Applying the Lessons of the Attack on the World Trade Center, 11th September 2001, to the Design and Use of Interactive Evacuation Simulations

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ABSTRACT
The collapse of buildings, such as terminal 2E at Paris' Charles de Gaule Airport, and of fires, such as the Rhode Island, Station Night Club tragedy, has focused public attention on the safety of large public buildings. Initiatives in the United States and in Europe have led to the development of interactive simulators that model evacuation from these buildings. The tools avoid some of the ethical and legal problems from simulating evacuations; many people were injured during the 1993 evacuation of the World Trade Center (WTC) complex. They also use many concepts that originate within the CHI communities. For instance, some simulators use simple task models to represent the occupants' goal structures as they search for an available exit. However, the recent release of the report from the National Commission on Terrorist Attacks upon the United States (the '9/11 commission') has posed serious questions about the design and use of this particular class of interactive systems. This paper argues that simulation research needs to draw on insights from the CHI communities in order to meet some the challenges identified by the 9/11 commission.

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H5.m. Information interfaces and presentation; H.1.2 User/Machine Systems.

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Safety; Simulation; Evacuation; User modeling.

INTRODUCTION
Events such as the collapse of terminal 2E at Paris' Charles de Gaule Airport and the recent fire at the Station Night Club in Rhode Island often focus public attention on the safety of large public buildings. In consequence, government initiatives in the US and in Europe have led to the development of evacuation simulators [1]. These tools have been developed because experiments involving real people and real fires are widely perceived to be unethical. Even the statutory fire drills in many work places can create risks for some groups, especially the disabled or those with cardio-vascular conditions.

The design, development and evaluation of evacuation simulators raise many questions that are relevant to the CHI communities. For example, the Transport Canada Personality Profile 2 (TCPP2) distinguishes between 13 characteristics that might influence behavior during aircraft evacuations. Experimental studies suggest that for a passenger load of 150 there would be approximately 28 individuals who might be identified as 'highly assertive' or 'goal directed'. These passengers have a total evacuation time of 3.08 minutes compared to 3.58 minutes for the 26 passengers in the lower assertiveness groups [16]. We have used these insights to develop primitive user models in our GES simulator. During the development of a particular simulation, we use psychometric techniques across a sample of the building's occupants to determine the distribution of the characteristics identified in the TCPP2 model. Unfortunately, specialist evacuation models such as TCPP2 often lack any clear relationship with more widespread personality instruments, such as Murray's variables of personality [20] or Wu and Clark's [24] more recent clinical models. These focus on aggression rather than the more nebulous concept of assertiveness. Further problems complicate these specialist evacuation user models. For example, psychological characteristics, such as aggression, cannot be viewed in isolation. A panicking individual is more likely to travel faster than a person who is calm. In the GES tool, each person is assigned an initial speed of 0.14 ms [23]. The user can calibrate this base speed, which will also be modified between 80-120% during a simulation depending on the state of the occupant model.

In addition to empirical studies, evacuation simulators often rely on studies of previous incident to calibrate their

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occupant models. The 2003 fire in Rhode Island's Station nightclub provides an example. A form of flocking combined with problems in the building layout. Most of the 300 occupants walked past the fire exits to the main entrance. They then had to force their way through a bottleneck created by a ticket booth causing many crush injuries. This reluctance to follow emergency signs and instead retrace the path back to an initial entrance is a seen in many accidents. The GES tool therefore implements two different occupant models. Under 'ideal' conditions, each individual tries to use the nearest available exit. Insights from the Rhode Island fire, led to the development of an alternate mode where a proportion of the occupants ignore fire exits and retrace their path to the entrances. Figure 3 illustrates the user interface to the GES tool.

