Simulation Modelling Practice and Theory 19 (2011) 1007–1019

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Computer simulations vs. building guidance to enhance evacuation performance of buildings during emergency events

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ARTICLE INFO

Article history:
Received 26 March 2009
Received in revised form 15 March 2010
Accepted 1 December 2010
Available online 23 December 2010

Keywords:
Building simulation
Building evacuation
Crowd modelling
Building guidance
Emergency events

ABSTRACT

Computer technologies can play an important role in the establishment of dynamic building information by introducing predictive modelling where behaviours of structures or groups of people can be simulated and observed. This way they can facilitate the design of the built environment to cope with emergency events. Modelling and simulation applications can be particularly useful at pre-planning, predicting possible damage, training responders, raising public awareness, and performance evaluation for reconstruction. They can be used for the development of virtual scenarios that include aspects of rescue operations, social behaviour of building occupants, and basic design requirements to test the current building codes and regulations. Within this context, the contribution of crowd simulation to improving the design of the built environment and guidelines is highlighted in this paper. Current building guidance for emergencies are summarised and the methodology developed to use crowd modelling to define design information associated with exit preferences of people during evacuations is explained. The results of the case studies underlined that there is a difference between the assumptions used for static information in current building guidance.

1. Introduction

The complexity of city life and the increase in the number of crowded public spaces such as entertainment, sports or transportation venues underline the need to identify risks and predict possible hazards to enhance the design of the built environment for increased safety and security. Several projects have explored the management of extreme events, especially during the response stage using emerging information, communication and computer technologies. One of these studies was a research project conducted at Loughborough University, entitled "ICT Enabled Solutions for Safety and Security Risks in the Built Environment". This study was focused on the deployment of Information and Communication Technologies (ICT) in disaster management and mitigation to improve safety and security within the built environment during the pre, during and post phases of disaster events. The research identified safety-aware building design as an important area in need of further investigation [1–3] and highlighted the need for the investigation of the potential application of computer simulations in crowd modelling to improve safety in building design. Most of the crowd simulation research deal with the development of simulation tools for the analysis of the evacuation process [4]. However, there is also a need to investigate the use of computer simulations to identify dynamic information required for building design guidance.

Design guidance (codes, standards, guidelines, etc.) is necessary to identify and apply the building and environmental requirements however their sole application does not provide sufficient designs. Each building complex has specific characteristics that produce unique and dynamic information based on the relationship between people and building, functions,

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doi:10.1016/j.simpat.2010.12.001

geometry and environmental factors. Predictive crowd simulations can support the building design process by exploring the designs under certain conditions that occur in different buildings and circumstances by using scenario-based studies. Brocklehurst et al. [5,6] focused on the use of crowd modelling to improve the design of sport stadia and schools, and highlighted the significance of capturing dynamic building information related to crowd movement. It shows that the design of buildings can be significantly improved by applying computer aided crowd modelling and simulation.

This research builds on the above work and aims to enhance safety through improved design of the built environment by investigating issues associated with emergencies and evacuations and to establish new building design guidelines. The focus at this study was on the exit preference of the building's occupants. Two types of case studies were designed; the first one based on observations of the real life evacuations and the second one on computer simulations. The use of exits during the evacuations was observed and the reasons for exit preferences were investigated in Observation Case Studies (OCS). The aim of the Simulation Case Studies (SCS) was to highlight the differences between the information given in the current building guidelines and the case studies while exploring how these differences influence the evacuations and building design in general. The case study buildings were modelled and various evacuation scenarios were simulated using the crowd modelling software buildingEXODUS. This paper summarises the current guidance on safe building design and explains the methodology and results of the Simulation Case Studies (SCS). Finally, the potential use of crowd modelling in further research for safe building design is discussed.

2. Research study

This research emphasizes the use of computer modelling and identifies building design issues associated with emergencies in order to improve safety during extreme events. The intent was to inform building design codes and standards using crowd modelling techniques, to establish ways of mitigating impacts of extreme events. The research can also inspire the future development of simulation technologies by defining specific requirements for modelling and simulating dynamic social behaviour. This study is of benefit to: architects, designers and civil engineers and will increase their awareness and knowledge of safe building design. This study will also benefit construction experts and regulatory bodies helping to define deficiencies in the current building codes while assisting ICT researchers and developers to develop a better understanding of safety requirements in the design of the built environment.

2.1. Aim and objectives

In this study, crowd behaviour in emergency situations is investigated in order to develop guidelines for the design and refurbishment of large circulation areas to improve the safety of occupants. The aim of this research is to enhance safety and security through improved design of the built environment to better cope with extreme events. The study of crowd behaviour in building evacuations will assist to develop guidelines for the design and refurbishment of large circulation areas. The main research objectives include:

- To review requirements and procedures for crowd safety during emergencies, and building design information, guidelines and standards used in design process of large public areas.
- To review people flow simulation tools and techniques to establish their suitability for use within the context of crowd modelling for emergency events.
- To define crowd safety requirements in emergency events.
- To customize a suitable crowd modelling software and conduct tests on a number of emergency scenario based case studies.
- To define guidelines that specifies improved designs that ensure better safety of users during emergency events within large public spaces.

The purpose of the Simulation Case Studies (SCS) was to investigate how the factors identified in the Observation Case Studies (OCS) affect evacuations using crowd modelling techniques. The objectives were:

- To identify evacuation times using different design parameters.
- To identify possible changes required to building design guidelines and standards to improve the safety of users in emergencies.

