Lessons from the Evacuation of the World Trade Centre, September 11th 2001 for the Development of Computer-Based Simulations

C.W. Johnson,

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

This paper provides an overview of the state of the art in evacuation simulations. These interactive computer based tools have been developed to help the owners and designers of large public buildings to assess the risks that occupants might face during emergency egress. The development of the Glasgow Evacuation Simulator is used to illustrate the existing generation of tools. This system uses Monte Carlo techniques to control individual and group movements during an evacuation. The end-user can interactively open and block emergency exits at any point. It is also possible to alter the priorities that individuals associate with particular exit routes. A final benefit is that the tool can derive evacuation simulations directly from existing architects models; this reduces the cost of simulations and creates a more prominent role for these tools in the iterative development of large-scale public buildings. Empirical studies have been used to validate the GES system as a tool to support evacuation training. The development of these tools has been informed by numerous human factors studies and by recent accident investigations. For example, the 2003 fire in the Station nightclub in Rhode Island illustrated the way in which most building occupants retrace their steps to an entrance even when there are alternate fire exits. The second half of this paper uses this introduction to criticise the existing state of the art in evacuation simulations. These criticisms are based on a detailed study of the recent findings from the 9/11 Commission (2004). Ten different lessons are identified. Some relate to the need to better understand the role of building management and security systems in controlling egress from public buildings. Others relate to the human factors involved in coordinating distributed groups of emergency personnel who may be physically exhausted by the demands of an evacuation. Arguably the most important findings centre on the need to model the ingress and egress of emergency personnel from these structures. The previous focus of nearly all-existing simulation tools has been on the evacuation of building occupants rather than on the safety of first responders[1].

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

1. Introduction

Recent terrorist actions, including the attack on the World Trade Centre complex, and the collapse of buildings, such as terminal 2E at Paris' Charles de Gaule Airport, have focussed attention on the safety of large public structures. Research initiatives have been launched to re-examine the physical characteristics of the materials that have been used in the construction of these buildings. Other parts of the US 'Homeland Safety' programme have reassessed the many different hazards that might affect public structures. These range from biochemical and biological contamination through to explosive devices and the kinetic and potential energy that might be transferred from new generations of aircraft, ships, road vehicles etc.

The paper begins be describing the design and development of a computer-based system for analyzing the evacuation of large public buildings. This system has many unique features; it was developed with support from a range of organizations and individuals including building managers, the regional fire service and government specialists in building safety. An important innovation is the ability to drive simulations easily and cheaply for existing architects drawings rather than requiring the costly development of specialized models, which was a weakness of other systems. The tool can, therefore, be used in real-time as the architect develops new buildings to provide a first impression of likely evacuation speeds at different levels of occupancy. The tool also combines traditional probabilistic simulation tools for the development of different populations within areas of the building and for the precise rate of an evacuation. The results produced from these techniques have been informed by human factors literature on evacuation behavior and from an analysis of occupant behavior during actual fires.

Major accidents provide an important opportunity to learn from previous failures and successes. The events of September 11th 2001 have had a tremendous impact on many involved in the design and operation of large public buildings. A series of regulatory and government initiatives have investigated both the construction techniques and

[1] Thanks are due to J. Appleby, P. Cooper, A. Foss, S. Hailey and B. Jenks who were responsible for the design and implementation of the GES application. They also drove the development of the Boyd Orr evacuation scenarios that are used to illustrate the opening sections of this paper.

the materials used in a host of structures, including tunnels, bridges and high-rise buildings. Requirements have been drafted in several countries to ensure that the managers of high occupancy buildings conduct a more explicit assessment of the risks that are associated with their operations. New research funding initiatives have been launched with the aim of increasing 'homeland security'. The developers of evacuation simulation tools have received some portion of this support. Their mathematical models and computer-based systems can be used explore the potential problems that might arise during the aftermath of an adverse event. However, relatively little attempt has been made to conduct a systematic review of the lessons learned from September 11th for the design and operation of these simulations.

The second part of this paper, therefore, summarizes the lessons that have been learned from the events of September 11th as they relate to the simulation of evacuations from large-scale public buildings. Many of these insights relate to the specific events that unfolded during this incident. However, there are also a host of more generic lessons that undermine many of the assumptions that guided the development of our initial simulations. For example, much of the previous work has focused narrowly on the time that it takes the public to get out from one of these structures rather than the time it might take for emergency personnel to move through an evacuation to reach different areas of a building. Other insights include the importance of information flows throughout a building. Many previous simulations seem to assume 'perfect knowledge' so that occupants immediately start to evacuate from every area of a building regardless of whether all or some of the alarm systems have been compromised. The closing sections of this paper look more broadly at the lessons September 11th has provided for the future role of evacuation simulators. For instance, preliminary discussions with fire personnel have suggested that these tools might be used during an emergency to help emergency officers anticipate the flow of people as they move through a damaged building.

1.1 Regulatory Background

Fire regulations, typically, impose a number of requirements upon architects and designers that are intended to ensure a prompt evacuation in the aftermath of an adverse event. For example, the International Building Code (IBC) has become a standard model for over 40 states in the USA. Under it's provisions, construction documents and floor plans are required to show the "construction, size and character of all portions of the means of egress". They must also show the number of occupants on every floor and in each room or space (IBC 2000, Section 106.1.2). The professionals in charge of designing new buildings are to be responsible reviewing and coordinating submittal documents prepared by others, including phased and deferred submittal items, for compatibility with the design of the building. (IBC 2000, Section 106.3.4). Although this code is under constant review, these provisions have remained through successive modifications to other areas of its requirements. However, the International Building Code is not universally accepted. For example, the city of New York relied on a plethora of local regulations until Mayor Bloomberg created a streamlining initiative in 2002. However, safety was not the primary motivating factor behind these revisions; "Our current Building Code's complexity is often an impediment to new construction and drives up the cost of building in New York City. A continuously updated Building Code will help generate more affordable housing and make New York City a more attractive place to do business" (New York City, 2002). In addition to local and state legislation, Federal agencies also publish requirements and recommendations that govern the evacuation of large public buildings. For instance, Occupational Safety and Health Administration identify "high-rise buildings" to be greater than 75 feet (25 m) in height from the lowest level of fire department vehicle access to the highest floor that can be occupied. In such buildings, employees should be provided with appropriate exits, alarms, emergency lighting, communication, systems, and sprinkler systems. They also state that 'when designing and maintaining exits, it is essential to ensure that routes leading to the exits, as well as the areas beyond the exits, are accessible and free from materials or items that would impede individuals from easily and effectively evacuating' (OSHA, 2003). The Code of Federal Regulations, Standard 29, Part 1910, Subpart E covers Exit Routes, Emergency Action Plans, and Fire Prevention Plans. Requires that employers prepare emergency action plans to address emergencies such as 'fire; toxic chemical releases; hurricanes; tornadoes; blizzards; floods; and others'. The employer should consider not simply the means necessary to effect a prompt evacuation. They must also consider those staff who must remain behind to assist emergency services and to control any hazardous processes.

European legislation reflects the diversity and complexity of the US experience. Two health and safety European Council Directives, 89/391/EEC and 89/654/EEC, were adopted in 1989. These specified expected standards that should be supported by the enactment of legislation in each of the member states. For instance, the UK legislation on fire evacuation is based around the Fire Precautions (Workplace) Regulations 1997, As Amended 1999. These amendments were necessary to meet the requirements of the 1989 EC directives. The UK amendments included provisions to ensure that all occupants are alerted and can leave the premises safely in the event of a fire and that employers will be responsible for the outcome of any adverse event. The focus of the UK amendment was to introduce risk assessment as the basis for fire regulations. Building owners and managers had to demonstrate that any precautions were appropriate to the likelihood and consequences of any hazard. Evacuation measures could be use to demonstrate mitigation of the potential consequences of an adverse event. However, this attempt to bring together previous legislation was further complicated by the provisions of other acts that have a baring on the design of large public buildings For example, it was intended that the Fire Precaution regulations would combine with the Disability Discrimination Act 1995 to ensure that people with disabilities are afforded better access a range of buildings. As in the United States, however, regional differences complicate matters even further. These differences are likely to continue with the Scottish Executives publication of the Fire (Scotland) Bill 2004. For instance, Building standards regulations are advisory in England and Wales but are mandatory in Scotland. One consequence of this is that in Scotland, all new buildings or new stairs in any buildings will have a refuge within the stairwell to afford some protection for injured or disabled occupants who cannot otherwise be evacuated. For instance, regulation 13 governs means of escape from fire, facilities for fire fighting and means of warning of fire in dwellings. Part E2.2 states that 'suitable means of escape for disabled people in the event of fire must be provided in every building or part of a building from any floor which is accessible to disabled people'. There have been further attempt to reform UK fire safety legislation. The most recent is the Regulatory Reform (Fire Safety) Order 2004, which aims to reduce burdens on business that are 'caused by the existence of multiple, overlapping general fire safety regimes – and consequently overlap of the responsibilities of enforcing authorities. The proposed order would consolidate and rationalize much existing fire safety legislation (currently scattered across a large number of statutes and secondary legislation) into one order. In doing so it would reduce the number of enforcing authorities dealing with general fire safety matters. The reform would maintain and enhance the protection afforded to users of premises (and others who might be affected by a fire on the premises) by the existing legislation' (UK Office of the Deputy Prime Minister, 2004).

The previous paragraphs have reviewed existing legislation in Europe and the USA as it applies to the evacuation of occupants from large public buildings. These acts ensure that designers, building managers and employers must prepare the means for occupants to escape from a range of potential hazards. In addition to these regulatory requirements, a number of voluntary guidelines support the design, construction and operation of large structures. In the UK these include British Standards 5588 Fire Precautions in the design and construction of buildings. British Standards can be awarded as a mark of quality providing developers meet the necessary requirements in the associated guidelines. For instance, Part 8 of BS 5588 provides the Code of practice for means of escape for disabled people. This document goes beyond many of the regulatory instruments by observing that 'management systems are an essential part of means of escape for disabled people'. These guidelines also make it clear that places of refuge are not intended to be locations where individuals must be left to wait for rescue by the emergency services. Section 3.14 defines a refuge to be an area that is served directly by a safe route to a storey exit, evacuation lift or final exit. In the United States, the National Fire Protection Association (2004) also publishes additional guidelines to support the evacuation of public buildings. Although these documents are advisory they have proven to be extremely influential. For example, the OSHA definition of a high-rise building that was cited in the previous paragraphs comes directly from the NFPA guidelines.

1.2 Previous Simulation Tools for the Evacuation of Public Buildings
The guidelines and legislation that govern the design, construction and operation of large public buildings in the US and European create a requirement to consider the evacuation of those structures under a range of potential hazards. This creates a number of practical problems for those groups and individuals who must demonstrate compliance with these requirements. Arguably the simplest means of documenting this process is through 'live' evacuation exercises. Most people are familiar with the monthly fire evacuation drills that are a feature of everyday life in many countries. These drills serve a double purpose. They can be used to establish that minimum evacuation times continue to be met. This is important because fire exits can be inadvertently locked or obstructed. Fire drills can also be used to ensure that occupants are familiar with necessary evacuation procedures and routes. Hence, in many countries it is a requirement that these drills be performed on a regular basis even after it has been demonstrated that a building meets the initial regulatory requirements, described in the previous sections.

A number of limitations affect the utility of 'live' fire drills as a means of assessing occupant's ability to escape from a large public building.

1. **Sustained Costs.** For most buildings, there are minimal costs associated with standard fire evacuation exercises. Employee's work may be disrupted for up to half an hour every week. However, this need not be the case for larger structures that contain tens of thousands of occupants or for buildings that must support 'round the clock' operations. These include public health institutions, such as hospitals, but also commercial organizations, including trading companies and safety-critical applications in the process industries. In such situations, each fire drill may carry enormous potential costs unless elaborate procedures are developed to provide for partial evacuations under specific circumstances.
2. **Limited Accuracy.** It can be hard to use fire drills to simulate a range of different potential hazards. There is a tendency to use these procedures simply to 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. The small numbers of drills that do focus on such scenarios require significant additional investment. They often involve the close participation of rescue services that increases the 'accuracy' of a simulation but with significant additional costs.

