their families, others had been unable to reach the hospital before the roads became impassable.

Our task timings also make assumptions about the equipment that is available to staff on a particular floor of a particular hospital. For instance, the wheelchairs in our local general hospital measure approximately 0.75 meters by 0.75 meters. However, there are several different models. Some wheelchairs are heavily upholstered, similar to a moveable armchair. Others are based around more conventional metal frames. If one of the larger wheelchairs is used then movement times can increase from 20 seconds up to 2 or 3 minutes. This reiterates the need to support analytical findings with direct observations of hospital wards and clinical equipment, as illustrated in Figure 1.

It is also important to consider the impact that particular evacuation scenarios have on these 'best case' timings. The previous analysis allowed twenty seconds to reach a place of safety within twenty meters of the patient's original location. This assumed that the evacuation is not hampered by either smoke or semi-permanent obstacles such as filing cabinets. However, hurricane Katrina left many hospitals littered by debris, including broken glass. Evacuations were further hindered by the lack of emergency lighting as generators and battery power were lost. Hence, figure 1 also shows that insights from previous emergencies must be used together with observations of live drills to further moderate the timings provided by an initial task analysis.

Table 1 provides empirical data that can be used to support the timings that are derived from a high-level task analysis. The maximum and minimum times refer to the delays observed in preparing a number of different patients to be evacuated from a general ward in our local hospital. This variation is in part explained by the skill and expertise of the nursing staff but also by the patient's condition. Mean values are, therefore, highly dependent on the patient population and are of limited value unless supported by a detailed survey of a particular healthcare organization. It is important to emphasize that the direct observations that

informed Table 1 cannot entirely replace the analytical techniques that help to derive timing predictions for different sub-tasks. In particular, we must estimate delays in situations that might otherwise risk patient safety or sacrifice valuable clinical resources, such as an MRI scanner, during repeated evacuation drills.

	Patient Category	Minimum delay (Secs)	Maximum delay (Secs)
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 1: Initial Preparation Times for Patient Evacuation

Our use of task models has been extended to represent and reason about some cognitive activities. For example, identifying the position to place a patient can involve looking at a potential area (150ms) and assessing the suitability of that location (1250-2000ms) [12]. At present our cognitive framework represents a considerable simplification over those that have been developed for many CHI applications. The behavioral simulations are closer to the Distract-R driver models that were presented at last year's CHI conference than the more sophisticated Act-R architecture [17]. Immediate cognitive activities and physical tasks dominate our timings. One reason for this is that higher-level plans are most likely to change as an emergency progresses. They are, therefore, very difficult to simulate. For instance, we cannot yet simulate the delays that arose from inter-agency disagreements about the potential destinations for patients being evacuated from New Orleans. This imbalance between immediate and tactical task modeling is likely to change as simulations account for the more strategic behaviors that will be described in the following sections.

Informing Task Analysis with Observed Behaviors

Many of the issues that arise from the use of task analysis in interface design also arise when these techniques inform the simulation of patient evacuations. In particular, the timings for each sub-task are based on assumptions about expert, error-free performance often by teams of staff. These predictions must, therefore, be validated by observations of human behavior in live drills and real emergencies, as shown in Figure 1. The importance of introducing this information can be illustrated by Tropical Storm Alison [6]. Although considerably smaller in scale, this emergency is a significant precursor to recent events in New Orleans. The intervening years have provided greater opportunities to study the lessons from this storm, as investigators continue to piece together details of the evacuations in the aftermath of hurricane Katrina.

Alison stalled over Houston releasing massive rainfall on June 8th and 9th 2001. It closed admissions to 3 hospitals and forced the evacuation of more than 2,000 general and 500 ICU beds. The buildings were designed to be 2 feet above the 100-year flood plain and were protected by flood prevention systems that had been developed after a 1976 storm. However, Brays Bayou failed to handle the rising storm water and Texas Medical Center began to flood around 23:00. Emergency generators provided power until electrical switchgear in the basement was flooded at 02:00. An internal hospital disaster was declared at 02:15. Staff had to work without electricity, water or a telephone service. The tasks and sub-tasks described in the emergency plans only dealt with a subset of the contingencies that faced hospital staff. A surgical operation was completed even though it was only mid-way through when the power was interrupted. In the ICU, some ventilators did not have battery power. Nursing staff had to stabilize the patients using manual bag-valve masks. Neonates were kept warm with chemical perineum pads but again nursing staff also had to rely on skin-to-skin contact.