2.2. Methodology

The main methodology to be used in the study of crowd behaviour in emergency events was based on:

- An extensive literature review on emergency events, crowd behaviour and crowd modelling.
- Detailed interviews conducted with experts within organisations that deal with crowd management, emergency planning, safety and security, public facilities management and the design of public buildings.
- Visual information from video recordings.
- Questionnaires.

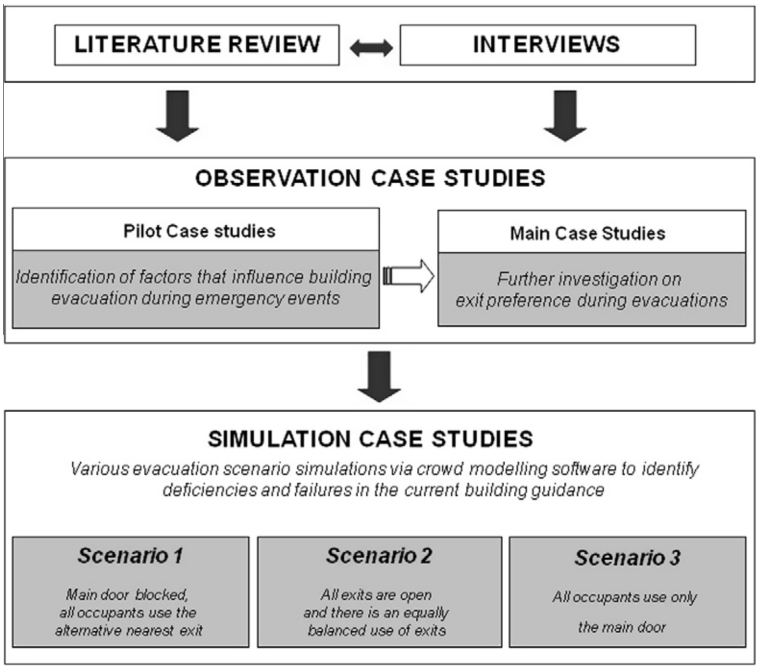

Fig. 1. Research methodology.

Two types of case studies, Observation Case Studies (OCS) and Simulation Case Studies (SCS) were conducted in three office buildings (see Fig. 1).

The literature review and interviews continued at each phase of the research. The first phase of case studies included the pilot and main OCS that aimed to investigate the patterns of behaviour, movement, and circulation as well as the reasons for exit preferences using camcorder records and questionnaires during the annual fire evacuation drills. The buildings were observed using digital camcorders to capture people's exit choices, their reactions when they first heard the alarm and the bottlenecks that occurred in or near the exits. The population in each building varied (80–120) according to the scale of the building. The occupants of the buildings were not informed about the fire drill and the fire marshals played their role to reflect the situation that would occur during a real emergency event during the OCS. It was anticipated and was also supported by the results of the questionnaires that they did not have an influence on exit preference but on the pre-movement time. The number of people using each exit door was determined using tally counters during the evacuation drills to identify the popular exit preferences. Finally, a questionnaire was distributed to all evacuees to identify the factors effecting the exit choice such as location of people in the building; exit choice, reasons for preferences, clarity of signs, and orientation of people by the marshals. The literature review and interviews with the emergency and building design experts helped to identify the building design aspects associated with emergencies and the design of the questionnaire.

The second phase of case studies included the SCS. Crowd modelling and simulations were used to investigate the relationship between the behaviour of people and architectural design and construction, and to help in defining the requirements for safe building design in open plan office buildings. SCS involved comparison of the information from current building guidelines and the findings from the real evacuation observations with a number of scenarios simulated using a crowd modelling software to identify and validate the important critical building design parameters for safe building evacuations. Crowd simulation software generally use the shortest route approach which leads to a somewhat imbalanced use of exits. Therefore the scenario models enable the simulation and comparison of balanced and imbalanced use of exits.

3. Guidance for safe building design

3.1. Current guidance for safe building

Although a prescribed design solution cannot be applied to all cases, there is a need to codify the basic safety knowledge in a way that designers can use. Design codes, standards and guidelines are forms of codifying design knowledge with references to minimum, maximum or average measurements. There is no coherent technical information that relates to emergencies. However, some of the building standards, guidelines or codes of practice highlight many of the building design aspects associated with crowd behaviour, movement or management in normal or emergency situations. These technical documents focus on certain aspects of this context such as fire safety, circulation, or accessibility. Information developed to assist architects, designers, civil engineers and fire engineers in safe and secure building design and construction is reviewed in the next section.