3. **Short Shelf Life.** As mentioned above, the insights that can be obtained from fire drills are of limited benefits when the non-permanent structures of a building can change extremely rapidly. Changes in occupancy and in building use can also affect the results from 'live' simulations, especially where owners and managers have previous developed more complex scenarios with the previous occupants.
4. **Lack of Design Focus**. It is difficult to use the insights from fire evacuation drills to inform the design of large public buildings. Numerous studies can be obtained from similar structures. However, previous investigations into the impact of even minor changes in the layout of large structures have shown that these can have a considerable impact on evacuation behavior (Johnson, 2003). Ideally, it would be useful to have a system that designers might use on an iterative basis to assess the effects that changes might have as they revise the layout and structure of a potential building. At present, designers, owners and occupants must wait until a structure is completed and most available finance has been spent before they can determine whether it will be possible to evacuate a building within a particular time at a specified occupancy level.
5. **Danger.** There is a paradox in that the more realistic a simulation becomes then the greater the potential hazards there can be to the participants in an exercise. For example, Helen Muir's (1996) aviation evacuation simulations offer financial incentives to the first participants who evacuate from a plane. The use of such incentives increases the involvement of participants but can also place others at risk as individuals strive to obtain the potential reward. In consequence, extreme care must be combined with appropriate risk assessments before such trials can be attempted. There are additional ethical and legal complications when subjects may be drawn from the potential occupants of a building. Disabled participants and individuals with pre-existing medical conditions such as coronary heart disease can be placed at risk from these exercises.
6. **Poor Reliability.** In addition to the problems listed above, it can be difficult to obtain reliable results from evacuation drills. By this we mean that if the same exercise is performed on several different occasions within a limited period of time then it is possible to obtain very different results. Contextual factors can have a profound impact upon evacuation rates. For instance, if an individual begins a prompt evacuation then their peers will often follow shortly behind. However, if individuals delay their initial evacuation to complete particular tasks, such as closing down a computer workstation, then others in the group will often feel the need to do the same before beginning to egress from the building. Such dynamics of group interaction reduce the reliability of results obtained from specific evacuation drills.

Mathematical models provide a means to partially address many of these limitations. These techniques provide assurance that it is theoretically possible to evacuate buildings within a certain time given the dimensions of corridors, doors etc at particular occupancy levels. The International Building Code and associated documentation provides an outline for performing these calculations. However, the code also recognizes a number of pragmatic difficulties that affect these studies. For instance, many existing methods fail to capture critical differences in speed and movement that arise for populations of different ages, physiological capacity and psychological profiles. The calculations are often complex and cannot easily account for the range of hazards that must be considered under the different national legislative requirements. For example, they cannot easily be used to consider the impact that structural failures will have on evacuation rates as the damage to a building increases during an adverse event. These additional factors can be introduced as parameters into more complex models. However, they considerably increase the complexity of the simulations and help to determine the need for computational support.

Before introducing a number of these existing systems, it is important to stress that they are intended to support a wide range of differing users and tasks. For instance, evacuation simulations might be used during the development and design of building. They might also be used by regulatory agencies, certification bodies or the emergency services during the approval process that is required before a building can be opened for operation or approved for construction. Occupiers can also use these tools to examine the potential impact of changes in the architecture or operation of a structure. Most of the following tools are intended to support this diversity. Few assumptions are made about the specific objectives and tasks that are to be realized using the simulations. Subsequent sections of this paper will argue that recent tragedies illustrate the importance of providing additional support to a far smaller set of potential applications than has previously been the case.

There have been a number of previous attempts to develop reliable computer-based simulations of evacuation behavior from large public buildings. It is important to stress that in almost all cases, these applications are intended to augment and not replace the use of evacuation drills. In particular, these exercises are typically used to validate or 'fine tune' the predictions that can be derived using mathematical approximations to eventual occupant behavior and building layout. For instance, the UK Atomic Energy Authority (2002) has developed the Egress simulator.

This tool enables users to draw a simple floor plan of the building under investigation. Hexagonal cells are then used to segment the area. Different types of cell are used to distinguish between internal walls, between areas that are already occupied by people and movable obstacles such as tables and chairs. A number of attractor cells can be specified as potential destinations for individuals within the simulation. The speed that each individual can move at towards these destinations can be calibrated experimentally. The results of a series of experimental studies are already used within the system to account for a number of different factors in determining default walking velocities. These are largely based on the work of Predtechenskii and Milinskii, (1969) however, the developers acknowledge the uncertainty in this data especially when considering the likely impact of collisions in crowd formations. Route planning algorithms determine the shortest path to any of a number of attractors that each individual in the simulation can move towards. Weightings can be introduced to prioritize different objectives. The resulting tool has been validate against experience in evacuations from a range of different structures including aircraft and public buildings.

The Fire Research Service (FRS) adopts a slight more elaborate approach to evacuation simulation (BRE, 2004). They provide two different forms of egress simulators. The GridFlow tool exploits a simplified model of human behaviour. For instance, the initial delay before a person moves after an alarm is represented by a single time delay that can be varied between individuals in the simulation. After this delay, each simulated occupant then modes to either the nearest exit or another exit that is chose at random. Hence, this approach avoids some of the additional complexity considered by the multiple attraction cells and goal directed motion in the AEA Egress system. However, validation has shown that this simplistic approach can still provide reliable results for many different evacuation behaviours. In contrast to GridFlow, the CRISP tool simulated entire fire scenarios rather than simple evacuation behaviour. The additional complexity of this tool carries over into the modelling of individuals within a building. It is possible for CRISP users to associate behaviours or actions with each occupant. These are described in terms of actions, which may be abandoned, and substituted by new ones in response to changes in their environment. The model attempts to calculate the delay before movement in terms of their predefined tasks rather than using a simple empirical distribution derived from 'real world' drills. Individuals can also investigate, warn others etc. before starting their evacuation. There are two modes within the CRISP system. In evacuation mode, all individuals are simultaneously alerted to the need to evacuate unless a more complex simulation scenario is pre-programmed into the system. In risk assessment mode, the model also keeps track of individual expose to smoke until a 'fractional effective dose' reaches 100%. The model then marks these individuals as having been killed during this particular run of the simulation. Both approaches offer important visualisation tools, including the ability to feed data into 3D animations.

Government laboratories produced Egress, GridFlow and CRISP. In contrast, public and commercial funding of University research contributed to the EXODUS system (Owen, Galea and Lawrence, 1996). This tool has evolved in a number of different directions with special adaptations for use in aviation, maritime and building evacuations. As with the previous tools there is also a desktop virtual reality extension. The evacuation modelling can be informed through a link to the SMARTFIRE computational fluid dynamics fire simulation software. Key attributes of the behavioural modelling include the ability to dynamicall insert individuals into a model during a simulation. It is also possible to insert influence nodes where users can directly affect the route taken by individuals. Similarly, users can specify restrictions on the use of certain evacuation routes. The EXODUS tool provides important facilities in terms of signage annotations so the end-users can simulate the impact of providing additional warning and information notices. Dynamic behaviours can be altered so that individuals will automatically seek alternatives if they see that a particular exit is already congested.

As mentioned in the previous paragraphs it is important to validate the insights obtained by these simulations tools. The most effective approach is to compare specific predictions with the results from a range of evacuation drills. This is not always possible. In such circumstances, regulators often perform comparisons between the insights provided by a number of different tools in a form of mutual validation. For instance, the US Building and Fire Research Labs within the National Institute for Standards and Technology were asked by the FAA to assess the usefulness of the airEXODUS tool for aircraft evacuation. The FAA acknowledged that the program developers had verified the results from their simulation using historic accident data. NIST were specifically requested to analyse the sensitivity of the tool to potential variations in user inputs. The intention was to determine if the results might be affected in ways that could not easily be anticipated by the end-users who need not be aware of the effects of small changes in their inputs. NIST studied evacuation times for a passenger rail coach car with exits at both ends. The results showed that the times predicted by airEXODUS and two other emergency evacuation models were nearly identical. However, they concluded that 'any decision of the suitability of the model for regulatory purposes can only be judged by the FAA' (Bukowski, Peacock and Jones, 1998).

2. What We Knew Before September 11th

The previous section has introduced a range of existing simulation tools. The following paragraphs focus more narrowly on the design and implementation of a particular system. The Glasgow Evacuation Simulator (GES) is typical of these applications. It relies on Monte Carlo techniques that are favored by the systems described above. It also exploits a grid architecture to model room layouts, this is similar to the approach embedded within the EGRESS system. Subsequent sections go on to identify the weaknesses in our approach and the GES system that were exposed by a careful examination of evacuation behavior during the collapse of the World Trade Centre.

Figure 1: Interior and Exterior Images of the Boyd Orr Building

To illustrate the application of the GES tool, this section focuses on evacuation patterns from one particular structure. The Boyd Orr building illustrated in Figure 1 is eleven stories high and has a capacity of around three thousand people. We were motivated to use this case study partially because it typifies a heavily used, public access building. Our choice was further justified by the fact that the authors of this paper use this building every day. In response to the UK Fire Precautions Act, 1971, there is a requirement that the occupants of public buildings be able to reach a place of safety within two and a half minutes. If this cannot be demonstrated then the existing building risk assessment must be revised to determine whether the occupancy level should be reduced or whether redesign would be necessary for some or part of the structure (Mourareau and Thomas, 1985). Under the Fire Precautions Act (1971), university buildings like the Boyd Orr are not required to be fire certificated. The Fire Precautions (Workplace) Act (1997) requires that fire safety officials assess the risks themselves and take appropriate actions to provide fire fighting and detection equipment, training and appropriate means of escape.

One innovative feature of the GES system is that it was developed to exploit existing 3D models that can be derived from architects design tools. Unlike many of the systems mentioned above, there is no need to build new and specialised models to input into the evacuation simulator. This reduces costs and for the first time allows a tight integration between the simulator and the design of such structures. The owners of the Boyd Orr building were able to provide AutoCAD files for every structure that they operated. These included three digit room numbers that could be linked to a Space Management database. This records the area, function, department and occupancy of each room in the University. As we shall see, all of this information can be used to inform the behaviour of subsequent simulations. It is important to stress that the GES tool was developed as a collaborative project between software engineers and fire safety officers. Many existing systems have suffered from a lack of specialist computational support and so have provided limited support for the loading of pre-existing drawings. The Boyd Orr was represented ain AutoCAD by a separate .dwg file for each level of the building. This is a proprietary format and so GES first converts the files into .dxf. This provides a common format for sharing files between varieties of architects' software.

2.1 Human Factors Data and Domain Expertise in Evacuation Simulations

The underlying models of human behaviour that are used to drive each 'scenario' determine the successful simulation of evacuation behaviour. These models must consider many different issues. For example, Proulx and Sime (1991) and Geyer et al (1988) have shown that people do not begin to evacuate immediately after they have heard a fire alarm. Any simulation must, therefore, consider those factors that might influence this delay. These include the perceived threat posed by the alarm, the degree of preoccupation with the task to hand, familiarity with evacuation procedures from previous drills etc. Once an individual has begun to evacuate, they must determine which exit to use. This can be influenced by the layout of the building, for example by the position, number and size of exits in each room. Sime (1983, 1985) has shown that this decision is also influenced proximity of an exit, its familiarity, and the number of people who are already moving towards it.