As the surrounding streets became impassable, the procedures moved from stabilization to evacuation. A triage officer, the surgeon medical director of the ICU and a senior nursing director implemented the contingency plans and determined the order of patients to be moved. Those who needed assistance with their breathing were moved first, beginning at 10:30 on the 7th. This was followed by an order for a complete evacuation at 14:00. Some patients were carried down 10 flights of stairs. Again, however, careful preparations were supplemented by ad hoc innovations. Patients were secured to backboards for transit, some neonates were strapped 5 to a board. By 15:00, on June 10th, 169 patients were discharged from the hospital and 406 patients were successfully transferred by ground and air ambulance to 29 hospitals throughout southeast Texas. The key point here is that such successful evacuations rely upon a mixture of detailed planning and a flexible response to contingencies as they arise. Any evacuation simulator must be able to reflect this blend.

A recent study of an emergency evacuation from a nursing home provides further insights into patient and staff behavior [8]. Only one psychiatric patient showed

symptoms of panic during the evacuation. This incident also illustrates the way in which groups often ignore the detailed plans that are revealed by a task analysis of evacuation procedures. 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 their use was justified. In consequence, the evacuation took longer than expected by the building designer and by the Emergency Officers who were involved in the certification of the building. This reluctance to use all 3 stairwells again illustrates the need to consider real incidents in order to identify the ways in which the tasks and sub-tasks of an emergency plan break down under the contingencies of an evacuation.

Accident reports also yield important insights into the complex scenarios that must be recreated by evacuation simulators. For example, the evacuation of a Virginia hospital was delayed because staff were busy with patient care tasks [21]. These delays were compounded by the lack of any system connecting the hospital alarm to the local fire department. This had been taken out of service some time previously. Direct patient care is often seen as the primary objective and issues such as evacuation and emergency planning are paradoxically seen as having a secondary importance. Such insights from previous evacuations are important because they can be used to inform the scenarios that are used in both the 'live' evacuation drills and computer simulations that are intended to validate the rules and procedures identified by an initial task analysis.

Insights from Evacuation Drills

Fortunately, emergency evacuations are relatively rare. It can also be difficult to apply lessons from other organizations to particular hospitals. It is for this reason that Figure 1 also uses observational insights from evacuation drills to focus the use of simulation tools. It is important to illustrate the scale and complexity of these evacuation exercises in healthcare organizations. For example, a US hospital recently conducted 3 mock evacuation drills during a 6-week period. As with most drills before Katrina, these scenarios focused on fire related hazards. One started when the tip of an electrosurgical pencil ignited a drape [14]. 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 drill 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 anesthesia machine with the patient. Many elements of these drills, including the use of manual ventilation techniques, have parallels in the events following hurricane Katrina. However, the scale of the emergency and the degree of improvisation before evacuation meant that other aspects of the drill did not transfer between the exercise and the events that faced medical teams. In particular, the focus in New Orleans was almost exclusively on evacuating the patients with little or no thought to the movement of supporting equipment beyond those devices that were necessary to stabilize the immediate condition of the patients.

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 anesthetist were 'injured' during the exercise. Debrief sessions also helped to identify problems that were not always visible to the organizers. For instance, one anesthetist 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. At present the scale of the tragedy in New Orleans has meant that the focus is only just beginning to turn to reconstruction. Hopefully, there will be time to conduct a sustained debriefing exercise to ensure that lessons from the evacuations after Katrina are fully learned.

These drills and 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 the paging system was 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. Many of these lessons had not been widely disseminated before hurricane Katrina, as flood damage and

the failure of emergency generators removed key elements of the communications infrastructure. Clinical personnel relied on their mobile telephones until these systems only permitted the periodic use of text messaging.

Evacuation drills disrupt complex healthcare schedules, including surgical lists. It is for this reason that the UK National Health Service (NHS) regulations, advocate that a risk assessment be used to determine those personnel who must be involved in evacuation drills [22]. It can also 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. Similarly, many exercises do not involve the participation of external agencies that may be required to enter the building to assist in hospital evacuations. Changes in building use affect the 'shelf life' of any results from exercises. 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. In consequence, a successful drill in the immediate past can provide only limited assurance of a successful evacuation in the future. In particular, staff had to move patients to make the best use of scarce resources in the days after hurricane Katrina. Other areas were closed by flood damage. This created new hospital layouts that were very different from those that had been considered during previous drills.