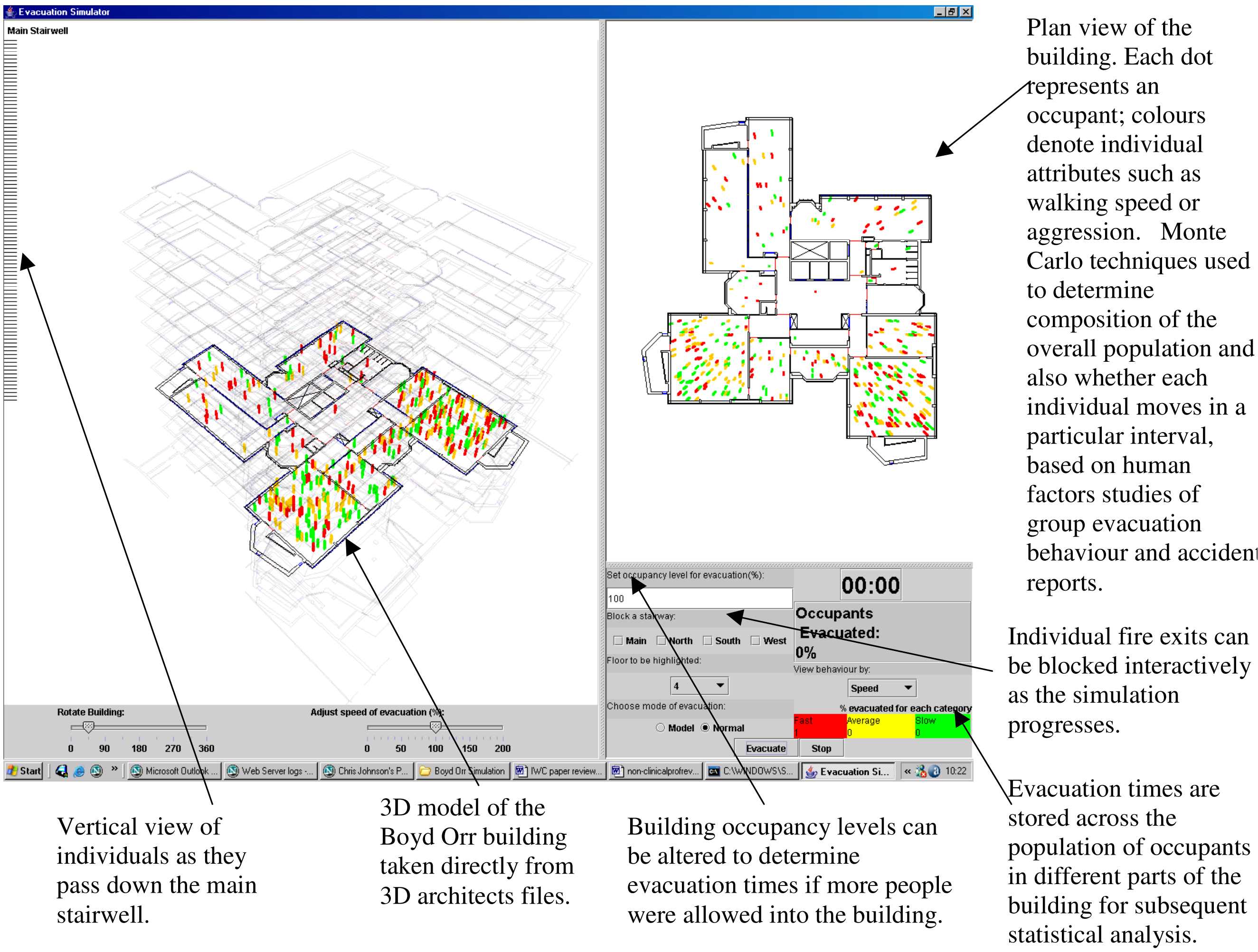

Figure 3: User Interface to the GES Evacuation Simulator

It can be difficult to validate the predictions made by evacuation simulations. Firstly, there is a generic problem with externally rationalizing 'in situ' behaviors. Post hoc interviews reveal a host of confounding influences that helped to determine survivors' actions [15]. The problems of analyzing behavior in a particular context are generic because the same issues arise when attempting to understand why the users of interactive software behave in different ways in laboratory studies compared to their eventual use in complex, working environments [18, 22]. We have taken a pragmatic approach using focus groups involving the building occupants, First Responders and fire officers responsible for the buildings being modeled. We have also conducted more formal evaluations of the GES as a training tool. For example, 40 occupants of the building illustrated in Figure 3 were interviewed about the route they would take in the event of a fire alarm. They were then shown 'ideal' evacuation simulations in which occupant models included a goal to reach the nearest available fire exit. They were also shown alternate simulations where most occupants retraced their way back to the entrance. Before the simulation, around 50% (21 out of 40) said they would use the nearest available fire exit. The remainder stated that they would use the route by which they had entered. This was a slightly higher proportion than had been anticipated by the domain experts. After we had shown the simulations to the building occupants, 30 stated that they would use the fire exits but 10 people still argued that they would use the main stairwell. A Chi-squared test showed that the GES tool had a statistically significant impact on the expressed choice of exit with a P-value of 0.001 with a single degree of freedom between the nearest fire exit or the way that they entered the building. However, the simulations failed to convince one quarter of this group that they should use the nearest fire exits. It is also important to ask whether these expressed attitudes provide an accurate indication of actual behavior during an evacuation. Previous sections have noted the significant impact of social and cognitive factors. For instance, flocking occurs when crowding acts as a catalyst to flight [3, 12]. These behaviors may be more powerful than the insights provided by short exposure to evacuation simulations.

THE IMPACT OF SEPTEMBER 11TH 2001

The events of September 11th 2001 have had a profound impact on everyone involved in the design and operation of large public buildings. The evacuation from the WTC complex is widely viewed as a success. Up to 99% of the building occupants below the level of impact survived. This achievement has been attributed to changes that were made both to the emergency exits and to fire evacuation-training programs following the bombing of the WTC in 1993. These included the use of photo-luminescent paint on exit routes and emergency lighting for the stairways [2]. However, there were also missed opportunities. For instance, many occupants were advised to remain in their officers and wait rescue when Stairwell A in the South Tower was still passable. This advice was largely based on experience from the 1993 bombing when many people were injured as a result of the evacuation.