3.1.1. UK technical information on safe building design

There are various technical documents in the UK that are published by organizations and institutes responsible for ensuring safety and security in the design and construction of the built environment. Their focus is primarily on fire safety including means of escape, crowd management, accessibility and circulation. Some of the most commonly used publications for design and construction are the British Standards (BS) series published by British Standards Institution (BSI). BS include technical specifications and guidelines to ensure reliability, safety, efficiency and interoperability in a wide range of concepts such as building construction, manufacturing, environment, transport, ICT, health and safety and security. The relevant BS for safe building design defines the internationally agreed terms associated with fire safety, evacuation and means of escape (*BS4422*); the management of fire safety and precautions in building design and the issues regarding special needs (*BS5588*); requirements for disabled people associated with building design (*BS8300); issues* on accessibility, for fire fighting, means of escape, building management and construction (*BS9999*). There are some other technical documents published by BSI such as Published Documents (PD) which are prepared by national committees but are not in line with BS requirements. There are also documents adopted from technical documents published by international organizations such as European Committee for Standardization (CEN), and International Organization for Standardization (ISO) (e.g. *PD 7974-6* that includes information on human factors, fire safety and evacuation strategies to assess the safety potential of a building for the occupants). The Publicly Available Specification (PAS) is another type of document commissioned by other organizations such as the UK Government, trade associations and private companies (e.g. *PAS 51* that covers issues on crowd management, emergency planning, health and safety and security issues for outdoor events).

Building regulations for fire safety are also covered in *Approved Document B* and *M* that include issues on means of escape, fire spread and access and facilities for fire services. *Green Building Guide* provides detailed information on ground management, for the safe accommodation of crowds in sports grounds. *CIBSE Guide E: Fire Engineering* published by the Chartered Institute of Building Services Engineers (CIBSE) also summarises legislations, giving references to other publications and websites.

3.1.2. International organizations and publications on safe building design

International standards and guidelines published in other countries are also worth exploring although there may be some differences in the implementations, resources, management, etc. The most common international technical documents are published by the *International Organization for Standardization* (*ISO*), *National Fire Protection Association* (*NFPA*), *National Institute of Standards and Technology* (*NIST*) and *the Federal Emergency Management Agency* (*FEMA*). ISO 13387 covers life safety, occupant behaviour, design fire scenarios and performance standards in addition to structural fire behaviour. Codes and standards published by NFPA give guidance on the design of buildings for extreme conditions as well as human factors that are needed to be considered in extreme situations. One of the NIST Labs focuses on building and fire research and has a number of publications on evacuation and fire safety including reports on investigations of case studies such as the evacuation modelling of the World Trade Centre Disaster. The Federal Emergency Management Agency (FEMA) produces publications on safe building design with a focus on terrorism, earthquake, flood, etc. The SFPE Handbook published by the Society of Fire Protection Engineers (SFPE) in the US can be used together with the nationally and internationally agreed standards and codes in the development of architectural designs for public buildings. There are other guidelines and handbooks that focus on specific aspects of building design for crowd safety such as emergency lighting, means of egress, circulation or designing against specific type of emergency. Information in any of the above documents can help in producing new design solutions.

3.2. Challenges for current building guidance

Although the technical documents reviewed above are updated in line with changes or developments in needs, environmental factors, and technological developments, they cannot, on their own, solve every design problem efficiently because they are mostly based on static building information that highlights some of the safety issues. They characterise minimum and/or maximum dimensions for circulation and exits in interior and exterior spaces, passages and circulation elements such as stairways, elevators, and escalators. These documents cannot support working solutions for all buildings and circumstances because each design has its own unique characteristic regarding environmental factors, client requirements, user needs, economical constraints, etc. Therefore, the fulfilment of building code requirements in the design process is not an assurance of efficiency in real life daily use [7].

Over-reliance on codes and standards may limit the designers in developing good design solutions. It can also limit deeper understanding of safety issues that may be specific to each building or designs. Moreover, this over-reliance on codes may also create a danger by limiting designer's responsibility in case of unexpected situations or design problems, allowing them to avoid some important design issues not covered by the standards or codes of practice [8].

Furthermore, most of the information in current building design codes, standards, etc. is based on inaccurate assumptions on the behaviour of people such as balanced use of circulation areas and exits. They are based on static building information that only highlights some of the safety issues such as dimensions needed for emergency exit doors, stairs, etc. Observations of crowd dynamics during extreme events can provide information on the failures found both in the design of environments and the management of venues and social events. Computer simulations have the potential to help with testing design solutions, in order to limit fatalities in the built environment and enhance safety in the built environment.

3.3. Improving design guidance for safer built environment

New research can improve codes and standards using computers to simulate the movement and interactions of people [9] as well as observations of historical and real life cases. As Hale et al. [8] stated, the design process must contain a learning loop and a memory regarding its successes and failures because this learning loop would help in predicting conditions of use and identifying problems from previous accidents and errors. Within this context, Fig. 2 demonstrates the methodology developed to improve building design guidance to cope with emergencies. The improvement process is a loop that includes observations of real cases, analysis of current information and testing design solutions and scenarios by computer simulations.

IT systems such as CCTV cameras enable the observation and collection of data and information about the behaviour of people in normal and emergency situations. Crowd modelling and simulations can use the information gathered in these observations as well as the information found in relevant building codes and standards. Crowd modelling is defined as a method of modelling crowds of moving people and their interaction with each other and their environment [9]. Modelling can be used to reduce vulnerability to "acceptable" levels of risk defined according to the characteristics of the hazard and the space [10] because simulations have the potential to help the testing of design solutions, as well as to identify the gaps in current building guidance to better control fatalities in the built environment. Scenario-based studies help to: increase awareness, define the levels of acceptable risk, and test designs in various reoccurrence frequencies, intensities and spatial distributions for different hazards and vulnerabilities [10].