Evacuation drills also carry risks both to staff and patients. Informed consent is required if members of the public are to be involved. Many US states, therefore, follow the Pennsylvania code in letting healthcare institutions decide whether or not to involve patients. Further problems arise because the results can be very different each time an evacuation exercise is performed. 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 patients and equipment. 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. Results from previous evacuation exercises can calibrate the findings from these simulations, which also avoid many of the costs and risks associated with exercises involving real patients. The following section, therefore, introduces the more detailed design challenges created by hospital evacuation simulators.

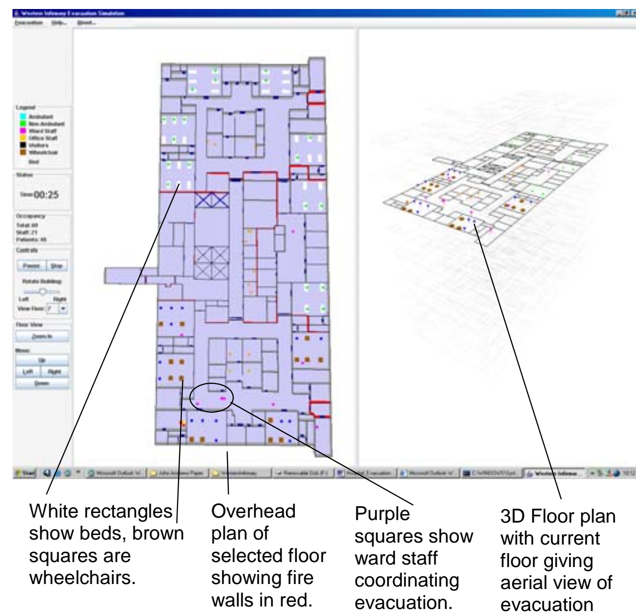

Figure 2: The User Interface to G-HES Evacuation Simulator

THE G-HES SIMULATOR

There have been relatively few attempts to develop interactive simulators specifically to support hospital evacuations [7]. This is a surprising omission given the importance of these structures and the difficulties experienced during tropical storm Alison and hurricane Katrina. Takenaka has developed the 'Assisted Evacuation Simulation System' [10]. This is unusual because it simulates stretchers, wheelchairs and evacuation by helpers' supporting patients on both sides. Other hospital evacuation simulations have extended systems that were originally developed to model egress from other public buildings [9]. It can be difficult to use these tools to model more detailed task allocations in the horizontal and vertical evacuation plans used by many hospitals. The reasons for this are complex and stem from the interaction between human behavior and building layout. 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 from several alternate routes between a patient's room and a place of safety. Simulations must account for the 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 are close to a hazard, such as a flood or fire. Simulators 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 hazard, such as a flood or fire, progresses and more routes become blocked.

Figure 1, therefore, illustrates the interface to a simulator that we developed to model the evacuation of hospital buildings using horizontal and vertical evacuation techniques. The G-HES software implementation of the occupant behaviors is based around autonomous threads. The program creates an independent process for each individual. These processes communicate through a form of message passing. The problems associated with navigation during horizontal and vertical evacuation from grid layouts in hospitals have been addressed using a variant of the A* algorithm. This Artificial Intelligence technique assumes that the simulated nurse can identify each of the next possible steps that they can take from their current location. They rank each of these moves and then only go on to consider the next set of available steps 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 for ranking potential evacuation routes. Euclidian distance can be used. Alternatively, more detailed information about the layout of the hospital can be used to guide the evacuation movements. Recall that an independent thread is used to implement each nurse. Each nurse also implements his or her own independent navigation strategy. Contention will occur if, for example, two nurses attempt to move two beds along the same narrow corridor. Specialist negotiation algorithms must then be used to resolve the simulated bottleneck that is a feature both of evacuation drills and emergency evacuations.