There is a widespread concern that similar attacks may be attempted in the future even if the mechanisms will be different [22]. It is, therefore, important that we learn as much as possible from this tragedy. The following pages use the recently published findings from the 9/11 Commission to evaluate the utility and usability of existing evacuation simulators. This analysis reveals many different areas for potential collaboration between the SIGCHI and simulation communities.

Model Changing Evacuation Policies

At 8:46:40, American Airlines Flight 11 flew into the North Tower. The aircraft cut through floors 93 to 99. It is likely that all 3 of the building's stairwells became blocked from the 92nd floor up. One of the most striking features of the immediate evacuation behavior was the role played by procedures that had been drafted before the disaster. Occupants began asking for guidance about whether or not to evacuate the building. Local telephone operators and the Fire Department of New York (FDNY) dispatchers relied on standard operating procedures for high-rise fires. The occupants were told to stay low, remain where they were and wait for emergency personnel. This advice was given to callers in the North Tower who were located below and above the impact area. However, the policy created in the aftermath of the 1993 bombing was clearly inappropriate in the context of 9/11. The FDNY chiefs immediately altered the policy and ordered an evacuation as soon as they arrived in the lobby of the North Tower.

Very few simulation scenarios have considered the possible confusion that can arise when a decision is made to revoke previous policy. For example, the GES tool assumes that all occupants will attempt to evacuate the building if possible. Imposing a delay before the occupants begin their evacuation can create a scenario that is similar to events in the North Tower. Unfortunately, this does not capture the complexity of the unfolding situation. Some occupants could not be informed of the change and remained where they were. In consequence, some areas of the evacuation followed the former policy while others evacuated as soon as possible. The complexity in the North Tower was also mirrored by the initial evacuation from the South Tower. Many occupants were unaware of what had happened in the other tower. Some even thought that the initial incident had occurred in their building. Many people decided to leave. Some were advised to do so by fire wardens and company security officers even though this contravened the policy mentioned above. The Public Address system in the South Tower told tenants that their building was safe and that they should remain in their offices. Many occupants, therefore, reversed their evacuation. At approximately 9:02, one minute before the second aircraft hit, the South Tower's public-address system advised occupants that they could begin an "orderly evacuation if conditions warranted".

Our analysis of the initial evacuation from the WTC emphasizes the need to look beyond anticipated behaviors in response to existing procedures to also consider the way in which behaviors change in response to an evolving scenario. The analysis of the 9/11 evacuation points to multiple conflicting behaviors that change rapidly over time. Some groups began to evacuate and then reversed their decision. Others delayed their evacuation even though their colleagues decided to leave. Such behaviors cannot easily be modeled using the simulators' existing goals structures without knowing far more about the context in which those goal structures will change. One of the reviewers of this paper referred to the analysis of the 9/11 evacuation as an 'ethnography' or 'social history'. They went on to comment that what emerges are not fully formed scenarios in the way that interaction scenarios have been used in the design of interactive computer systems [6, 7]. Rather our observations identify points of concern, each of which needs to be more fully explored within the simulation community and in cooperation with members of the CHI communities.

Model Alternate Communications

Many simulators already model communication between building occupants. For instance, if one group finds that an exit is blocked during a scenario then they may pass this information to other groups in the same area of the simulated building. However, the multiple communications channels that were used during September 11th illustrate the naivety of these computational models. In particular, no previous scenarios seem to consider the impact of widespread cellular telecommunications on evacuation behavior. Fire and impact damage prevented many occupants from hearing the North Tower's deputy fire safety director when he advised tenants to descend at least two floors below the smoke or fire and to wait there. Similarly, many occupants could not use the emergency intercom phones, which they had been trained to use in fire drills. In consequence, many people dialed the US emergency number '911'. However, the 911 operators and FDNY dispatchers could not tell callers whether they were above or below the fire. Similarly, the operators were unaware of the New York Police Department's decision not to attempt rooftop rescues. By 8:57, FDNY chiefs had instructed local police and building personnel to evacuate the South Tower because of the damage caused by the first plane's impact. Again, this information was not conveyed to 911 operators or to FDNY dispatchers. One group of occupants on the 83rd floor repeatedly asked 911 operators if the fire was above or below them. The callers were transferred several times and were eventually advised to stay where they were. These callers are unlikely to have survived. Several operators independently decided to tell callers to evacuate if they could. In the South Tower, many occupants continued to call for advice after the second plane hit. The investigation concluded that the 911 system "remained plagued by the operators' lack of awareness". This lack of information "combined with the general advice to remain where they were, may have caused civilians above the impact not to attempt to descend" when the South Tower's stairwell A may still have been passable.

The passage of information between different individuals and groups clearly had a profound impact on the course of the evacuation. Most simulators model this at some level of abstraction. For instance, individuals in a simulation may pass information on to other groups if they find that an exit is blocked during a scenario. However, very few simulators consider anything like the degree of complexity that arose during the WTC evacuation. At present, the simulation community has no clear means of modeling or even analyzing the mass of formal and informal communications channels that were witnessed during the evacuation of the WTC complex. The relevance of these observations to the CHI communities is that we could benefit strongly from collaboration with groups who have studied less extreme forms of communication in the workplace. For instance, the analytical work of Clark and Brennan [8] on implicit and explicit communication in group-work might be applied to help bring the existing, primitive occupant models closer to the behaviors seen in the 9/11 tragedy.