It is necessary to observe human motion in order to build accurate and more realistic models of movement of people [11]. The results of various design and event scenarios can assist to identify building design problems and propose new design solutions by highlighting the critical issues, problems in design solutions and differences that would occur in real life cases. The proposed solutions would then be used to improve the current design procedures or to help development of new standards for future building design and construction (see Fig. 1).

4. Contributions of crowd modelling to safe building design

Computer models and simulations are especially useful to explore the performance of complex systems under a wide range of circumstances as they provide the flexibility for easy reconfiguration of the spaces and patterns of flows saving time

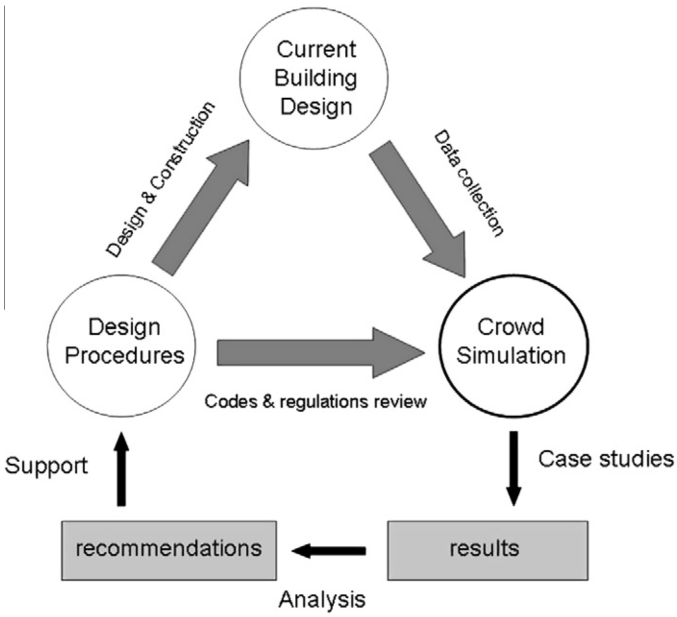

Fig. 2. Development of design solutions using crowd simulations.

in the testing of numerous possible design configurations and alternatives. Virtual scenarios can also be useful for identifying and testing design aspects related to rescue operations and the behaviour of disabled occupants. Below, the role of computer modelling and simulations in safe building design is explained in more detail.

4.1. Role of computer modelling and simulation for safer design

Computer simulations can help the development of building design guidelines that consider the key factors (such as number of routes and doors, travel distances, dimension of the routes and doors, etc.). The scenario-based studies involve the representation and observation of different cases in the virtual environment. Virtual Environments can provide visual, auditory and haptic representations where the representations of people are created to guide the observer. These virtual humans are called *avatars* and can model human characteristics. Virtual humans and crowds as representatives of real building occupants can generate problems due to the amount of information that needs to be modelled and displayed. Artificial Intelligence is widely used for imitating part of real human behaviour in computer applications such as neural networks and expert systems. Virtual humans can be used as substitutes for testing and evaluation purposes for [12]:

- The time needed to find the way out during hazardous situations.
- Crowding and queuing while people try to find their way out to a safe location.
- The path followed by occupants to reach their safe location.
- The perception of occupants in specific environmental conditions (such as various lighting, heating, acoustic, etc. conditions).
- The efficient use of the building.
- The training of workers on the building site.

The main objective of crowd simulations is to identify the issues that can reduce the risks which threaten human life [9]. In early crowd flow studies, the carrying capacity of the building elements, flow rates and types of exit routes were considered, focusing on the width and capacity of exits. However, there is a need to focus on understanding the relationships between people and the built environment [13]. This approach requires consideration of the dynamic nature of evacuations and means of escape which presents many challenges related to the circumstances, characteristics of building occupants and rescue operations. It is essential to have information on the range of building occupants characteristics (age, sex, abilities, etc.) to anticipate the problems. The behaviour of people differs in an emergency event according to their interactions with the other people and their immediate environment. Different types of crowds behave in different ways. A crowd in a football match is very different from a crowd in a shopping centre or concert venue. Most people ignore alternate routes but prefer to take the route that they are most familiar with. Therefore, they usually choose to use the same routes that they came in and doors that they are familiar with. Mawson [14] states that people prefer to be with familiar people (family, friends, etc.) and in familiar places, even if this means moving toward the danger and they tend to move not toward an objectively safe place but toward people and places they perceive to be familiar or safe. Including such basic factors found in real-life situations can produce more realistic results in simulation studies. In the cases studies, there were no known cases of filial bonds that might have influenced people's behaviour in an emergency situation.

4.2. Evacuation modelling approaches

There are various evacuation models offering different degrees of sophistication. These include simple approaches that treat the crowd as a homogeneous fluid or dull particles to concentrate on the flow capacity of the spaces as well as more detailed simulations where explicit behavioural rules of individuals are considered. On the one hand, macroscopic modelling approaches describe pedestrian flows with differential equations and claim that the movement of pedestrians can be conducted analogous to fluids and gases [15]. On the other hand, Casburn et al. [11] categorise micro simulation models as cellular automata models, agent-based (or AI-based) models, and behavioural force models. In the cellular automata models, space is divided into cells. Casburn et al. [11] stated that agent-based models are successful for the simulation of low to moderate pedestrian densities. It is easier to create heterogeneous populations because each occupant model has a unique behaviour. Behavioural force models are force-based and help in the prediction of a variety of phenomena that would occur in high crowd densities. However, they represent unnatural behaviour because of restricted motion abilities [11].