Occupant Characteristics	Building Characteristics	Fire Characteristics
Profile Gender Age Ability Limitation	**Occupancy** Residential(low-rise, mid-rise, high-rise) Office Factory Hospital Hotel Cinema College and University Shopping Centre	**Visual Cues** Flame Smoke(colour, thickness) Deflection of wall, ceiling, floor
Knowledge and Experience Familiarity with the Building Past fire experience Fire Safety Training Other emergency training	**Architecture** Number of floors Floor area Location of exit Location of stairwells Complexity of space/way-finding Building Shape Visual access	**Olfactory cues** Smell of burning Acrid smell
Condition at the Time of Event Alone vs. with others Active vs. passive Alert Under Drug/Alcohol/Medication	**Activities in the Building** Working Sleeping Eating Shopping Watching a play, a film, etc.	**Other cues** Heat
Personality Influenced by others Leadership Negative toward authority Anxious	**Fire Safety Features** Fire alarm signal(type, audibility, location, number of false alarms) Voice communication System Fire safety plan Trained staff Refuge area	
Role Visitor Employee Owner		

Table 1: Factors affecting human behaviour in fire (Based on Proulx, 2001)

Table 1 summarises those factors that affect human behaviour in the evacuation of a building. Even this list is incomplete (Proulx, 2001). As we shall see, it only provides a high level summary of the group or team factors that have a profound influence on the pattern of any evacuation. The key point here is that it would be difficult to simulate anything but a handful of these different factors. The main barriers are not computational. They are conceptual. In other words, it is difficult to know how to quantify the impact that a 'negative (attitude) towards authority' might have on an individual's behaviour. Further human factors research and empirical evaluations are required before such factors can be explicitly considered within a computational model. In consequence, most simulation tools such as GES focus on the impact of a narrower subset of these factors that influence human behaviour during the evacuation of public buildings.

It is important to consider those "social factors..., [which] influence... decisions about flight, including when and toward which exit to begin moving, whether to move slowly or more rapidly, and whether to follow civility norms that govern taking turns or to set aside those norms and compete for early access to an exit."(Johnson and Feinberg, 1997). For example, studies into human behaviour under stress have shown that the composition and nature of the groups involved will have a significant impact upon individual actions. Colleagues evacuating from a shared office will react very differently from family groups trying to escape in the company of strangers. For instance, the Federal Emergency Management Agencies have argued that the stronger the bond between group members, the more likely it is that one member will put their own life at risk to protect another group member. An initial analysis of the evacuation from the World Trade Centre found that "some mobility-impaired occupants were carried down many flights of stairs by other occupants. There were also reports of people frequently stepping aside and temporarily stopping their evacuation to let burned and badly injured occupants pass by" (Baker, Barnett, Marrion, Milke and Nelson, 2002).

Cognitive factors interact with the social characteristics mentioned above. It is widely believed that panic is the most common response to an emergency situation, but studies by social scientists argue that panic behaviour in a fire is rare (Proulx, 2001). Cornwell (2003) has argued that behaviour, which in hindsight seems to be inexplicable, is often the result of considered decision-making based on limited information under stressful conditions. He also argues that these decisions are seldom made in isolation and that we "look to others to help interpret ambiguous cues… [they] confirm these potentially threatening cues with other people before taking action". Tong and Carter (1985) have confirmed many of these observations but go on to look at a range of other group-based behaviours. As crowds grow, and groups converge towards busy areas, two more complications arise. A phenomenon known as "Flocking" occurs, attracting more people to the already crowded area. The crowding can act as a catalyst to flight and can make human behaviour even more difficult to predict (Goldenstein et al, 2001, Batty, Desyllas and Duxbury, 2003).

Personality traits such as assertiveness have been shown to influence decision-making and behaviour under stress. It is for this reason that organisations such as Transport Canada have conducted human factors studies into the impact of these characteristics on evacuation times. They have development more complex models, including the Canada Personality Profile 2 (TCPP2) that distinguishes between 13 characteristics that might influence behavior during aircraft evacuations. Projections based on the results of their experimental studies have suggested that for a passenger load of 150 there would be approximately 28 passengers who might be identified as 'highly assertive' or 'goal directed'. These individuals would have a total evacuation time of 3.08 minutes compared to 3.58 minutes for the 26 passengers in the lower assertiveness and goal-oriented groups (Latman, 2004).

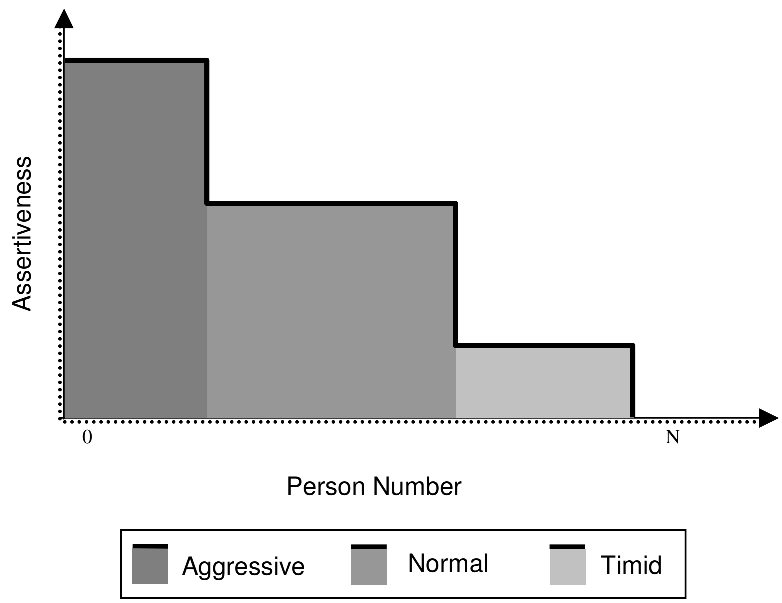

Figure 2: Assertiveness Distributions in the GES Tool

Figure 2 provides a simplified overview of the manner in which personality traits such as assertiveness are handled within the GES tool. The user of the system specifies a distribution over the total population. The proportion in each category will differ depending on the building being considered. In our case, the Boyd Orr is populated by large groups of young students and hence the distribution will be skewed towards more aggressive individuals and groups than might otherwise be the case. Such assumptions can, of course, be validated using techniques such as those used to assess the TCPP2 scheme cited above. It is also possible to use Monte Carlo techniques so that the precise composition of a population will change between different runs of the simulation.

Not only must the simulator consider social and cognitive characteristics, it must also account for the different physiologies of an occupant population. Age and physical limitations determine the speeds at which people will travel through the building during an evacuation. However, these characteristics cannot be viewed in isolation; a panicking individual is more likely to travel at greater speed than a person who is calm. In the GES tool, each person is assigned an initial speed. The medium speed is initially set to be 1.4 ms^{-1} based on studies by Older (1964) and more recent work by Thompson and Marchant (1995). The low and high-speed groups are set to have a pace that is 80 and 120 percent of this respectively. These values can be set by the user to calibrate their system. Work is continuing to vary individual speed to take account of changing conditions during an evacuation. However, these initial values are based on empirical observations that take into account individual pace under different crowd densities. This preferred walking speed of evacuation is sustained unless they cannot make any further progress because one or more people in front of them block their path. The preferred evacuation speed of the individuals within the simulation has important consequences for the quality of interaction with the system. As mentioned, the medium group move at 1.4 ms^{-1}. GES uses a floor grid system based on cells that are 0.4m by 0.4m; this represents a considerable simplification based on the average size of an adult but is configurable by the end user. Under these circumstances, a medium paced individual should take a step every [0.4m / 1.4ms^{-1} = 0.286 seconds]. Hence the simulator clock cycles at one update every 143ms allowing the real-time simulation of people at up to twice the average speed. Again, however, the clock period can be configured by the end-user.

2.2 Using Accident Reports to Inform the Simulation of Evacuations

Sime (1987) notes that "the first difficulty with any research on human behaviours in fires is that experiments involving real people and real fires are unethical.". This bluntly sums up the dilemma facing work in this area. The experimental results that validate many of the human factors observations are often derived from situations that are very different from those that hold during a 'real world' emergency evacuation. In consequence, it is important that we learn as much as we can from those accidents and incident that do take place. This is not a novel observation. Many of the safety regulations and procedures, cited in previous paragraphs, are a direct result of previous accidents. For example, a 1942 fire in a Boston nightclub called The Cocoanut Grove led to revised requirements for door design. The fire killed 492 people but it is estimated that the casualties would have been much lower if the building had doors that swung outward. Instead, the occupants were forced to push their way through a revolving door that quickly became jammed from a mass of bodies. The UK Fire Precautions Act 1971 now demands that swing doors must be provided next to any revolving doors.

The application of accident information to inform the subsequent simulation of evacuation behaviour is not as simple as it might seem. The analysis of previous incidents serves to underline the diversity of human responses in the face of adverse conditions. For example, Johnson and Feinberg's (1997) study of the Beverly Hills Supper Club fire showed that "many interviewees reported that they or others stepped aside to let others move ahead". This orderly behaviour can be contrasted with the response to the San Paula fire where most deaths occurred because people jumped from windows, even though the fire was under control and helicopter loudspeakers were conveying this information to them.

Many simulators assume that building occupants will behave rationally. For instance, they are all assumed to move away from the source of a fire and towards an exit. However, it can be difficult to sustain these assumptions in the face of evidence from previous evacuations. For instance, CCTV footage revealed that at least one individual continued to walk against the flow of people into the Kings Cross fire. Another started to use a photo booth even though the platform had already filled with smoke. Similarly, 9 of the 10 deaths in the 1979 Woolworth's fire in Manchester occurred in the canteen. Eyewitnesses observed that many were reluctant to leave without finishing their meal or paying for what they had consumed. These behaviours can be explained in terms of 'task fixation'. Individuals are so preoccupied with other tasks that overlook the need to evacuate an area. . This task fixation is also apparent in a study of the evacuation from the World Trade Centre after the 1993 explosion. The interval between the moment when an occupant was aware of a fire or explosion and the time at which they began to leave the building ranged from 1 second to more than 4 hours. The estimated mean time to departure was 11.3 minutes with a median time of 5 minutes (Fahy and Proulx, 1997). The same study reported that during a previous fire drill under 10% of the occupants began to evacuate. Similar observations were made about the Beverly Hills fire. Approximately 80% of those who reported hearing the fire alarms returned to other routine activities. Unfortunately, it is very difficult to simulate the impact of this fixation because little is know about the precursors that lead to such behaviour.

Observations from a number of other accidents also call into question the assumption of rational behaviour. For example, the Birmingham City tragedy in 1985 demonstrated that many people are reluctant to break established norms even in extreme situations. Fans refused to step over the 3-foot barrier onto the pitch despite people being burned behind them. Conversely, other accidents have shown that individuals will ignore even the most obvious of signs and emergency exits. Proulx (2001) describes how the occupants of Munich Airport ignored fire exit signs and thereby caused a number of crush fatalities. Similarly, two people were killed in the evacuation of the Lowenbrauskeller in Munich (1973). The occupants went straight to the main exit walking past signs for at least eight other emergency exits. There was no fire in the building, but the fatalities occurred when a mass of people pushed to use this single main exit. The 2003 fire in Rhode Island's Station nightclub illustrates how such behaviours combine with other problems in the layout and operation of public buildings. After pyrotechnic devices inadvertently ignited foam-based sound proofing material, the 300 customers had four possible exit routes. One was via the kitchen and was only known to employees and regular customers. An inner door accessed the path to the exit next to the stage and few people used it preferring to retrace their steps back through the main exit. Those who reached this area had to force their way through a bottleneck created by a ticket booth leading to numerous crush injuries (Kurkjian, Ebbert, and Farragher, 2003). This reluctance to follow emergency signage and instead retrace the path back to an initial entrance is a common feature in many accidents. It does not represent 'irrational' behaviour given that many fire exits can be blocked or alarmed. Arguably, individuals exhibit a preference to follow what they believe to be a 'sure route' to safety rather than take a chance on following fire exit signs in a direction that they are not familiar with.