Simulating Decision Making Under Uncertainty

From the earliest moment of the rescue efforts, the course of the evacuation was dependent upon a series of key decisions taken by groups of emergency personnel. A battalion chief and two ladder and two engine companies arrived at the North Tower at approximately 08:52. Minutes later, the on-duty division chief for Lower Manhattan arrived and took over. Together they gradually attempted to piece together the limited information that they had available about the state of the buildings. All 99 elevators in the North Tower appeared to be out. There were no assurances that sprinklers or standpipes were working on upper floors. These observations motivated their decision to focus on evacuation rather than fire fighting. They also decided to ask both building personnel and a Port Authority police officer to evacuate the South Tower. They were concerned that the impact of the plane into the North Tower had made the entire complex unsafe. They had not considered the possibility of a second plane striking the South Tower. The 9/11 report observes with considerable understatement that the "FDNY chiefs in the increasingly crowded North Tower lobby were confronting critical choices with little to no information". Even those individuals who had a better overview of events could still make assumptions that seem unwarranted, with the benefit of hindsight; "a senior FDNY chief who knew that the South Tower had collapsed strongly expressed the opinion that the North Tower would not collapse, because unlike the South Tower, it had not been hit on a corner".

Existing simulators seldom seem to consider the uncertainty that was faced by teams of first responders during the evacuation of the WTC. One way of addressing these issues would be to use simulators within evacuation exercises. For example, rather than simply focusing on the speed and direction of crowd flows, the scope of many simulators could be extended and integrated into wider forms of training. Tools such as the GES can be used in role-play exercises where first responders and building managers are asked to simulate the decision making under uncertainty that characterized the immediate aftermath of the attacks on the WTC. Again, we need to recruit help from the CHI communities. There is a considerable literature on the use of computer-based simulations in training exercises [9]. Similarly, there have been ethnographic studies of firefighter behavior, for example by Camp, Hudson, Keldorph, Lewis and Mynatt at Georgia Tech [5]. We could also benefit from many of the ideas put forward by Laurillard on the integration of practical and theoretical training [17]. She has sketched an iterative framework that has been applied to model Computer Assisted Learning. In this framework, the software forms part of a wider dialogue between an instructor and their class. Student responses to prompts by the software must be examined at several different levels. A failure to comprehend key topics reflects the student's difficulties; it also provides valuable insights for the redesign of the CAL system. From our perspective, the failure to evacuate individuals from a simulation exercise not only reflects problems in the planning and execution of emergency personnel. It may also provide key insights for the redesign of simulation tools.

Model Dynamic Group Behaviors

Most simulation tools explicitly consider group behaviors when they model evacuation scenarios. This ranges from complex motivational models through to more simple crowd-based movement. The events at the World Trade Centre have forced us to reconsider evacuation strategies when large groups of occupants are distributed throughout a damaged building. In the North Tower, after the first aircraft struck, hundreds of civilians were trapped on or above the 92nd floor in large and small groups. It would have been difficult, if not impossible, for them to evacuate. However, there were other groups below the impact zone who were either trapped or were waiting for guidance. Most of these groups were on floors in the 70s and 80s but there were further clusters on the 47th and 22nd floors. Many of these groups appear to have acted collectively, either deciding to evacuate together or to wait for further assistance. The decision to wait together was often motivated by damage to the building. Many groups were dissuaded from continuing an evacuation because doors appeared to be locked when they were jammed by debris or distortion from the impact of the plane. These collective decisions may also have been reinforced by the panic and confusion in increasingly crowded stairwells.

Few simulation tools model the interaction between individual and group behaviors that the 9/11 enquiry found in the evacuation of the WTC. For example, one occupant of the South Tower, close to the impact site on the 78th floor, "seized the initiative and shouted that anyone who could walk should walk to the stairs, and anyone who could help should help others in need of assistance". Partly as a result of their intervention two small groups formed and both were able to evacuate from this floor even though it was very badly damaged. Again, it is possible to see links between the observed deficiencies in evacuation simulators and previous work within CHI. Many in the field of CSCW have considered the ways in which individuals influence group behaviors or help to shape joint problem-solving [11, 13]. For example, Fischer, Lemke, Mastaglio and Morch have considered the manner in which critiquing can alter the course of group decision making over time [10]. Similarly, Haynes and Sen have investigated the positive and negative effects of conflict on team behaviors [14]. Many of the generic behaviors identified in this work are also apparent in the evacuation behaviors reported by the 9/11 Commission. In particular, the study of scenarios and critiquing provides important insights into the evolving strategy of the first responders as they shaped and reshaped their plans for the evacuation.