Previous sections have described how our simulations rely upon a high-level analysis of evacuation procedures as well as direct observations of human behavior during drills and emergencies. In computational terms, this involves the use of Monte Carlo techniques to determine the real-time duration of particular subtasks. Random numbers are generated and compared with probability distributions that represent the likelihood of a task being completed within a particular time interval. These distributions can be assessed using observations from drills similar to those described in previous sections, illustrated in Table 1. Monte Carlo techniques drive the behavior of clinical staff. They can also be used to simulate the many friends and family who sought shelter in the hospitals following hurricane Katrina.

The G-HES enables users to estimate the time that is required to move different numbers of patients with different degrees of mobility to various places of safety at different staffing levels. However, this raises questions that do not arise in more conventional simulators. For example, the evacuation of an office block usually ends when all occupants have left the building. In a hospital, horizontal and vertical evacuation techniques rely upon the movement of patients to areas that have a tenable exit and are protected, for example by fire resistant walls and doors. If a fire or flood continues to develop, however, patients and staff can still be placed at risk in this initial 'place of safety'. The users of the G-HES simulator, therefore, have the option to continue the evacuation triggering the staff to move the patients to another place of safety further away from the developing hazard.

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 2: Fully-Staffed Evacuations (6 Nurses, 10 Runs each)

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 3: Reduced Staff Evacuations (3 Nurses, 10 Runs each)

One immediate application of the G-HES simulator was to explore the impact that different staffing levels had on evacuation times. As mentioned, many hospitals had to form makeshift evacuation teams because many staff were trapped in their homes or had already been evacuated. Tables 2 and 3 summarize the results of this analysis for the ward shown in Figure 2. The mean times for each ratio of ambulant to non-ambulant patients were obtained over ten runs. Recall that the simulator uses Monte Carlo techniques over probability distributions associated with task completion times, hence the results are non-deterministic. They capture the variations that can be observed within evacuation drills. Each table, therefore, captures 70

different simulation runs that would otherwise have required several weeks of drills. We cannot claim to have solved the theoretical, practical and ethical problems of validating hospital evacuation simulations. However, our results must be placed in the context of recent events in New Orleans and predictions about the increasing frequency of similar storms. These preliminary figures for evacuation times have motivated several hospitals to conduct live drills to validate our findings. The results from these exercises will inform and guide further simulation follows the iterative model proposed by Figure 1.

CONCLUSIONS AND FURTHER WORK

Hurricane Katrina is teaching us important lessons about the evacuation of large, public buildings. There were precursors, such as Tropical Storm Alison. However, the warnings were not heeded. In consequence, legal action has been started against hospital and care home administrators.

This paper forms part of a wider response to the events around New Orleans. In particular, we have argued that CHI techniques can support an integrated approach to emergency planning. Task analysis can be used to identify the key objectives and roles that determine individual or team behaviors during an evacuation. The results from such studies must be informed by direct observations from live evacuation drills and insights from previous emergency evacuations. Together these sources of information help to drive interactive evacuation simulators. These systems **supplement but do not replace** live evacuation exercises. They offer particular benefits where ethical, legal and organizational barriers limit patient and staff involvement in hospital evacuation drills.

Much remains to be done. There are technical limitations. As mentioned, the cognitive models that drive the simulated behavior of individuals within an evacuation are relatively crude. They lack the more detailed architecture provided by the ACT-R framework, for example. There are also limitations to the scale of our simulations. Hurricane Katrina has forced us to consider the evacuation of hospital complexes across an entire region and not simply single buildings. Finally, this work has revealed deeper problems at a national and international level. Work in this area is continually hindered by the lack of a central archive for evacuation information. There is no equivalent of the US National Transportation Safety Board where hospital administrators and first responders can learn about previous emergency evacuations. This is an important omission. As we have seen, the occupant models that drive our simulations must be informed by both the results of drills and by insights from previous real evacuations. In consequence, we are forced to rely on ‘war stories’ and anecdotes that leave us ill prepared to face future emergencies on the scale of Katrina.