The GES tool embodies a number of features that are based on these observations of previous evacuations. For instance, the system has two evacuation modes. Under 'model' conditions, each individual in the simulation associates a high priority with the nearest available exit. This reflects an assumption that is often made when building operators perform a risk assessment. As we have seen, however, from the Lowenbraukeller and Rhode Island fires there is often a strong preference for occupants to retrace their steps and leave the same way that they came in. They will do this even though there are well-marked and available emergency exits that offer more direct route to safety. There is therefore another 'normal' mode in which a proportion of the occupants associate a higher priority with the route that leads back to the main entrance of the building. By default, 80% of the occupants are assigned this priority. This proportion can be changed to reflect the impact of evacuation drills and other forms of exercise to familiarise occupants with the available exits. Again, this facility to change the proportion of occupants leaving via the main entrance can be justified by previous accidents. During the Summerland fire in the Isle of Man, the greatest number of injuries was clustered around the main entrance. 51% of the occupants used this as their exit route. Of these 37 were guests and 1 was a member of staff. In contrast, 49% of the occupants used the emergency exit but 23 were guests and 14 were members of staff. This higher proportion of staff has been used to argue that additional drills will help people to familiarise themselves with emergency exits and therefore prepare them to use them during any subsequent evacuation.

Analysis of previous accidents, such as the Rhode Island fire, has shown how difficult it can be to predict which exit routes will be open and which will be closed. It is, therefore, possible for users of the GES tool to dynamically open and close each of the potential exits as the simulation progresses. Individuals in the simulation must then begin to search for alternate routes. Figure 3 illustrates the user interface to the GES tool. As can be seen, the 3D view derived directly from the architect's AutoCAD files is combined with an overhead plan view. At the end of each simulated evacuation an information panel provides statistical data on the speed of any evacuation and breaks down mean times for individuals in each of a number of different groups. For instance, the time taken by assertive individuals can be contrasted with that taken by more timid colleagues.

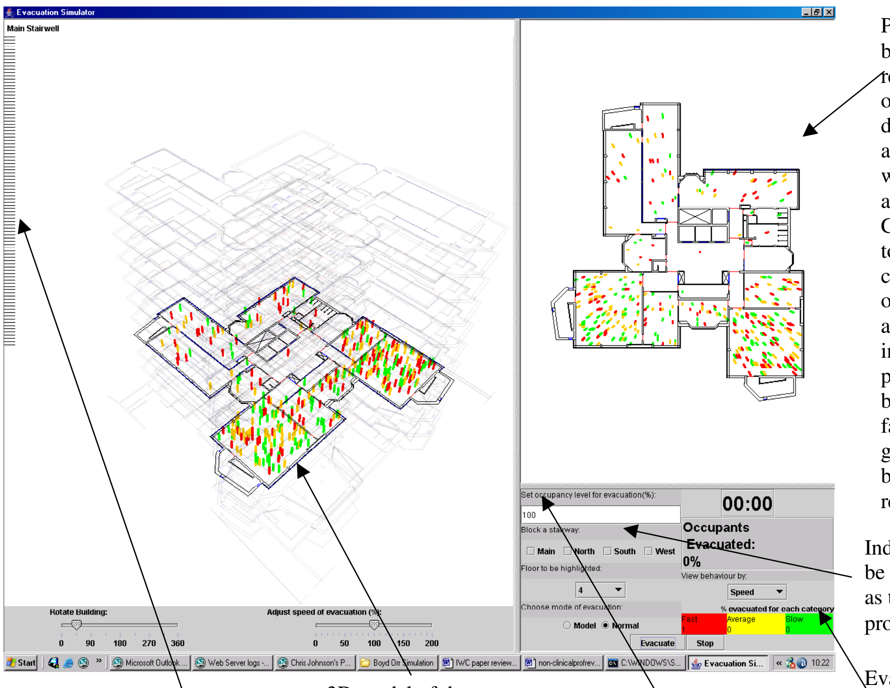

Figure 3: Overview of the GES User Interface

A key issue in the development and application of any evacuation simulation is whether or not it can be used to yield any new information about a building and its occupants. Figure 3 illustrates the user interface to the GES tool. As mentioned in previous paragraphs, this has been applied to model a range of evacuation scenarios for the Boyd Orr building. These scenarios exploit the simulators facility to block or unblock different exit routes during the simulation. They were also used to assess the evacuation times under the 'model' and 'normal' modes mentioned in previous paragraphs. Recall that the 'model' mode used accident information to increase the attractiveness of the main entrance route for up to 80% of the individuals in the simulation. The scenarios used to test the Boyd Orr evacuation plan also examined behaviours for a variety of different occupancy levels ranging from 10% to 200% of the current maximum specified usage. Table 2 illustrates the format of results after approximately 20 runs in each condition. The columns present the mean evacuation time in seconds for different occupancy levels, in this case ranging from 110% to 200% of the permitted maximum. Each row represents a different scenario in which different exit route are closed. Rows also distinguish between whether or not the occupants attempted to find the nearest exit (model conditions) or tended to seek the entrance (normal). The figures under the main rows represent the standard deviations associated with each mean value.

Stair Closed	Evac. Mode	% Occupancy									
		110%	120%	130%	140%	150%	160%	170%	180%	190%	200%
None	*Model*	0:38	0:39	0:41	0:44	0:47	0:50	0:53	0:55	0:59	1:02
		0:03	0:01	0:01	0:01	0:01	0:02	0:02	0:02	0:01	0:02
	Normal	0:48	0:50	0:51	0:53	0:53	0:55	0:56	0:59	0:59	1:02
		0:02	0:01	0:01	0:01	0:02	0:02	0:02	0:02	0:02	0:01
Main	*Model*	0:35	0:38	0:40	0:44	0:47	0:50	0:53	0:56	0:59	1:02
		0:02	0:01	0:02	0:01	0:02	0:01	0:02	0:02	0:02	0:02
	Normal	0:35	0:39	0:42	0:43	0:47	0:50	0:54	0:56	0:59	1:01
		0:01	0:02	0:01	0:02	0:02	0:01	0:02	0:01	0:02	0:02
North	*Model*	0:47	0:47	0:47	0:48	0:49	0:51	0:52	0:55	0:58	1:01
		0:02	0:02	0:01	0:02	0:01	0:01	0:02	0:02	0:02	0:02
	Normal	1:00	1:04	1:06	1:08	1:12	1:14	1:16	1:19	1:22	1:25
		0:02	0:01	0:02	0:02	0:02	0:02	0:02	0:02	0:02	0:02
South	*Model*	0:55	1:00	1:02	1:06	1:08	1:13	1:16	1:20	1:22	1:27
		0:01	0:01	0:01	0:01	0:01	0:02	0:01	0:02	0:02	0:02
	Normal	1:01	1:05	1:08	1:13	1:16	1:20	1:23	1:28	1:31	1:35
		0:01	0:01	0:01	0:02	0:02	0:02	0:01	0:02	0:03	0:02
West	*Model*	1:06	1:10	1:14	1:17	1:19	1:22	1:27	1:29	1:34	1:36
		0:02	0:02	0:02	0:02	0:02	0:01	0:01	0:02	0:02	0:03
	Normal	1:06	1:10	1:13	1:17	1:20	1:23	1:26	1:30	1:34	1:36
		0:02	0:02	0:02	0:01	0:02	0:01	0:01	0:02	0:02	0:03

Table 2: Mean Evacuation Times for a Subset of the Boyd Orr Simulations

Further analysis is required to interpret the different mean evacuation speeds illustrated for different conditions in Table 2. Brevity prevents a full exposition of these results; this is beyond the scope of what is already a long paper. Instead, the following paragraphs provide a brief illustration of one of the insights that was obtained from out development of the Boyd Orr simulation using the GES tool.

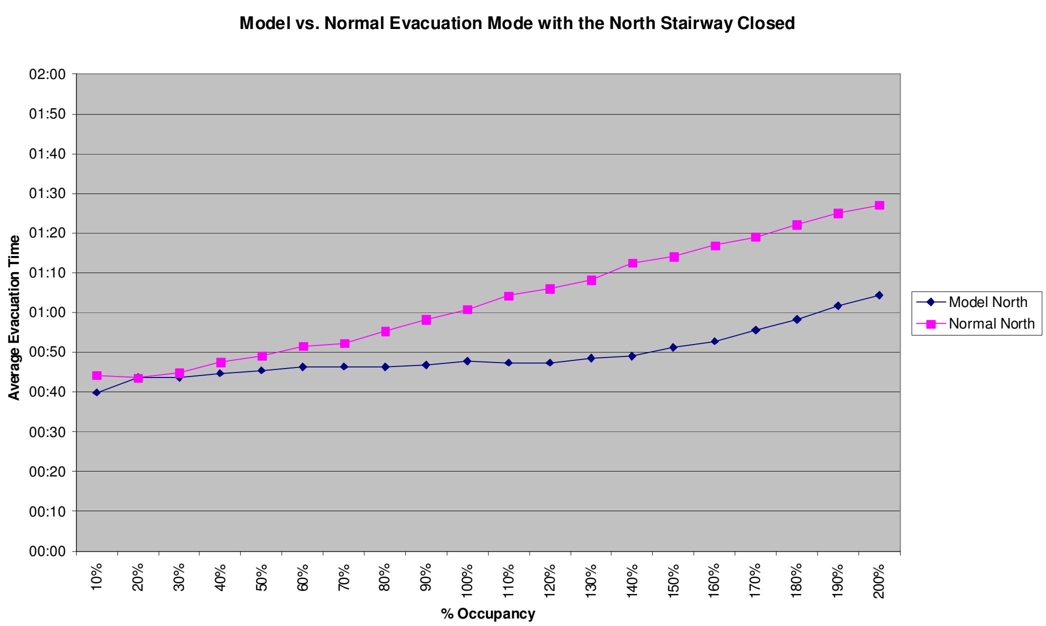

Figure 4: Graphing Mean Evacuation Times when the North Exit Route is Closed

Figure 4 graphs some of the mean values derived from the previous table. In particular, it compares the times to evacuate the building when the North stairwell is closed. The top line shows mean evacuation times under different occupancy levels when occupants follow the 'normal' pattern. In this scenario a higher value is associated with the main route into the building. The lower line provides the same information for 'model' evacuations in which each occupant attempts to exit by the nearest available route. This simulates the intended effect of training, signage and evacuation drills but arguably does not reflect the insights obtained from previous accident investigations. The results show that initially, when the North stairway is closed, the evacuation times for Normal and Model evacuation modes are similar. As the occupancy level increases, the evacuation time for the Normal mode increases at a much faster rate. The evacuation time for the Model evacuation mode increases very slowly until approximately 150% occupancy is reached. This difference between the model and the normal mean evacuation times is much greater than for the other emergency exits and illustrates the importance of the North route when compared to the South and West. Hence, considerable efforts should be made to ensure that this route is preserved under a range of potential hazards. Alternatively, the simulation results suggest that additional design efforts could be focused to increase the potential gains to be obtained from easing access to the other emergency routes. In all cases, the simulations highlighted the potential benefits that might be obtained if users were persuaded to use all available exits and not simply retrace the main entrance route.

Evacuation simulation tools such as the GES system have a variety of applications. The previous paragraphs have described the most common use of these systems to predict potential evacuation times. They can also play an important role in educating potential occupants of the need to follow evacuation procedures. This can be illustrated by a summative evaluation of the Boyd Orr simulation. The method used was to interview 40 people who regularly used the building to ask them about the route they would take in the event of a fire alarm. They were then shown the model and the normal evacuation scenarios embedded with the GES tool. The order of presentation for each of these modes was counterbalanced. The parameters of each evaluation were exactly the same for each run apart from the mode of evacuation. There were no blocked exits; the tool was set at 100% of the maximum occupancy level. The 3D model was viewed at the same angle and the simulation speed was set to a constant 100%, in other words to 'pseudo real-time'. The results showed that all of the people interviewed had received training in evacuation procedures; this confirms that the buildings owners have successfully implemented an important objective in their fire policy. Approximately 60% of the participants stated that they had been involved in an evacuation drill in the Boyd Orr. Just over 50% (21 out of 40) stated that they would use the nearest available fire exit. The remainder stated that they would use the route by which they had entered the building. This shows a slightly higher proportion than had been anticipated by the domain experts. These results indicate that the fire drills and previous training had achieved their intended effect of encouraging more people to use the fire exits. 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. However, the Boyd Orr 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 behaviour during an evacuation. Previous sections have noted the significant impact of social and cognitive factors such as flocking. These behaviours may be more powerful than the insights provided by short exposure to evacuation simulations. These issues remain a focus for current research.