Model Building Information and Security Systems

The hijacked American Airlines Flight 11 flew into the upper portion of the North Tower at 08.46.40. However, it was not until approximately 09:30 that a "lock release" order was issued to the buildings' computerized security systems from the Security Command Centre in the North Tower. This command should have provided unrestricted access to all areas, including the exits that led to the roofs. By this time, fire damage had affected many of the buildings' internal systems. In consequence, the order never reached many critical areas in the towers.

It is difficult to underestimate the importance of these events for the future simulation of evacuations from large public buildings. The last decade has seen enormous changes in the role that computer controlled systems play in the management of many structures. It is likely that this trend will continue. A number of recent research initiatives have begun to place 'hardened' sensor networks into buildings. These provide real-time information about the course of a fire so that emergency personnel can gain an overview of the hazards facing occupants and their colleagues. Such proposals address the lack of information that frustrated the evacuation of the World Trade Centre. The 9/11 investigation reports the comments of one FDNY fire chief who argues, "People watching on TV certainly had more knowledge of what was happening a hundred floors above us than we did in the lobby… Without critical information coming in . . . it's very difficult to make informed, critical decisions". Previous paragraphs have described the impact that this lack of information had on subsequent decision-making. Chiefs in the lobby disagreed over whether anyone could be rescued at or above the impact zone. Others were unsure whether or not there should be limited firefighting, if only to cut exit routes through the fires. The proposed building information systems and distributed sensor networks might help to inform the decision-making in future disasters. It has even been proposed that live data from these applications might be used to direct simulations in 'real time' so that emergency personnel can view some of the possible evacuation routes being used by building occupants.

However, the events at the World Trade Centre reveal some of the dangers associated with relying on this new generation of building information systems. Very few of these proposed applications would survive the extent of the damage inflicted in a broad area around the impact sites. Even if sensor networks could be made robust enough, it is unclear how useful the data would be, given that fire chiefs had to make decisions based on the distribution and condition of occupants that cannot easily be detected by the proposed sensors. A meta-level point is that these applications have the ability both to support but also to hinder the course of any evacuation. Distributed sensor networks might be used to provide critical information to first responders. However, there is also a danger that they may overwhelm users with detail or even provide misleading information about the state of a building. In the same way, the World Trade Center's computerized security system could have facilitated evacuations by opening all of the locked doors. The fact that this command was not received in many areas of the building illustrates the potential risks that are implicit within these systems.

The CHI communities have begun to consider interaction with building management systems. This ranges from extensions of Mantei, Baecker, Sellen, Buxton and Milligan's [19] early work on media spaces through to the more recent Co-Build workshops on cooperative buildings. Unfortunately, very little research has addressed the combined themes for this year's conference 'Technology, Safety and Community'. The focus has been on the development of innovative user experiences and applications. However, the events of 9/11 show that the usability of building management systems is of critical importance during an evacuation. Simulation tools provide means of assessing the role that building management software can play during an evacuation. However, there must also be some way of connecting these scenarios to standard forms of usability testing, for instance to see whether first responders can use the management systems to help occupants escape under a range of different scenarios. Unless this is done then it is likely that building occupants will be faced with locked doors as they attempt to escape from future emergencies.

Model Worst Plausible Scenarios

The events of September 11th have redefined 'the plausible worst case scenarios' that guide emergency planning [22]. Prior to the attack on the WTC, it was considered plausible that a building complex might suffer a single aircraft strike. Few considered the possibility of multiple strikes within a short period of time. The official report argues that after the second aircraft hit the South Tower; "what had been the largest and most complicated rescue operation in city history instantly doubled in magnitude". These events not only helped to redefine our view of the 'worst plausible circumstances' in terms of the nature of the attack. The more detailed evacuation behavior of groups of individuals also reveals how limited many existing simulators are in their emulation of human problem solving under uncertainty and extreme stress. Many of the occupants of the South Tower who were in or above the impact zone began to ascend the stairs. One small group reversed this decision and began to go down an unblocked stairwell having been told that the floors above them were in flames. One person in this group survived to describe how others joined them on the 91st floor. Some decided to go down even though the 82nd floor transfer hallway was on fire while others decided to climb back up again. It seems clear that the occupants were faced with the decision to either face the flames on the 82nd floor with the hope of evacuating below the level of the fire or of climbing above the flames in the hope of egress via the roof or of waiting until the fire had been extinguished. Other aspects of this tragedy provide further lessons for scenario generation. The US National Institute for Standards and Technology's Building and Fire Research Laboratory continues to study the ways in which damage to the building affected evacuation behavior. In the North Tower, attempts to descend through the damaged floor were frustrated by jammed or locked doors in stairwells. Other occupants became confused by the structure of the stairwell deviations. However, other areas were comparatively unaffected. By the lower 70s, stairwells A and B were well lit with reasonable ventilation. However, by fifteen minutes after the impact debilitating smoke had begun to reach as far up as the 100th floor. Severe smoke conditions were reported between the 90th and 100th floors in the following half hour.