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REFERENCES

1. Batty, M., Desyllas, J., and Duxbury, E. (2003), Safety in Numbers? Modeling Crowds and Designing Control for the Notting Hill Carnival. Urban Studies, (40)8:1573-1590.
2. Bryan, J.L., (1982) Human behavior in the MGM Grand Hotel fire. Fire Journal. 76:37–48.
3. P.J. Camp, P.J., Hudson, J.M., Keldorph, R.B., Lewis, S. and Mynatt, E.D., (2000), Supporting communication and collaboration practices in safety-critical situations. ACM CHI 2000, v.2:249-250.
4. Carroll, J.M., (2000), Making Use: Scenario-Based Design of Human-Computer Interactions. MIT Press, Boston.
5. Carroll, J.M., Mack, R.L., Robertson, S.P. and Rosson, M.B., (1994) Binding Objects to Scenarios of Use. Int. Journal of Human-Computer Studies, (41)1:243-276.
6. Cocanour, C., Allen, S., Mazabob, J., Sparkes, J. Fischer, C., Romas, J. and Lally, K., (2002), Lessons Learned from the Evacuation of an Urban Teaching Hospital. Archives of Surgery, 137, pp. 1141-1144.
7. Drager, K.H., Lovas, G., Wiklund J., Soma, H., Duong, D., Violas, A. and Laneres, V., (1992) EVACSIM - A comprehensive evacuation simulation tool. In Proc. of the 1992 Emergency Management and Engineering Conf., Soc. for Computer Simulation, Orlando, Florida, 101-108.
8. Edelman, P., Herz, E. and Bickman, L., (1980) A model of behavior in fires applied to a nursing home fire. In: Canter D, ed. Fires and fire behavior. John Wiley and Sons, Chichester, UK.
9. Gwynne, S., Galea, E.R., Parke, J. and Hickson, J., (2003), The Collection of Pre-Evacuation Times from Evacuation Trials Involving a Hospital Outpatient Area and a University Library Facility. In D. Evans (ed.) Proceedings of 7th IAFS Symposium WPI, USA, pp877-888.
10. Jafari, M. Bakhadyrov, I. and Maher, A., (2003) Technological Advances in Evacuation Planning and Emergency Management: Current State of the Art, Technical Report to the Federal Highway Administration, EVAC-RU4474, Center for Advanced Infrastructure & Transportation, Rutgers University, New Jersey, USA.
11. John, B.E., Prevas, K., Salvucci, D.D. & Koedinger, K., (2004), Predictive Human Performance Modeling Made Easy, ACM CHI 2004, 455-462, New York, ACM Press.

12. Johnson, C.W., (2003) A Handbook of Accident and Incident Reporting, Glasgow University Press, Glasgow, 2003. http://www.dcs.gla.ac.uk/~johnson/book
13. Johnson, C.W., (2005) Applying the Lessons of the Attack on the World Trade Center, 11th September 2001, to the Design and Use of Interactive Evacuation Simulations, In Proceedings of ACM CHI 2005, ACM Press, New York, USA, 651-660.
14. McCarthy, P.M., and Gaucher, K.A., (2004) Fire in the Operating Room—Developing a Fire Safety Plan, AORN Journal (Journal of the Association of Perioperative Registered Nurses), 79:3.
15. Murray, H.A., (1938) Explorations in Personality, Oxford University Press, Oxford, UK.
16. Paternò, F. (2003), ConcurTaskTrees: an engineering notation for task models. In Dan Diaper & Neville A. Stanton (Eds.) The Handbook of Task Analysis for Human Computer Interaction. London: Lawrence Erlbaum Associates,483-503.
17. Salvucci, D.D., Zuber, M., Beregovaia, E., Markley, D., (2005) Distract-R: Rapid Prototyping and Evaluation of In-Vehicle Interfaces, Proceedings of ACM CHI 2005, 581-589.
18. Suchman, L., (1987) Plans and Situated Actions, Cambridge University Press.
19. Thompson, P.A. and Marchant, E.W., (1995) Computer and fluid modeling of evacuation. Safety Science, (18)277–289.
20. US National Fire Protection Association (NFPA), (1993) Summary Fire Investigation Report—Hospital Fire, Brooklyn New York, 1/9/1993, Department Secretary for Fire Investigation, National Fire Protection Association (NFPA).
21. US National Fire Protection Association (NFPA), (2005) Summary Fire Investigation Report---Hospital Fire, Petersburg, Virginia 5 People Killed, 12/31/1994, Department Secretary for Fire Investigation, National Fire Protection Association (NFPA).
22. UK NHS (2001), Fire Safety Policy, Directorate of Finance, Health Department, Scottish Executive NHS HDL(2001) 20, 2001.
23. Wu, K.D., and Clark, L.A., (2003) Relations between personality traits and self-reports of daily behavior. Journal of Research in Personality, (37)231-256.