Another approach by Lo et al. [13] categorises the network models into two types: 'coarse' and 'fine'. They explain the "coarse network" approach focused on the movement of people as a unified homogenous "mass" with emphasis on flow rates and the average speed. These models do not consider the individual movement pattern and are advantageous because they require less input and computational power [13]. EVACNET, WAYOUT, EXIT89 and Modified Network Model are some examples of coarse network models. Lo et al. [13] define the "fine network" model as an approach for individual perspective that divides a space into many fine network nodes in the form of finite square nodes (e.g. EXODUS), hexagonal grids (e.g. AEA EGRESS), distance maps (e.g. SIMULEX) or finite non-uniform grids (e.g. SGEM). In fine network models, each grid may be "occupied" representing an "empty" space or a volume of space occupied by a person. Fine network models aim to model real-life situations; hence their construction is more complex requiring large amounts of input and case specific programming [13].

4.3. Related research on crowd behaviour and modelling

One fundamental research focus in the mitigation against the impact of disasters and emergencies is computer simulations of the building evacuation process using flow-based modelling, cellular automata, agent-based modelling and social factors based crowd movement. GridFlow developed by the Building Research Establishment (BRE), is a simplified model of human behaviour, where all the pre-movement activities are represented by a single time delay [16]. In this model, occupants evacuate the building via the nearest or randomly-chosen exit. Another model developed by BRE with more detailed behavioural simulations is CRISP based on a risk assessment tool and used to simulate fire evacuation scenarios. Another Example is the analysis tool developed within Myriad (an Integrated Crowd Dynamics Modelling Suite) that is designed to observe how the crowd uses the available space [17]. There are also various research projects conducted by universities and research institutes around the world. These can be summarised but not limited to multi-agent based framework for studying human and social behaviour during building emergency evacuations at Stanford University [18,19]; the simulation of crowd behaviour in computer games at Lulea University of Technology [20]; crowd behaviour, escape and egress studies at Babes-Bolyai and Chung-Ang Universities [21]; the development of a Crowd Behaviour Application Programming Interface at the Virginia Modelling, Analysis and Simulation Centre, Old Dominion University [22]; the development of a methodology that involves a Virtual Reality based Belief, Desire, and Intention (BDI) software agent to construct crowd simulation that cope with terrorist bomb attacks in Arizona State University [23]; the development of a Situated Cellular Agent (SCA) Model at the Dipartimento di Informatica, Sistemistica e Comunicazione Universit'a degli Studi [24]; research on design strategies related to crowd behaviour that trigger jamming at the University of Puerto Rico, Mayaguez [25]; crowd simulation research based on balance dynamics at the University of Virginia [26]; research on behavioural model based on pedestrian dynamics at the Swiss Institute of Technology [27]; research on crowd dynamics related to social force model at Colorado State University [28]; crowd behaviour architecture related to military crowd requirements including the design of an Application Programming Interface (API) layer to connect layers of cognitive and physical models [29]; and Crowd–Anticrowd Theory of Collective Dynamics in Competitive Multi-Agent Populations and Networks [30].

Most of these research projects focus on the development of crowd modelling and simulation of crowd behaviour rather than the use of crowd simulation for identification of dynamic information required for building design guidance. The case studies in this research were designed to gather dynamic information and to use crowd modelling and simulations to test building designs in various crowd behaviours and scenarios.

5. Case studies

5.1. Observation and Simulation Case Studies

An imbalanced use of exits during evacuations was observed in the OCS which conflicts with the assumptions found in current building guidelines. The two factors that are significantly important in exit preference were found to be ‘perceived distance’ (27%, 48% and 57%) and ‘familiarity with the exits’ in all three case studies (19%, 13% and 18%). Percentages of use of main exits were found to be 92%, 51% and 70%, respectively, for the three cases, which are significantly higher than the percentage of use of alternative exits for all three cases. The other factors (entrance door, emergency signs, visibility, following other people, crowd, bottleneck, obstacles and orientation by fire marshals) indicated as important for exit preferences in the literature were not found to be significantly important in statistical analysis.

OCS was followed by a set of Simulation Case Studies to test different scenarios for the building evacuation process based on the findings from the OCS. The three buildings which were used during the OCS were modelled in SCS. The case study buildings were all open plan office buildings and had one, two or three levels with multiple exits. Each building had a main familiar door used for entering and leaving the building in everyday use. The number of people in SCS was the same as the number of people in OCS for each building, 50% male and 50% female. The populations did not include disabled people.

A fourth building simulation was also conducted on a new building in the process of being designed. It is a high rise tower with more than 42 levels. In this study, the evacuation of levels 32–42 was modelled. Since most people use the stairs near the elevators and lifts [31], it was assumed that the staircase near the elevators is the familiar main exit for the building occupants.

5.2. Simulation tool and modelling process

After each fire evacuation drill observation, the case study buildings were modelled using buildingEXODUS which is a crowd modelling software developed by the Fire Safety Engineering Group at Greenwich University [32]. It is a tool that simulates people–people, people–fire and people–structure interactions (Fig. 3). It was chosen because it has a user friendly interface and can import ‘.dxf’ files for the geometry of the buildings. Moreover, it enables the user to create various scenarios by making changes to the properties of the people (sex, age, disabilities, etc.), the speed of their movement during in both horizontal and vertical flow, and the properties of exits (open, closed, main, alternative, etc.).