The conditions within the towers were determined by a mixture of pathological and relatively minor damage. This arose because the planes did not follow the worst imaginable flight path. While the attack on the North Tower isolated most of the floors above the impact, the plane that hit the South Tower banked immediately before impact. This left portions of the impact floors in a relatively good condition and, in consequence, stairwell A remained open from the 91st floor down. Four people were able to use this route to escape from the 81st floor or above. Although the stairway was dark and difficult to navigate, luminous strips on the stairs and handrails assisted their egress. Many of these had been introduced following the 1993 bombing of the World Trade Centre. However, other aspects of the incident were far worse than people might have imagined. The impact on the South Tower extended down to the 78th floor where hundreds of people had been waiting to evacuate using the sky lobby elevators after witnessing the attack on the North Tower. Many of these people were killed or severely injured while others were unharmed. It is difficult to determine whether there are any areas of research within the CHI communities that might help address the problem of determining the 'worst plausible scenario'. At present, the simulation community can offer almost no advice on how to use computer-based tools to develop this mixture of pathological failures and 'good fortune' that characterize most emergencies. Clearly, human computer interaction with these simulators involves strong forms of creativity in predicting what might happen so that end-users will develop 'realistic scenarios' [6, 7]. One of the aims of this paper is to establish links between work in these two areas and it would be very valuable to hear of related work in other areas of CHI.

Model the Ingress and Egress of Emergency Services

Previous generations of evacuation simulation systems have focused almost exclusively on the egress of occupants from a building. However, the events at the WTC complex reinforced a lesson that should have been learned from previous tragedies. It is critically important that these systems be extended to consider the potential problems that could arise from the ingress and then the eventual egress of emergency personnel from a damaged building. There was considerable disagreement over whether anyone could be rescued above the impact zone in the North Tower or whether limited fire fighting should be started to try and reach any survivors in that area. In consequence, firefighting units were instructed to go up towards the impact zone and report back via radio. The companies began to ascend stairwell B of the North Tower at approximately 09:07. They each carried around 100 pounds of protective clothing, self-contained breathing apparatuses, and other equipment such as hoses and cutting tools. The units stopped on some of the floor to look for injured occupants and also any people who were uninjured but were waiting for instructions. Simulations might have provided additional information not simply on the time taken to ascend these structures carrying such an array of equipment but also to consider the impact that their movements would have on those occupants who were still trying to get out of the damaged building. The firefighters were passing a steady stream of people. The 9/11 investigation concluded that performing these duties was "hard work even for physically fit firefighters" and that some firefighters became separated from the rest of their units as they began to suffer different levels of fatigue.

Not only can fire personnel use simulations to analyze the physical demands of ingress during a range of adverse scenarios, these same tools might then be used to analyze the evacuation of emergency personnel. The events of September 11th proved just how hard it is to coordinate a decision to withdraw units from a damaged building. At 09:32, a senior chief radioed all units in the North Tower to return to the lobby. There is no evidence that any units actually returned to the lobby. As units climbed higher, their ability to communicate using the tactical radio systems became more sporadic. Just prior to 10:00, in the North Tower one engine company had climbed to the 54th floor, at least two other companies of firefighters had reached the sky lobby on the 44th floor, and numerous units were located between the 5th and 37th floors. The complexity of the ingress into the North Tower was replicated in the South. The 9/11 investigations revealed the piecemeal nature of progress in freeing trapped occupants and in initiating their evacuation. A ladder company took a working elevator to the 40th floor and then began to climb up stairwell B. Another team began to rescue civilians trapped in an elevator between the first and second floors. A further FDNY ladder company encountered numerous seriously injured civilians on the 70th floor. A security guard helped another company to find a group of civilians trapped in an elevator on the 78th floor sky lobby.

The problems of ingress were complicated by the need to integrate resources drawn from several different agencies. The first NYPD Emergency Service Unit (ESU) team entered the North Tower and attempted to check in with the FDNY chiefs present. The 9/11-investigation team reports that these attempts to support the FDNY were "rebuffed". Members of the Mayor's Office of Emergency Management did not intervene and so the ESU began to climb the stairs. A second NYPD ESU team had more success in checking in with the FDNY chief when they entered the South Tower. However, a third ESU team made no attempt to coordinate their efforts with the FDNY command structure as they entered the North Tower. By approximately 9:50, the lead ESU team had reached the 31st floor. There seemed to be no more civilians descending but they did administer oxygen to a number of firefighters who appeared to be exhausted. Meanwhile, the ESU teams in the South Tower were making slow progress in their ascent because of the number of occupants who were descending the stairwells.

The attack on the WTC also reinforced the importance of extending simulations to consider the area immediately surrounding large public buildings. For example, an important strength of the GES simulator is that it uses existing architects' drawings and 3D models to drive the simulation scenarios. This creates potential problems because the simulations only extend as far as the architect's models. The events of September 11th affected all of the buildings in the World Trade Centre Complex and not just the twin towers that were the focus of most attention. For example, the Marriott Hotel ran between the North and South towers. It suffered significant damage when the South Tower collapsed. Occupants and emergency personnel were knocked to the floor in the lobby and were soon in darkness. People in the hotel began to evacuate but others were severely injured or trapped. The scope of the rescue activities had to be extended to include the buildings surrounding the towers. For instance, one team of firefighters found approximately 50 occupants taking shelter in the restaurant. Other firefighters were distributed across the area between the two towers. Two companies were either at the eastern side of the North Tower lobby or were near to the mall concourse as they tried to reach the South Tower when it collapsed. They then attempted to regroup in the debris cloud to continue evacuating both themselves and any remaining occupants. They were unaware that the South Tower had collapsed. The need to understand evacuations across multiple buildings is reinforced by the fact that several groups of emergency staff replicated the work of their colleagues, often exposing themselves to unnecessary hazards. For instance, one group from these firefighters went on to search the Port Authority Trans-Hudson (PATH) station below the WTC complex, which had already been cleared of occupants by Port Authority policy around 9:19.