Previous sections have described how accidents and incidents have informed the development of evacuation simulators. For instance, the Lowenbraukeller fire and the Summerland fire led to the introduction of normal and model evacuation modes in the GES. The insights obtained from the Station nightclub fire in Rhode Island reinforced the need to block or unblock exits during a simulation scenario. The Manchester Airport fire together with a body of related human factors work led to the development of different personality traits in many similar evacuation tools. The remainder of this paper builds on this previous discussion to identify the lessons that can be learned from the evacuation of the World Trade Centre. The following sections are based narrowly on the findings of the National Commission on Terrorist Attacks Upon the United States, known as the '9/11 Commission' (2004). Their public report was released on the 22nd July 2004. We might have conducted this analysis in the intervening years after the attack. Other sources were available, including a number of autobiographical narratives. However, we decided to postpone our analysis until the National Commission had completed its work by gathering together and validating the insights provided from these earlier accounts.

3. What We Learned From September 11th

The events of September 11th 2001 have had a profound impact on everyone involved in the design and operation of large public buildings. This impact can be explained in a number of different ways. The media coverage and the scale of the terrorist actions were arguably unprecedented. Although some had predicted such potential hazards, few thought that there was an immediate threat. It is, therefore, important that we learn as much as possible from the attack on the twin towers. There is, however, a danger that we may focus too narrowly on the atypical events associated with this tragedy. We may create simulations and develop new evacuation policies in the aftermath of this incident that are inappropriate for the majority of future accidents. It is for this reason that the following paragraphs identify generic lessons from the events at the World Trade Centre. The intention is not to develop specific simulations of the evacuation behaviour that took place on the morning of September 11th.

It is also important to stress that the evacuation from the World Trade Centre 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 changed that were made both to the emergency exits and to fire evacuation training programs following the bombing of the World Trade Centre in 1993; "Important modifications to building egress made following the 1993 WTC bombing included the placement of photo-luminescent paint on the egress path to assist in way finding… and provision of emergency lighting for the stairways" (Baker et al, 2002).

3.1 Model The Changing Impact of Different 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 three of the building's stairwells became blocked from the 92nd floor up. The 9/11 enquiry argued that "Everything that would happen to the (occupants) during the next few minutes would turn on their circumstances and their preparedness, assisted by building personnel on-site". One of the most striking features of the immediate evacuation behavior was the role played by policies and 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 to reach them. This advice was given to callers in the North Tower who were located below and above the impact area. This policy reflects the risks associated with any fire drill from a high-rise building. Many of the injuries associated with the 1993 bombing were caused by the evacuation rather than the initial blast. 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.

This decision to revoke a previous policy is important. Very few simulation scenarios have considered the impact of such changes on evacuation behavior. For example, the GES tool assumes that all occupants will attempt to evacuate the building if possible. A scenario that is similar to events in the North Tower can be created, for example by imposing a delay before the occupants begin their evacuation. Unfortunately, this does not capture the complexity of the unfolding situation. Some occupants could not be informed of the change in procedure 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 even though this contravened the policy mentioned above. The security officers of several firms in the South Tower advised all of their employees to evacuate. In contrast, the public-address system in the South Tower was used to state that the incident had occurred in the other building. Tenants were told that their building was safe and that they should remain in their offices. Many civilians reversed their evacuation. Security officials in the ground floor lobby and in the upper sky lobby gave similar advice. 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 both the North and the South Towers illustrates the importance of considering not just the uniform evacuation from large public buildings. It also emphasizes the use of scenarios that replicate a piecemeal evacuation where some occupants have been told to evacuate or decide to leave on their own initiative while others decide to remain where they are. The actions of the security officers also illustrate the way in which conflicting advice may affect evacuation behavior. These issues are beginning to be introduced in the goal-based behaviors associated with building occupants in some simulators (Johnson, 2003). However, this is far from common.

3.2 Model Alternate Communications

The previous section has argued that simulators must consider scenarios in which revisions may have to be made to existing evacuation policies. In such circumstances, it is necessary to consider the different communication channels that might be used to convey this revised information to the building's occupants. Again, the events of September 11th illustrate some of the complexity involved in attempting to incorporate these issues into a simulation. For instance, it is unclear when the first full building evacuation order was attempted over the North Tower's public-address system. The deputy fire safety director in the lobby was immediately aware that a major incident had occurred. Following the established protocol mentioned above, he initially gave announcements to those floors that had generated computerized alarms. He advised these tenants to descend at least two floors below the smoke or fire and to wait there for further instructions. However, it was a further ten minutes before he announced a general evacuation. Confusion arose because the Port Authority fire safety director advised the first FDNY chiefs to arrive in the lobby that the full building evacuation announcement had been made within one minute of the building being hit. Irrespective of when the announcement was made, damage to building systems caused by the impact of the plane meant that public-address announcements were not heard in many locations. Similarly, many occupants could not use the emergency intercom phones, which they had been trained to use in fire drills.

In consequence, many occupants dialed the US emergency number '911'. However, the volume of calls that it received quickly overwhelmed this system. The 911 operators and FDNY dispatchers had no information about either the location or the magnitude of the impact zone. They could, therefore, not tell callers in the North Tower whether they were above or below the fire. Similarly, the operators had not been informed 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 magnitude of the damage caused by the first plane's impact. Again, this information was not conveyed to 911 operators or to FDNY dispatchers. For instance, one group of occupants was trapped on the 83rd floor. They 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. The 911 investigations concluded that these callers are unlikely to have survived.

In the meantime, however, operators had realized the seriousness of the developing situation and had themselves begun to depart from the agreed protocols. Several operators told callers to evacuate if they could. Most civilians in the North Tower began evacuating without waiting for instructions over the intercom system. However, some continued to wait for help as recommended by the 911 operators. Others simply continued to work or collected personal items, as has been observed in several of the other evacuations described in previous sections. This advice of the 911 operators and FDNY dispatchers contrasts with that provided by other organizations. For instance, the 911 investigations found that the Port Authority police desk at Newark Airport told a third party that a group of Port Authority civilian employees on the 64th floor should evacuate. This third party then attempted to pass the message on to the group on the 64th floor.

In the South Tower, many occupants continued to call for advice after the second plane hit. Several groups were trapped on the 88th and 89th floor. The investigation concluded that the 911 system "remained plagued by the operators' lack of awareness" and that "just as in the North Tower, callers from below and above the impact zone were advised to remain where they were and wait for help". 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". This had considerable consequences at a time when stairwell A may still have been passable in the South Tower.

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, by simulating the flocking behavior that occurs when individuals find that an exit is blocked and then pass this information to other groups that were heading in the same direction in the simulation. However, very few simulators or simulation scenarios consider anything like the degree of complexity or confusion that arose during the evacuation of the World Trade Centre. The impact of external communication might be introduced in future tools. For example, the 911 and FDNY operators played an important role in providing information to the occupants of the North and South Towers. In other incidents, rescue services have used signals from cellular telephones to track the position of individuals who have become trapped within damaged buildings (Johnson, 2003). This could be simulated by revising the objectives of some individuals within a simulation to reflect the provision of information from external sources such as 911 operators. Similarly, it is relatively simple to extend simulation tools such as the GES to model the provision of information to some groups in some areas of an evacuation and not to others. This might reflect the partial breakdown in the public address systems in the World Trade Centre. In both cases, however, the 911 investigation has shown that the influence of external sources might both delay as well as support a prompt evacuation from endangered structures.

3.3 Model a Wider Range of Group Behaviors

Most simulation tools explicitly consider group behaviors when they model evacuation scenarios. Previous sections have described how this can range from complex motivational models through to more simple flocking behaviors. The events at the World Trade Centre provided a number of important lessons for the ways in which these simulations might be conducted in the future. At the most basic level, the tragedy forced reconsideration of 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. Occupants were also trapped in elevators. These groups would have been difficult, if not impossible, to evacuate. However, there were other groups below the impact zone who were either trapped or were left waiting for guidance before beginning their evacuation. Most of these groups were distributed on floors in the 70s and 80s but there were further clusters on the 47th and 22nd floors. The task of evacuating these groups was complicated because of the damage to the building. Many doors dissuaded groups from continuing an evacuation because they appeared to be locked but were actually jammed by debris or distortion from the impact of the plane. The difficulty of the evacuation was also exacerbated not so much by panic but by confusion caused by the increasingly crowded stairwell; "the evacuation was relatively calm and orderly".

To summarize, the events of September 11^{th} illustrate the way in which building occupants will form groups of many different sizes during an evacuation. These groups seem to have been based around teams of co-workers but were also the result of chance groupings of individuals caught in the same location. Many of these groups appear to have acted collectively, either deciding to evacuate together or to wait for further assistance. The progress of groups that did evacuate was halted by heat and smoke but also by physical barriers, such as debris, and by the distortion of internal structures. All of these observations have important consequences for the future development of evacuation scenarios. None are well supported by the existing generation of tools, including the GES. Similarly, few tools model the interaction between individual and group behaviors that the subsequent enquiry found to have been an important factor in the successful evacuation of the World Trade Centre. For example, one occupant of the South Tower, close to the impact site on the 78^{th} 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.

3.4 Model the Ingress and Egress of Emergency Services as well as Occupants

Previous generations of evacuation simulation systems have focused almost exclusively on the egress of occupants from a building. The evacuation of the World trade Centre illustrated some important weaknesses in the egress models already used by the GES tool. For example, the existing algorithms described in previous pages assume that the last evacuees can attain the same walking pace as the first providing that their route is clear. However, the 9/11 enquiry noted that by 09.55 in the North Tower, only a few civilians were descending above the 25th floor in stairwell B. These were "injured, handicapped, elderly, or severely overweight civilians, in some cases being assisted by other civilians". Similar patterns were observed in other areas of the evacuation. Existing evacuation models also often neglect the triage and distribution tasks performed by the emergency services at key bottlenecks in complex structures. All civilians who reached the lobby of the North Tower were directed by NYPD and Port Authority Police Department officers into the concourse and then out of the complex to the north and east to avoid falling debris and victims.

The events at the World trade Centre also reinforced a more general 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 11^{th} 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. Other chiefs continued operations. 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 initiative their evacuation. A ladder company took a working elevator to the 40th floor and then began to climb up stairwell B. Another ladder began to rescue civilians trapped in an elevator between the first and second floors. Another FDNY ladder company encountered numerous seriously injured civilians on the 70th floor. With the assistance of a security guard a group of civilians trapped in an elevator on the 78th-floor sky lobby were found by an FDNY company.

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 Mayors 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 FDN command structure as they entered the North Tower. Over the thirty minutes or so, three more ESU teams arrived on the scene. 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 via the stairs because of the number of occupants who were descending the stairwells.

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 World trade Centre 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 be difficult to anticipate and model the valuable work that these small teams did in providing information back to the coordinators of the evacuation. 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. This illustrates a key point; the events at the World Trade Centre encourage us not simply to model the passage of people within a damaged building but also to consider the transfer of information and the decision-making processes that arguably had the greatest impact on the overall course of the evacuations.