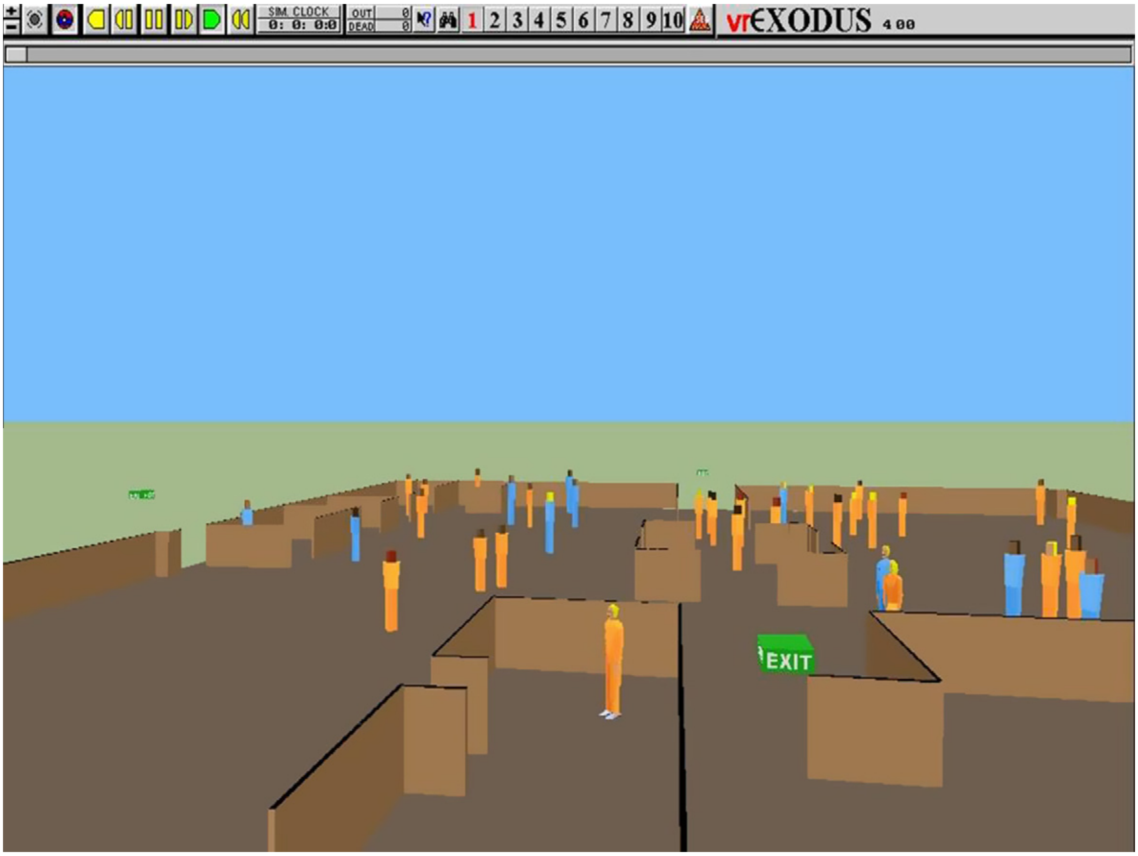

Fig. 3. A 3D model in EXODUS.

In the modelling process, the 3D CAD drawings were used to trace the geometry of each building. Then the traced drawings in '.dwg' format were converted into '.dxf' format to be used in the software model. Each level of the building was loaded into EXODUS individually as a separate floor and modelled using the node flooding method.

A node can be defined as a region of space occupied by a single person [32]. Each node represents a 50 × 50 cm area in EXODUS where one person can stand. All nodes are connected horizontally, vertically and diagonally by arcs and the movement of a person is simulated by jumping from one node to another through the arcs in any direction. Node flooding is a method used for covering the defined geometry with nodes to represent the movement of users. Fig. 3 shows the representation of a node flooded small room. Female and male figures are represented by red and blue circles, respectively.

Each floor was connected by stairs in buildings with two or more levels. The interior and exterior doors in the building were located and connected to the corresponding nodes (Fig. 4). The evacuation simulations of each building tested various scenarios where the familiar main door and alternative exit doors were changed. The properties of the doors were also modified according to the simulation scenarios.

5.3. Scenarios

All scenario simulations were conducted with the same number of people and the following occupant characteristics as defined in PD 7974 "The application of fire safety engineering principles to fire safety design of buildings; Part 6" [33]:

- The response time after the emergency alarm was identified as 30–90 s.
- Fast walk speed was identified as 1.2 m/s.
- Stair down speed was identified as 0.8 m/s.

The following three scenarios were tested for each building where the evacuation process was observed (see Fig. 2) when:

- The main door was closed but all other alternative exits were open (Scenario 1).
- All the doors were open and there is a equally balanced use of exit (Scenario 2).
- All alternative doors were closed and only the main door was open (Scenario 3).