The attack on the WTC shows that the analysis of ingress and egress by first responders poses as many challenges as the simulation of building occupants. The FDNY personnel who received the evacuation order in the North Tower responded in many different ways. Some paused to help injured occupants, even though some knew that the South Tower had collapsed. Other units that had become separated under the physical exertion of the climb began to reassemble to descend as a team. Other individuals remained on the steps waiting to recover a little before going down even as their colleagues urged them to leave. Many groups began the evacuation at a relatively leisurely pace because they still did not know that the South Tower had completely collapsed. The official investigation also heard accounts of units that had descended into the lobby and were then persuaded to go back to look for particular colleagues who had been left behind. This great diversity of behavior is equal in complexity to the many different reactions observed amongst the occupants of public buildings under such adverse conditions.

The consequence of not considering the detailed procedures and practices governing the evacuation of emergency personnel were also eloquently illustrated by the events of September 11th. Five companies of fire fighters reached the North Tower lobby around 10.24 using stairwell B. As described in previous sections, many of the senior personnel had been withdrawn earlier. As a result, these teams stood in the lobby for more than a minute. They were uncertain what to do and there were no chiefs present. Finally, one firefighter urged them all to leave. He had seen that the South Tower had come down and believed that the North Tower would shortly follow. The units began to exit onto West Street as the North Tower began its 'pancake collapse'. Several firefighters in this group were killed.

Having argued that evacuation simulations should be developed to consider the ingress of emergency services and not simply the egress of occupants, the events at the WTC can also be used to identify a number of potential difficulties. With egress, simulation scenarios can focus on likely routes and times for the majority of building occupants. However, ingress models must also consider the impact that small teams of emergency workers can have upon the course of an evacuation. For example, three plainclothes NYPD officers ascended stairwell A or C of the North Tower. They began checking for occupants from the 12th floor onwards. These officers continued their check even though their chief had ordered them to leave the North Tower. It would have been difficult to predict the way in which these small teams disseminated information within the WTC before the attacks. Hence, they could not easily have been included in any simulation Not only did they speed the evacuation of the North Tower but they may also have persuaded coordinators not to commit more teams into the building given that only limited numbers of civilians had remained.

The work of these small teams illustrates another key point. The events at the WTC encourage us to go further than simply modeling the passage of people within a damaged building. The 9./11 attacks also suggest the importance of considering the transfer of information and the decision-making processes that arguably had the greatest impact on the overall course of the evacuations. Emergency personnel not only help to fight fires and protect evacuation routes. They also provide information to building occupants and other first responders. This is seldom modeled in existing simulators. It is important to stress that we are as guilty in this neglect as our colleagues who have developed the existing generation of evacuation simulators. The omission of first responders in existing simulation tools arguably left us unprepared for the loss of so many police and fire fighters in the WTC complex. A closer involvement with the CHI communities might have identified this omission sooner, for example by conducting a more extensive stakeholder analysis or even engaging in more participatory forms of development [11].

Model Coordination Between Emergency Services

The 9/11 investigations revealed that information was not always shared as effectively as might have been desired, at least in retrospect. For instance, one of the NYPD Aviation Units reported that the South Tower had collapsed immediately after it happened. The crew recommended that all people in the World Trade Centre complex should be evacuated. At 10:04, NYPD aviation reported that the top 15 stories of the North Tower "were glowing red" and that they might collapse. Four minutes later, a helicopter pilot warned that he did not believe the North Tower would last much longer. It was not, however, easy to ensure that this information was communicated either to the NYPD officers in the complex or to their colleagues in the FDNY. Most of the NYPD radio frequencies became overwhelmed with transmissions after the South Tower collapsed. Even so, it was possible to coordinate the movement of the two closest NYPD mobilization points away from the complex. Similarly, an Emergency Service Unit (ESU) commander who had observed the destruction of the South Tower was able to order the evacuation of all ESU units from the complex. His instructions were clearly heard by the two ESU units already in the North Tower and the other ESU unit preparing to enter the tower. However, one of the ESU teams in the North Tower could not believe that the South Tower had been destroyed and so radioed the command post to confirm the message.