3.5 Integrate Simulations into Broader Studies of Decision Making

The need to model decision-making affects many different aspects of evacuation simulation. Informal risk assessments and decision making under uncertainty also affected individual building occupants. As we have seen, a wide variety of factors affected the occupants' decisions about when to begin evacuating. Some people left their floors as soon as they detected the initial impact. Others waited to gather further instructions, for example from safety officers or via the 911 operators. . The previous section has sketched some of the issues concerned with the coordination of emergency units entering into a damaged building. From the earliest moment of the rescue efforts, the course of the evacuation was dependent upon a series of key decisions taken by emergency personnel. A battalion chief and two ladder and two engine companies arrived at the North Tower at approximately 08:52. This battalion chief was initially in charge of the FDNY response as the senior incident commander on the spot. 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".

Previous sections have described how the overall coordination failed to prevent individual units, such as the NYPD ESUs, from acting on their own initiative. Communications failures also prevented senior personnel from grasping some of the details of the damage to different floors or from gaining a clear picture of the location of many of the occupants. There were also problems in gaining detailed information about the state of the building systems. None of this is surprising given the nature of the incident. However, very few of these issues ever seem to be considered in the existing generation of evacuation simulations. One way of addressing these issues would be to extend the scope and role of emergency scenarios. 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. In this view, tools such as the GES would be used by emergency services and building managers in role play exercises where they are asked to simulate the decision making under uncertainty that characterized the immediate aftermath of the attacks on each of the towers.

The lack of information clearly affected decision-making throughout the events at the World Trade Centre. Previous simulations and fire safety studies could not grasp some of the problems that affected occupants and emergency personnel as the morning unfolded. For example, firefighters on the upper floors of the North Tower heard a violent roar when the South Tower collapsed. Some were knocked from their feet and saw debris coming up the stairs. Most observed that power was lost and the emergency lights came on. However, those occupants who were not standing near south-facing windows had no way of knowing that the South Tower had collapsed. The 9/11 investigation describes how some thought that a bomb had exploded or that there had only been a partial collapse of the North Tower. The occupants of the North Tower lobby did not know that the South Tower had collapsed. Further examples can be provided by the actions of the senior staff coordinating the FDNY response to the tragedy. At approximately 10:25, they radioed for two ladder companies to go to the Marriott Hotel that ran between the North and South Towers. The senior staff was aware that both FDNY personnel and civilians were trapped in this building. However, many senior officers remained unaware that the South Tower had collapsed until 30 minutes or more after the event. Even those individuals who had a better overview of events could still make assumptions that seem unwarranted, with the benefit of hindsight; 2 eyewitnesses stated that "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".

The post hoc analysis of this incident reveals how lack of information, based on a local rather than global view of events, had a significant impact on the course of an evacuation. This is not a new observation; most simulations embody local models of the information that is available to individual occupants. The events of September 11th show the limited information that is available when occupants make key evacuation decisions. They also provide extreme examples of the decision making under uncertainty by key evacuation personnel. The impact of these decisions on the course of an evacuation is seldom embedded within current simulators that focus on the limited information available to building occupants.

3.6 Model the Worst Plausible Circumstances in Simulation Scenarios

Previous sections have described how most evacuation simulators have an implicit model of the types of scenarios that they can be used to emulate. Although it is possible to block the fire exits on different levels of the GES simulation of the Boyd Orr, the existing tools do not provide means of simulating significant damage within a particular floor. Arguably the most important lesson from the events at the World Trade Centre for simulation tools was to force developed to reconsider these simplifying assumptions. They help developers by reducing the burdens of system design and implementation. However, the events of September 11th showed that they may also radically over-simplify the problems of evacuating large scale public buildings. Although there is so much about this incident that is atypical and hopefully will not be repeated. This incident did help to redefine what has previously been referred to as 'the plausible worst case scenario' (Johnson, 2003). This concept guides simulation because on the one had it is important not to waste resources on scenarios that are implausible but on the other it is equally important to identify the complex, adverse events that might frustrate future evacuations for large-scale public buildings. Prior to September 11th, it was considered plausible that a building complex might suffer a single aircraft strike but 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".

Few anticipated that events would unfold in the way that they did even after the planes had struck. For example, as early as 09:37 an occupant on the 106th floor of the South Tower reported to a 911 operator that the "90-something floor" was collapsing. The 911 operator reported this information to an NYPD dispatcher. However, the details of the message became increasingly confused as it was passed from person to person. The NYPD officers at the World Trade Centre complex were informed that "the 106th floor is crumbling" fifteen minutes after the original call was made. The South Tower collapsed at 09:58:59. This lasted approximately ten seconds, killing all occupants and emergency personnel inside. Debris also claimed the lives of occupants and emergency personnel in the concourse, in the neighboring Marriott Hotel and in adjacent streets. Forensic investigations are still continuing to identify the reasons why the collapse occurred so soon after the impact. It is clear, however, that very few simulators have ever been used to consider what might happen in similar circumstances. It is equally clear that identifying the worst possible moment for building collapse will be a significant focus for further work in this area, especially as we move from the previous focus on occupant egress to consider the ingress of first responders.

The events at the World Trade Centre 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 either via the roof or eventually after the fire had been extinguished. The official report describes a number of communication problems that frustrated the dissemination of information about the earlier decision that no rooftop evacuations would be possible in the rising heat and smoke.

There were other aspects of this tragedy that provide further lessons for scenario generation. The US National Institute for Standards and Technology's Building and Fire Research Laboratory continue to study the ways in which damage to the building affected evacuation behaviour. In the North Tower, attempts to descend through the damaged floor were 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, the 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. This combination makes evacuation extremely problematic. Some form of triage is usually required to ensure that as many people as possible can be helped to leave the site of the incident as quickly as possible. Hence not only did the terrorist attacks help to redefine the worst plausible scenarios in evacuation simulation, they also acted as a salient reminder of the problems that arise when attempting to replicate the mixture of circumstances that both support and complicate evacuation during 'real' disasters.

It is probably unrealistic to expect simulations to replicate the individual trajectories that are witnessed in adverse events that are as complex as the attack on the World Trace Centre. However, these individual accounts can be used to analyze the way in which pathological situations and unlikely opportunities combine during these extreme situations. Only one survivor escaped from the heart of the impact zone on the 81st floor in the South Tower. The wing of the plane sliced through their office filling the surrounding area with a smell of jet fuel that was so strong it became difficult to breathe. They escaped with help from a civilian fire warden who had descended from a higher floor. Their escape was partially due to the fact that the warden had been equipped with a flashlight. It is important to emphasize that this account and that of the group which escaped using stairwell A represent the experiences of a minute fraction of the people who were caught up in this tragedy. However, their experiences provide important insights that can be used in simulations to move beyond the 'worst plausible scenario' to consider what additional actions might have mitigated the consequences of this attack. For example, subjunctive simulations might be developed to consider what might have happened if more people had been provided with flashlights as they descended the stairwells. Other scenarios might consider what might have happened if emergency personnel had been provided with clearer information about the state of stairwell A in the vicinity of the impact site.

3.7 Model the Impact of 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. Unfortunately, by this stage fire damage had affected many of the buildings' internal systems. In consequence, the order never reached most of the critical areas throughout 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 have 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. For example, proposals have been made to extend building security systems and fire monitoring applications. 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 that "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 provide means of better informing such 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 actually be given that fire chiefs had to make decisions based on the distribution and condition of occupants that cannot easily be sensed by even the most advanced systems. 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 actual state of the building. In the same way, the World Trade Centre'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 the design of these systems.

Very few simulation tools consider the ways in which building security systems can interact with the course of different evacuation scenarios. Those systems that have been used in this way, typically, assume total failure. Very few are related to the risk-based models that influence the engineering of these systems. Hence there is often a disconnect between the hazards that are considered during the development of building control applications and the scenarios that are used during subsequent evacuation simulations. The lack of sufficient technical expertise in the modeling of these systems failures is also apparent in subsequent investigations. For example, the 9/11 report described how 'damage to the software controlling the system, resulting from the impact of the plane, prevented this order from being executed". This seems to reveal some confusion over the nature of software in what is otherwise a most authoritative account. It seems unlikely that there was physical damage to the software. In contrast, it is more likely that physical damage to the sensor network or communications infrastructure prevented the software from executing the command to open access throughout the buildings.

3.8 Extend The Zone of the Evacuation

The events of September 11th taught a number of more prosaic lessons in addition to providing insights about the potential strengths and weaknesses of future building information systems. In particular, this tragedy reinforced the importance of extending simulations to consider the area immediately surrounding large public buildings. For example, an important strength of the GES simulation of the Boyd Orr building introduced in previous sections was that it developed evacuation scenarios based on the digitized form of the original architects' drawings. This creates potential problems because the simulations only extend as far as the architect's models. For instance, 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 and so 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.

In many other public buildings, however, it is also necessary to consider evacuation routes that extend beyond the immediate confines of any particular building. It is necessary to consider the routes that occupants can follow as they are dispersed into the care of the emergency services. For example, the West Street lobby of the South Tower was 'overwhelmed' by occupants and emergency personnel by 09:35. In particular, the lobby was filling with people who had been injured. They had evacuated to the lobby but were having difficulty going on. Anyone who could move from the lobby was directed to exit north or east through the concourse and out of the World Trade Centre complex. The handling of the bottlenecks in the lobby and concourse areas proved to be just as important as the rate with which occupants could descend from the higher floors of the buildings. The subsequent collapses illustrated and associated deaths and injuries in the surrounding streets illustrate the importance of extending the geographical extent of future simulations beyond the narrow confined of particular buildings.

The geographical location of emergency personnel outside the towers also had a significant impact on subsequent evacuations. These locations would not routinely have been considered in evacuation simulations. In particular, the Fire chiefs who had been in charge of the overall command post on West Street had to rush to find shelter in the underground parking garage at Number 2, World Financial Centre during the collapse of the South Tower. The FDNY boat on the Hudson River transmitted the information about the collapse but all of the other FDNY command posts had also been evacuated. In consequence, key personnel were unavailable to influence FDNY operations for the first ten minutes after the initial collapse. Their location and the difficulty of reestablishing communications with their teams frustrated attempts to initiate a full withdrawal from the North Tower. Even though he did not have full information about the collapse, a chief in the North Tower lobby independently sent out an order to evacuate the building within a minute of the collapse. Again, however, it would be difficult to have anticipated the actual course of events within any simulation. These evacuation orders did not follow the established protocol for an imminent collapse that should have involved constantly repeating “Mayday, Mayday, Mayday” for the 29 minutes between the fall of the South Tower and that of the North Tower.

The attack on the World Trade Centre suggests that the scope of evacuation simulations should be extended beyond the narrow confines of individual buildings and their occupants. However, this creates considerable additional challenges for research in an area that is only just beginning to achieve more general acceptance. One of the challenges stems from the dynamic manner in which participants, especially emergency service personnel, will move between the affected areas. For example, the FDNY Chief of Department and the Chief of Safety returned to the West Street command Centre from the parking garage after the collapse of the South Tower around 10.15. As mentioned above, they issued radio orders to evacuate the North Tower and then *moved* the FDNY command post further north on West Street, also ordering the other FDNT units north along West Street toward Chambers Street.

These specific observations about the events on September 11th illustrate a number of more general points about the future role of evacuation simulations. In particular, the manner in which an initial attack spread from a single building to affect an entire complex has much wider parallels. Many fires spread beyond the buildings in which they originated, even with the intervention of the emergency services. Even those that are contained often trigger the evacuation of many surrounding premises. As we have seen, this creates problems in the areas in which the former occupants of public buildings are expected to congregate. These groups are often vulnerable, not simply to falling debris as was the case in the World Trade Centre, but also to road traffic and to the emergency vehicles as they arrive at the scene of an incident. Very few of these issues have ever been considered within evacuation simulations where, as mentioned, the focus has been rather narrowly on the time it takes individuals to descend from particular floors to the assigned exit points.

3.9 Extend Simulations After the Evacuation of Building Occupants

The events at the World trade Centre also illustrate the importance of extending simulation tools to consider a longer interval of time. This builds on a previous point about the need to consider ingress by the emergency services as well as the evacuation of previous occupants. The attacks in New York provided a clear reminder that even this is insufficient and that simulations must go on to consider the egress of emergency personnel as well as their ingress against the flow of evacuating occupants. By 10:28, it is likely that most occupants in the North Tower had descended from below the impact line if they were physically or emotionally fit for evacuation. NYPD, FDNY and Port Authority personnel were still helping people to evacuate from the bottom of stairwell C.