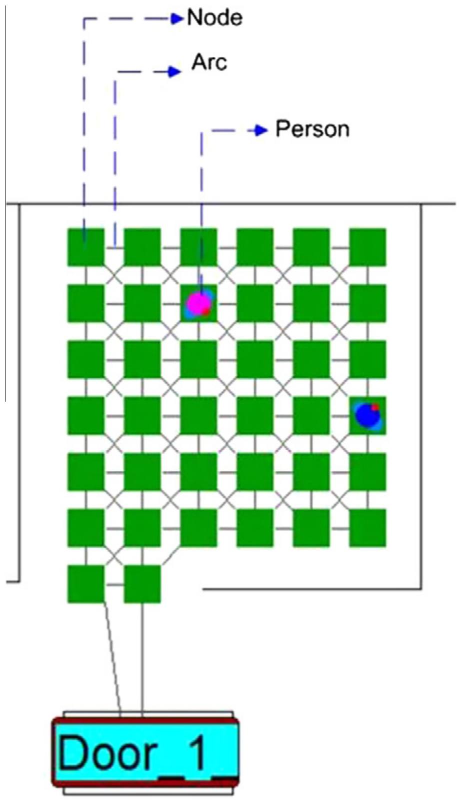

Fig. 4. Representation of the model of a small room in buildingEXODUS.

The assumption made by the current building guidelines (such as building codes, regulations and standards) was simulated in Scenario 2 where there is an equally balanced use of all available exits during an evacuation test [33]. The other two scenarios reflected extreme cases where various doors were blocked. The blocked door(s) in the simulations represent the unused door(s) which may be a result of a hazard, fire and/or obstruction near the door(s), or personal rejection. The effect of familiarity of the occupants with the exits on evacuation time was also simulated by changing the properties of the doors.

5.4. Results

The first case study was modelled in EXODUS to simulate the three evacuation scenarios explained above where the use of main familiar and alternative doors differs (see Fig. 5).

The evacuation times observed in the three simulations for each building are presented in Table 1. The difference in evacuation times of Scenarios 1 and 2 are very low and can be neglected in all cases (2, 1 and 3 s).

However, the difference in evacuation times of Scenarios 2 and 3 are quite high for all cases (21, 19 and 40 s) showing about a 20% increase on average. This percentage was increased even higher for the high rise building case study conducted subsequently (Table 2).

The three scenarios were also simulated for the high rise building case to check if there is an increase in evacuation time difference between Scenarios 1, 2 and 3 (see Fig. 6).

The difference in evacuation times in Scenarios 2 and 3 for the high rise building is 145 and 210 s which represents about 25% and 36% increase in the evacuation time of Scenario 1. This illustrates a huge difference that may seriously affect design decisions based on the current building design guidelines (Table 2). This big difference may be due to the nature of the high rise buildings which are more complex as a result of longer vertical travel distances and more interactions resulting from higher number of building occupants, combinations of open plan and boundary defined rooms, and different types of vertical circulation (staircase, lifts, elevators, etc.). There are various factors at individual, organizational and environmental levels associated with evacuation of high rise buildings [34] that need further investigation through case studies and analysis of the previous cases.

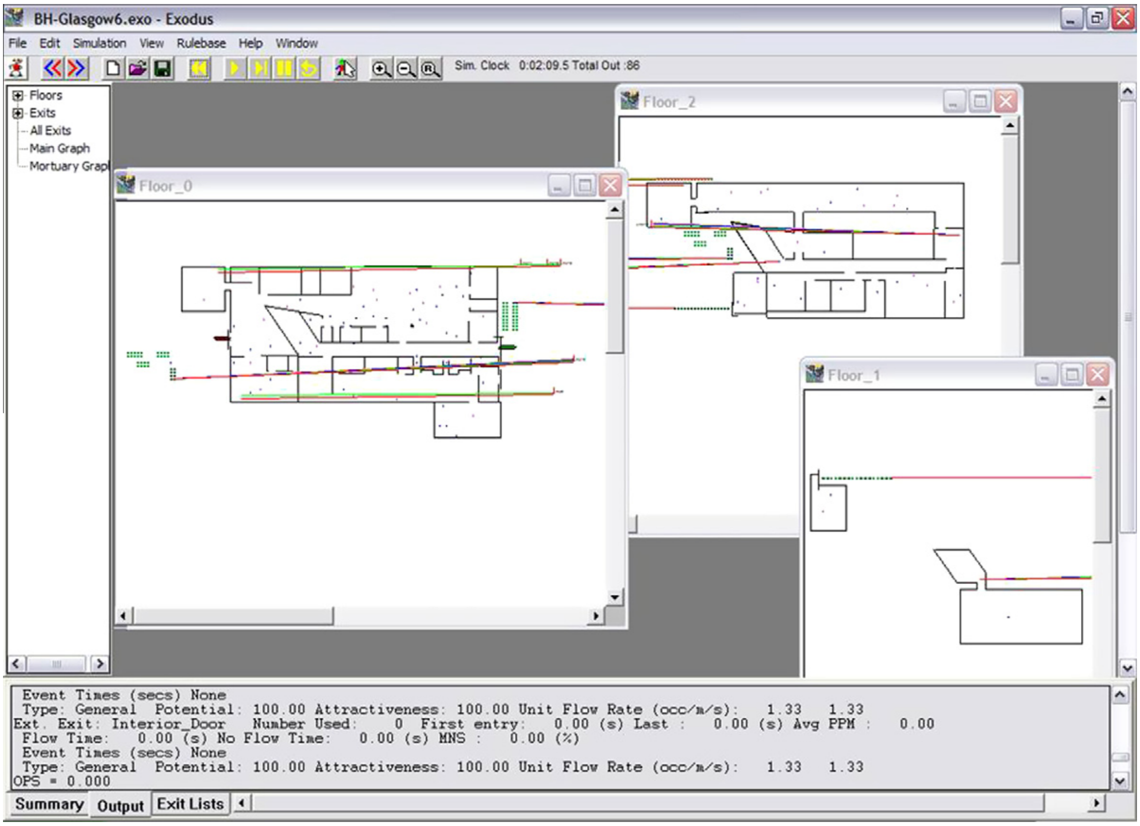

Fig. 5. 2D representation of the model of Building III in EXODUS.