The smaller numbers of NYPD personnel and the location of key officers both within the Towers and at their command Centers arguably made it easier to communicate the order to evacuate than was the case for the FDNY officers. The ESU teams within the North Tower quickly began to pass on the evacuation order to FDNY personnel. Together they began to descend using stairwell B. As they went down, they reported seeing many firefighters who were resting from their exertions in taking equipment into the North Tower. The NYPD officers advised these firefighters to evacuate. Some refused to "take orders from a cop" [22], others reported that ESU officers passed them without telling them about the evacuation order. Either way, the stress and confusion of their circumstances help to explain the breakdown of communication between the different teams involved.

Officers from the Port Authority Police Department (PAPD) supported the NYPD and the FDNY. The collapse of the South Tower forced the evacuation of the PAPD command post to the north of its initial location. Many PAPD officers did not have WTC command radios and so few received the evacuation order. Some in the North Tower decided to evacuate, either on their own or in consultation with other first responders they came across. Again, however, the need to improvise of coordination and communication between different emergency services illustrates the importance of considering these issues in anticipation of future adverse events. Simulation is just one of many techniques that might be used to flush these issues into the open.

The poverty of existing evacuation simulations is further emphasized when one examines the way in which the emergency services responded to changing circumstances during the evacuation of the World Trade Centre. For instance, an ESU team on the 11th floor began descending stairwell C after receiving the evacuation order. Once some of the group reached the mezzanine floor, they formed a chain back up several flights. They used flashlights to provide a path of beacons through the darkness for the remaining occupants and other members of the evacuating emergency services. When no one else appeared on the stairs they ran to an adjacent building where they conducted additional searches for civilians. All but two of them died in the aftermath of the collapse of the North Tower. Another ESU team had been preparing to enter the North Tower when the South Tower collapsed. They too formed a chain and helped further groups of occupants to evacuate by going down the stairs on the north side of the complex. They remained until the North Tower collapsed, all survived. Future generations of simulation tool might be extended to consider the impact that specific evacuation techniques, such as ESU chaining, might have both on the egress of occupants and on the timing of any evacuation command for the emergency services. At present, such techniques are widely used in 'real' evacuations but seldom appear in the current generation of computer-based tools.

The North Tower collapsed at 10:28:25 A.M., killing all civilians alive on the upper floors and many in the emergency services scattered throughout this and adjacent buildings. The FDNY Chief of Department, the Port Authority Police Department Superintendent, and many of their senior staff were killed.

Conclusions and Future Work

Evacuation simulation software is intended to help the owners and designers of large public buildings assess the risks that occupants might face during emergency egress [4]. The development of these tools has been informed by human factors studies. For example, to show that occupants will delay their departure from a building if they are engaged in goal related activities that distract them. Previous accident investigations have also been used to validate human factors studies. For instance, the 2004 fire in the Station nightclub, Rhode Island illustrated the way in which most building occupants will attempt to retrace their steps to the entrance rather than use fire escapes even though they are adequately signposted.

This paper has argued that the CHI communities have a significant role to play in the future development of evacuation simulators. Evidence for this argument has been provided by a detailed study of the 9/11 Commission's report into the attacks on the World Trade Center. This study has revealed many limitations of existing simulation tools, for example in modeling interaction with building management software and in the modeling of interaction between teams of co-workers. It has also challenged us to think about whether such tools might be integrated into other forms of 'live' exercises to test decision making amongst first responders and building managers. Although there is relatively little work that can be directly transferred, the CHI community does offer a number of useful insights. For example, Grudin and others have considered the ways in which individuals influence group behaviors [13]. Most of this work focuses on the interactions that take place between groups of co-workers in everyday office environments. Further work is required to consider the changes that occur when the same teams of co-workers find themselves faced with the more extreme demands of emergency egress. Similarly, Carroll and his colleagues have looked at the integration of scenarios into design [6]. This work is relevant because each evacuation simulation provides a scenario that should inform the design and operation of large public buildings. Unfortunately, this valuable research on scenario-based design is not widely known in the simulation community.

Evacuation tools often depend on existing architect's drawings. These contain little information about the disposition of non-permanent internal structures such as partition walls and desks in an office or beds and trolleys in a hospital. The placement of these objects is often determined by working practices that change over time just as the flow of people around a building will evolve with their everyday activities. These issues have only just begun to be considered in our work. We are drawing on activity theory as a means of trying to analyze the impact of situated actions on the placement of non-permanent objects and on the flow of people within a building [21].

The events of the 11th September have acted as a catalyst for more radical thinking. For instance, a joint meeting of the National Conference of States on Building Codes and Standards and the Association of Major City/County Building Officials recently proposed the development of a secure database for first responders. This would contain evacuation plans for major public buildings. Other research initiatives are consider the installation of distributed sensor networks to provide first responders with a real-time analysis of the damage to a building as an evacuation progresses. Such initiatives create new roles for evacuation simulations run directly from the source drawings and models in the NCSBCS and AMCBO database. In the future, therefore, these tools might have a greater presence at the scene of an incident as it develops. The simulations might be constantly updated by input from the proposed sensor networks. The new opportunity is to integrate command functions and not simply predictive facilities into this new generation of simulators. The usability issues that will arise with these systems are immense; we will be sending police and fire fighters into buildings on their advice. It is, therefore, critical that we achieve closer contact between our two communities.

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