The importance of considering the eventual withdrawal of emergency personnel in simulator studies can be revealed by the problems that arose following the collapse of the South Tower. Within minutes, firefighters began to hear evacuation orders and battalion chiefs on the upper floors soon began to pass the message on to anyone they could contact. Some, including a chief on the 23rd floor, ‘aggressively took charge’ to ensure that all firefighters on the floors in the immediate area were evacuating. A chief on the 35th floor used both his radio and a loudspeaker or bullhorn to shout the evacuation order down each of the stairwells. Other firefighters did not receive the evacuation transmissions. The 9/11 investigations identified four potential problems that prevented the communication of this information:

1. Some FDNY radios did not pick up the transmission because of the difficulties of radio communications in high-rises.
2. The numbers trying to use the tactical communications system after the South Tower collapsed may have drowned out some evacuation instructions.
3. Some firefighters in the North Tower were off-duty and did not have radios.

4. Some firefighters in the North Tower had been dispatched to the South Tower and were on probably using a different tactical channel assigned to that tower.

The simulation of the ingress and egress of fire personnel is a relatively unexplored field. However, the events in the World Trade Centre show that it poses as many challenges as the simulated evacuation of building occupants. The FDNY personnel who received the evacuation order 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 begin the descent 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 then were 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. There 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.

3.10 Model Coordination Between Emergency Services

Previous sections have argued that we should extend the scope of evacuation simulations to look beyond the egress of building occupants to consider the ingress and eventual egress of emergency service personnel. The previous paragraphs have also emphasized some of the difficulties that this creates; the lack of reliable communications and the distribution of FDNY search teams across several buildings makes it difficult to develop a single model of behavior. The range of responses, for example, to the collapse of the South Tower is every bit as complex as those of the building occupants in response to the initial strikes from both aircraft. However, the analysis of any emergency response is further complicated by the observation that the response to the initial attacks involved the coordination of several different emergency services. The 9/11 investigation revealed that information was not always shared as effectively as might have been desired, at least in retrospect. For instance, the NYPD had clear warning that the North Tower was extremely likely to collapse. One of their 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, a 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 Centres 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 communicate 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", 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 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 World Trade Centre 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 the complex by going down the stairs on the north side of the complex. They remained there until the North Tower collapsed, all survived. Future generations of simulation tool might be extended to consider the impact the specific evacuation techniques, such as the ESU chaining, might have both on the evacuation 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.

4. Conclusions and Future Work

This paper has two principle aims. The first is to provide an overview of the state of the art in evacuation simulations. These interactive computer based tools have been developed to help the owners and designers of large public buildings to assess the risks that occupants might face during emergency egress. The development of these tools has been informed by numerous human factors studies. These have helped to identify the factors that may delay an evacuation, for example if occupants are engaged in goal related activities that distract them from attending to warnings and alarm. Empirical studies can also be used to predict cognitive and social factors that affect the direction and speed of an evacuation. Subsequent sections in this overview have described how previous accident investigations have been used to validate many of the human factors studies. For instance, the Station nightclub fires 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. Similarly, the Summerland fire showed that training in fire evacuation can help to address this tendency especially if accompanied by regular evacuation drills.

The development of the Glasgow Evacuation Simulator is used to illustrate the existing generation of tools. In particular, we have described how this application was used to develop an interactive model of egress from a large public building. The system uses Monte Carlo techniques to control the population distributions of occupants in each scenario so that personality traits, such as assertiveness, and physiological characteristics match those of a sample population of building occupants. Similar techniques are used to determine each individuals movements throughout the structure. The speed of evacuation is also modified by the human factors literature on average speed of movement in particular crowd densities. The end-user of this tool can interactively open and block emergency exits at any point during the run. It is also possible to alter the priorities that individuals associate with particular exit routes. Hence it is possible to emulate the preference for retracing entry routes that has been identified from previous evacuations. Finally, the opening sections closed by presenting the results of empirical validations to illustrate the effectiveness of the GES tool as a training system; building occupants can be shown the importance of using emergency exits in terms of an interactive simulation of potential evacuations.

The second half of this paper extends the use of official investigations to review the insights for evacuations simulations from the reports of the 9/11 commission. The first problem in performing such an analysis is to determine whether this incident and the subsequent evacuation are so atypical that it is impossible to derive any generic lessons. The World Trade Centre complex was unusual both in the scale of the buildings involved and in the number of occupants affected. The form of attack was both unexpected and arguably unprecedented. However, there seems to be a consensus that the events of September 11th 2001 provide important warnings for potential future disasters. Certainly, some of the insights that can be derived from the commissions' findings might easily be extended to, for instance, underground transportation systems or to a significant number of other public buildings that are of comparable capacity to the Twin Towers complex.

The previous paragraphs have identified a large number of lessons that can be drawn from the evacuation of the World Trade Centre. It can be argued that the events of September 11th have cut away at many of the underlying assumptions that have previously supported the application of evacuation simulations. Fir example, it can be argued that we have focussed too much on the evacuation of building occupants rather than the ingress and egress of emergency personnel. The insights derived from the commission's report can be summarised as follows:

1. ***Model the dynamic effects of changing procedures and protocols.*** The 1993 bombing of the World Trade Centre had led to the revision of many of the protocols that governed the evacuation of this complex. Evacuation simulations have tended to use these procedures to guide the generation of scenarios. However, most of these revised procedures did not survive beyond the initial impact on the North Tower. For example, the standard advice to building occupants was to remain on their floors and await assistance from emergency personnel. The intention was to minimise the injuries that were anticipated from an evacuation. As we have seen, however, this policy was quickly abandoned when individual operators and then eventually FDNY chiefs ordered an immediate evacuation. Similarly, procedures for issuing the eventual order to evacuate emergency personnel from the South Tower were also abandoned following the disruption caused by the collapse of the North Tower. Very few simulators have been used to analyse or model the impact of changing procedures and priorities during the course of a large-scale evacuation. Partly in consequence, many dispatchers and operators were unsure about what advice to give to callers who were caught up in the evacuation.

2. ***Model a Wider Range of Alternate Communication Channels.*** Many evacuation simulators assume that building occupants have an almost perfect knowledge about the manner in which they should respond to alarms. Very few scenarios model the uncertainty and confusion that was apparent during the initial events of September 11th. As we have seen, the Port Authority fire safety director reported that a general evacuation had been ordered from the North Tower within one minute of it being hit, others said that the announcement was not issued until ten minutes after the impact. The damage to the building information systems removed most of the official communication channels, including the emergency intercom phone that occupants had been trained to rely on. In consequence, occupants received information from 911 operators or from colleagues who contacted them over the cellular networks as they watched news feeds of the unfolding tragedy. The impact of these alternate communications channels was to further increase the diversity of response. Some occupants immediately began to evacuate on the advice from their colleagues. Others were told to remain where they were by 911 operators and FDNY dispatchers. Given the difficulty of preserving static communications channels under similar circumstances, it would seem that future incidents will also lead to the use of informal channels, including cellular telephones. The impact of such external information sources has been largely neglected both in the analysis of major emergencies and in the modelling of evacuation behaviour.

3. ***Model Wider Range of Group Behaviours.*** Previous simulation tools, including the GES, have distinguished between individual and group behaviour. Human factors studies and incident investigations have identified phenomena, such as flocking, that influence the movements of groups in the aftermath of major adverse events. The evacuation from the World Trade Centre illustrates the importance of many of these phenomena but it also points to a number of other behaviours that have not been so well considered. For instance, some groups showed considerable resilience when faced with potential barriers such as doors that were either locked or had been distorted by structural damage. Other groups in similar situations failed to respond to these barriers and instead waited for further help from the emergency services. Similar distinctions have been introduced into the goal-directed and problem-solving models of individual occupants in building simulators. However, very few consider the group based characteristics that seem to have played an important part in whether or not particular groups were able to exit from the North and South towers.

4. ***Model the Ingress and Egress of Emergency Services Not Just Occupants.*** The events of the 11th September have reshaped many of the previously held notions about the role and nature of evacuation simulation. Arguably the greatest lesson to be learned from this tragedy was the need to safeguard the ingress and egress of emergency services into endangered buildings. Previous incidents have taught similar lessons. For instance, the Smithfield Market fire in London in 1958 led to a detailed revision of the rules and procedures for the deployment of emergency services in large fires. However, many of the issues identified from previous fires had not been recognised in the development of evacuation simulation tools that focused almost entirely on the egress of occupants. Hopefully this will change. For instance, there is a clear role for such tools in assessing the physiological demands that can reasonably be met by individuals carrying over 100 pounds of equipment over many flights of stairs. Many of the teams that were caught in the collapse of the South Tower seem to have been overcome by their exertions in reaching the higher floors before they were told to evacuate.

5. ***Model and Integrate Emergency Service Decision Making.*** The evacuation of the Twin Towers and other areas of the World Trade Centre forced many people to make many difficult decisions. They had incomplete information and very limited resources of time, people and equipment. Our analysis would suggest that these issues are far more important than simulations that predict average evacuation times based on physiological, cognitive and social characteristics of individual occupants. For instance, the FDNY chiefs determined when the general orders were issued to initiate the evacuation. This, in turn should have affected the advice issued by dispatchers and 911 operators. Similarly, the decision to initiate the prompt withdrawal of NYPD ESU teams from the South Tower saved lives as they descended and distributed their instructions to other groups still working there. It follows that evacuation simulations should play a more prominent role in wider forms of role-play for the emergency services. This would provide police and fire service personnel with greater practice in decision-making and communication in any future adverse events. At present computer-based models do play a limited role in these training exercises. However, there is still a reliance on the use of physical simulations that follow tightly scripted scenarios. These often lack the flexibility and complexity of computer-based simulations that can be directed to probe for weaknesses in an initial response. In consequence, many of the drills and exercises to test civil defences are many years behind the more dynamic simulation techniques that have been developed within military training regimes (Johnson, 2004).

6. ***Model Worst Plausible Circumstance.*** Prior to the attacks of September 11th, several studies had considered the possibility of aircraft hitting large public buildings. Most assessments focused on accidental collision as the result of navigation or control problems. Not only had previous studies failed to consider the scale of such attacks, they had also failed to consider the complexity of trying to evacuate such large public structures. The destruction of critical information systems has been mentioned. Further problems stemmed from the lack of structural information that was available during the course of the incident. The sheer amount of guesswork that went on is difficult to underestimate. Some occupants were told to climb higher, some were told to descend and others to remain where they were as emergency services struggled to determine the location of the impact site. Several groups of occupants began moving in one direction and then reversed their decision. Even when accurate information was obtained, the details became confused as they were passed from 911 operators to FDNY personnel. Our initial analysis of existing simulation tools has shown that none have so far been used to consider the pathological combination of factors that complicated the evacuation from the World Trade Centre complex.

7. ***Model the Impact of Current Building Management Systems.*** Many of the groups involved in the development of evacuation simulators include software engineers. It is, therefore, surprising that relatively few of these groups have begun to consider the impact of building information and management systems on the occupants' ability to egress for a building. The delay in issuing the open command from the centralised Security Command Centre from the 22nd floor of the North Tower is a salient warning of things to come. Very often these systems assume that the default is to close and lock all door to preserve the security of a building, especially where criminal activities can threaten the work of financial companies. It can be very difficult to over-ride such defaults under emergency conditions when critical network infrastructure is degraded or lost. More attention must be paid to the regulation and certification of these systems. Also any simulation that contributes to the risk assessment of large public building *must* consider the associated failure modes for these security and building management applications.

8. ***Model an Extended Evacuation Zone.*** Previous evacuation simulations have often focussed on particular buildings or even on the floors and corridors within a single building. For example the GES tool can semi-automatically derive evacuation simulations from architects drawings. These are usually provided for specific buildings rather than the wider area in which that structure is located. The events of September 11th show the importance of taking a far broader view. The attacks threatened all areas of the World Trade Centre complex. Even if the focus is directed at the North and South Towers and the Marriott Hotel, it is important to consider the evacuation routes that were used as occupants streamed away from these buildings into streets and plazas that were already very congested. The problems of falling debris and of people from the Towers also reinforce the importance of this broader view in evacuation simulation. It can be argued that the scale and extent of this tragedy were atypical. However, many fires extend beyond the confines of a single building. Even those that can be contained often trigger the simultaneous evacuation of many other buildings in the surrounding area. It is important not to underestimate the problems that such crowds create for the emergency services that must gain ingress into these public structures. Getting people out of the building may only be the start of the problems involved in incident evacuation.

9. ***Model Post-Evacuation Events.*** The previous paragraph has emphasised that simulations must be extended to consider the impact of an evacuation on surrounding areas, for example as other buildings evacuate in response to an initial alarm. We have also argued that simulations should be extended to

consider the ingress and egress of emergency personnel. One benefit of these extended models is that they might also consider the effective control of units as they emerge from a damaged building. Our analysis of the 9/11 commission's report identified the problems that several units faced when they completed their descent from the South Tower. Some of the ESU's retreated to locations that were too close to the danger area. Several of the FDNY units were uncertain what to do when they emerged into the lobby and several were killed as they eventually began to retreat toward West Street.

10. ***Model Coordination Between Emergency Services.*** Previous evacuation simulation tools have provided rudimentary models of the manner in which individual building occupants might work together by forming common goals. The most primitive of these behaviours can be seen in the 'flocking' mentioned earlier. If we extend the scope of these tools to consider the activities of the emergency services then it seems appropriate to develop models of coordination and communication between different groups of primary responders. The closing sections of this paper have described numerous instances where cooperation broke down amidst the chaos and uncertainty of the attacks on the World Trade Centre. Some of the initial NYPD ESU teams were not 'recognised' by FDNY personnel and were forced to improvise a response. At other times, coordination worked well as FDNY staff helped their NYPD colleagues to find tasks that they could perform given their lack of breathing apparatus etc.

Our analysis of the 9/11 commission report has provided a number of insights for the future development of evacuation simulations. The modelling of emergency service personnel as they move in and then out of large public buildings has been almost entirely neglected. The emphasis on the computational modelling of decision making by building occupants has obscured the importance of understanding those critical decisions that must be made by fire officers as they deploy their units into hazardous situations. It can, therefore, be argued that we need to extend the scope of accident simulations and also consider how they might be better integrated into emergency planning exercises. It seems clear that we need to include the impact of fire service personnel and of police intervention on the movements of building occupants. We might also consider whether simulations should be routinely integrated into emergency planning exercises so that we can obtain more evidence about the likely actions of senior staff during these rare events. At present, there seems to be a considerable gulf between the rather primitive simulation tools that are used in emergency planning exercises and the more sophisticated systems, mentioned in this paper, that tend to be used in a stand-alone capacity by designers and building operators. The application of the GES tool illustrates this gulf; it has been used to help plan evacuation drills and assess the design of existing buildings but has never been used interactively with senior personnel to trace key decisions during the course of an evacuation.

These suggestions are not radical; they represent an evolution rather than a revolution in current practice. However, the events of the 11th September have acted as a catalyst for more radical thinking. For instance, a joint conference of the National Conference of States on Building Codes and Standards (NCSBCS) and the Association of Major City/County Building Officials (AMCBO) recently proposed the development of secure database for first responders. This would contain information about the design and evacuation plans for major public buildings. The intention was also to use these resources to help identify "retrofit actions to make buildings more resistant to bioterrorism; savings to the public, government and industry by streamlining building codes administrative procedures through the use of information technology; and the need for a common family of coordinated building codes" (National Conference of States on Building Codes and Standards, 2002). Previous sections have described how other research initiatives in the US and Europe are consider the installation of distributed sensor networks to provide first responders with a real-time analysis of the damage done to a building as an evacuation progresses. Such initiatives create new roles for evacuation simulations. Tools such as GES can run different scenarios directly from existing architect's drawings. Evacuation simulations could be run directly from the source drawings and models provided by the NCSBCS and AMCBO database. The simulations might be constantly updated by input from the proposed sensor networks. In the future, therefore, these tools might have a greater presence at the scene of an incident as it develops. They already provide powerful 3D models of the movement of people within complex structures. The new opportunity is to integrate command functions and not simply predictive facilities into this new generation of simulators. It is important, however, to temper these ambitious new proposals with a 'reality check'. There are enormous technical and practical barriers to be addressed before such tools might provide any benefits to their proposed users. The uncertainty and confusion that arose in the Twin Towers and the failure of many technological systems, such as the centralised security software, illustrate just how unprepared we are to support the evacuation of many large public buildings.

Computer based tools have come a long way in the last twenty years. Agent-based programming languages, the development of cognitive user models, the beginnings of computational tools for understanding group behaviour are all relatively recent developments. However, these tools only provide abstraction representations of real-world behaviours. It will never be possible or indeed beneficial to model every aspect of evacuations from large-scale public buildings. The key point here is that evacuations help us to focus on and animate those behaviours that we consider to be important in determining whether people will survive extreme situations. The real insight from the attack on the World Trade Centre is that it has changed our beliefs about those things that are, and those things that are not important in the modelling of evacuation behaviour.

Acknowledgements
I would like to thank the other members of the Department of Computing Science, University of Glasgow for their support. Thanks are due to Prof. R. Eatock Taylor, Dept of Engineering Science, University of Oxford and Dr James Hill, Building and Fire Research Laboratory, US National Institute of Standards and Technology for providing valuable encouragement during the initial stages of this work.

References

UK Atomic Energy Authority, A Technical Summary of the AEA Egress Code, technical report AET/NOIL/27812001/002(2), Issue 1, Warrington UK, 2002.

W. Baker, J. Barnett, C. Marrion, J. Milke and H. Nelson, H. (2002) Chapter 2: WTC1 and WTC2. In Federal Emergency Management Agency, World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and recommendations. Washington D.C., 2002.

M. Batty, J. Desyllas, and E. Duxbury. Safety in Numbers? Modelling Crowds and Designing Control for the Notting Hill Carnival. Urban Studies 40:8, 1573- 1590, 2003.

UK Building Research Establishment, Evacuation Modeling: GridFlow and CRISP, Watford, UK, 2004. Available on: http://www.bre.co.uk/frs/

R.W. Bukowski, R. D. Peacock and W.W. Jones, Sensitivity Examination of the airEXODUS Aircraft Evacuation Simulation Model, International Aircraft Fire and Cabin Safety Research Conference. Proceedings. November 16-20, 1998, Atlantic City, NJ, 1-14 pp, 1998.

B. Cornwell. (2003). Bonded Fatalities: relational and Ecological Dimensions of a Fire Evacuation. The Sociological Quarterly, 44:4, pp617-638. 2003.

R.F. Fahy and G. Proulx, Human Behavior in the World Trade Center Evacuation. In Y. Hasemi (ed), Proceedings. Fifth (5th) International Symposium International Association for Fire Safety Science. Fire Safety Science. Proceedings. March 3-7, 1997, Melbourne, Australia, 713-724 pp, 1997.

T. Geyer, L. Bellamy, R. Max-Lino, P. Harrison, Z. Bahrami and B. Modha, An Evaluation of the Effectiveness of the Components of Informative Fire Warning Systems. In J. Sime, Ed., Safety in the Built Environment. London: E. & F. N. Spon, 1988, pp. 36-47.

S. Goldenstein, M. Karavelas, D. Metaxas, L. Guibas, E. Aaron and A. Goswami, Scalable nonlinear dynamical systems for agent steering and crowd simulation. Computers & Graphics 25/6, 983-998. 2001.

C.W. Johnson, A Handbook of Accident and Incident Reporting, Glasgow University Press, Glasgow, 2003. Available on-line at: http://www.dcs.gla.ac.uk/~johnson/book

C.W. Johnson, The Role of Nght Vision Equipment in Military Incidents and Accidents. In C.W. Johnson and P. Palanque (eds), Human Error, Safety and Systems Development, Kluwer Academic Press, Boston, USA, 1-16, 2004.

N.R. Johnson and W.E. Feinberg, The Impact Of Exit Instructions And Number Of Exits In Fire Emergencies: A Computer Simulation Investigation. Department of Sociology, University of Cincinnati, U.S.A, 1997.

S. Kurkjian, S. Ebbert, and T. Farragher, Behind the Rhode Island Nightclub Fire: Series of errors sealed crowd's fate, The Boston Globe, 6th September 2003.

N. Latman, TCPP Personality Profile, In The Fourth Triennial International Fire and Cabin Safety Research Conference, 15-18 November 2004, Parque das Naçoes Conference Centre, Lisbon, Portugal, 2004.

R. Mourareau and M. Thomas (eds), Fire In Buildings. Elsevier Applied Science Publishers Ltd, 1985.

H. Muir, Research into the factors influencing survival in aircraft accidents. The Aeronautical Journal, May 1996, 177-181.

New York City Government, Mayor Michael R. Bloomberg Announces Commission To Study International Building Code, Press release PR-284-02, November 2002, Available on www.nyc.gov.

US National Commission on Terrorist Attacks Upon the United States, The 9/11 Commission Report, Washington DC, 2004. Available from: http://www.9-11commission.gov/report/index.htm

US National Conference of States on Building Codes and Standards, News release: At NCSBCS Annual Conference, Construction Industry, Building Regulators Discuss Coordinated Actions Critical to Economic Competitiveness, Public Safety and Homeland Security, 2002. Available on: http://www.ncsbcs.com/

US National Fire Protection Association, High-Rise Building Fires: Frequently Asked Questions, 2004. Available on http://www.nfpa.org/

US Occupational Safety and Health Administration, OSHA Factsheet: Evacuating High-rise Buildings, US Department of Labor, Washington DC, 2003. Available on http://www.osha.gov

UK Office of the Deputy Prime Minister, The Regulatory Reform (Fire Safety) Order Stateent by the Office of the Deputy Prime Minister, UK Government, 2004. Available on: http://www.odpm.gov.uk/

M Owen, E Galea and P Lawrence, The EXODUS Evacuation Model Applied to Building Evacuation Scenarios. Journal of Fire Protection Engineering 1996, Vol.8(2), pp 65-86.

V.M. Predtechenskii and A.I. Milinskii, Planning for Foot Traffic Flow in Buildings, Stroiizdat, Moscow, 1969.

G. Proulx and J. Sime, To Prevent Panic in an Underground Emergency: Why not Tell People the Truth. In G. Cox and B. Langsford, Eds, Fire Safety Science, Proceedings of the Third International Symposium. London: Elsevier, pp. 843-852. 1991.

G. Proulx, Occupant Behaviour and Evacuation. Proceedings of the 9th International Fire Protection Symposium, Munich, 25-26, pp 219-232, 2001.

J. Sime, Affiliative behaviour during escape to building exits. Journal of Environmental Psychology 3, 21-41, 1983.

J. Sime, Movement toward the familiar: person and place affiliation in a fire entrapment setting. Environment and Behaviour 17, 697-724, 1985.

J. Sime, Research on escape behaviour in fires: New Directions. *Fire* Research News 9, 3-5. 1987.

D. Tong and D. Canter, The Decision to Evacuate: A study of Motivations which Contribute to Evacuation in the Event of Fire. Fire Safety Journal 9:257-265. 1985.

S.J. Older, Pedestrians. Department of Scientific and Industrial Research Laboratory, LN 275/SJO. Crowthorne, England, 1965.

P.A. Thompson and E.W. Marchant, Computer and fluid modelling of evacuation. *Safety Sci* **18**, pp. 277–289, 1995.