Table 1
Scenario descriptions and evaluation time results.

	Building I			Building II			Building III		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Evacuation time (in seconds)	109	107	128	110	109	128	195	192	232
Number of people	100	100	100	102	102	102	86	86	86
Number of people using the main door	0	35	100	0	39	102	0	26	86
Number of people using alternative exits	100	65	0	102	63	0	86	60	0
Number of people on the ground floor	100	100	100	65	65	65	45	45	45
Number of people on the first floor	NA	NA	NA	37	37	37	28	28	28
Number of people on the mezzanine floor	NA	NA	NA	NA	NA	NA	13	13	13

Table 2
Scenario descriptions and evacuation time results for a high rise office building.

	S2	S1	S3
Evacuation time (in seconds)	787	577	722
Number of people	427	427	427
Number of people using the main door	0	237	427
Number of people using alternative exits	427	190	0

6. Conclusion and further research

It is a fact that most victims die during crowding rather than by the emergency events [35]. An efficient building layout can increase safety of people in crowded events. Increased safety can be achieved with correct design decisions that consider the functional relationships in the building, circulation and occupant characteristics during extreme events. Building codes and standards can identify and apply the requirements for building design for crowded public environments although they

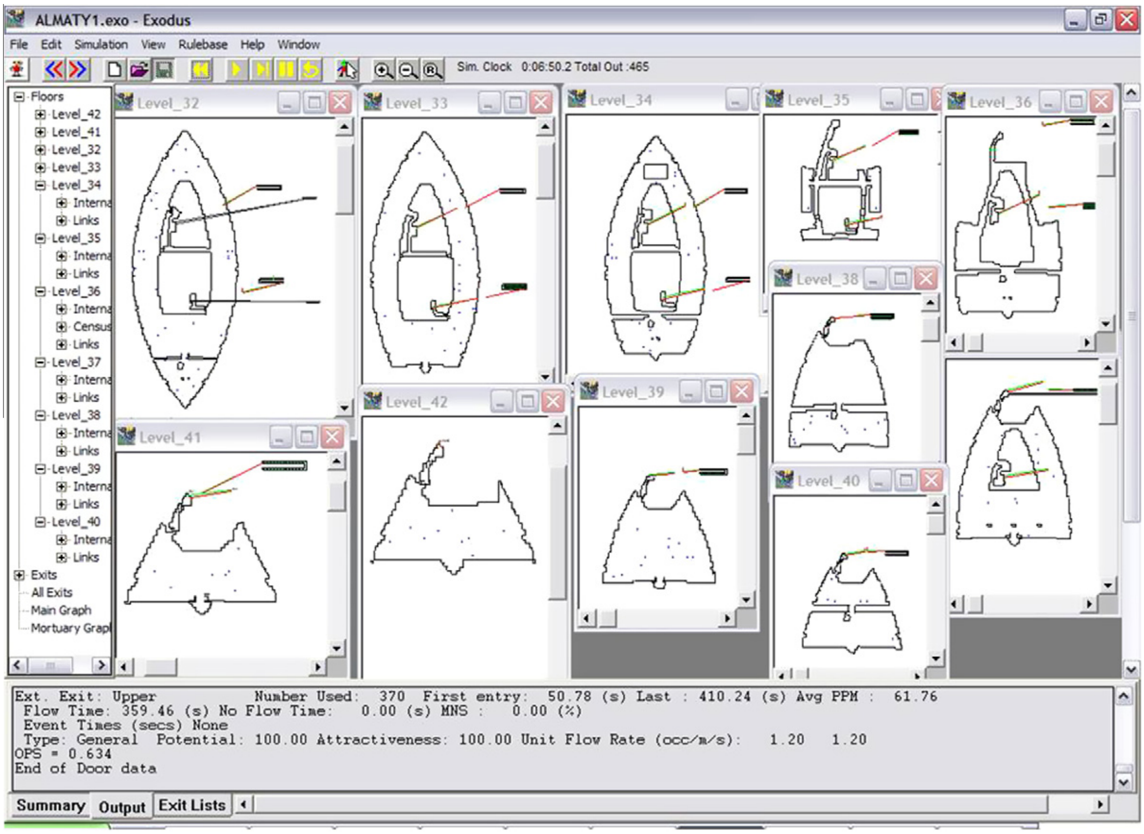

Fig. 6. A high rise office building modelled in EXODUS (modelled by Dr. David Brocklehurst).

only present the static data related to buildings. Each building has its unique characteristics, hence requires exclusive analysis regarding the relationship of people and its functions, geometry and environmental factors. As Fruin [7] stated, there is not enough focus on the movement of people during the initial stages of the building design, except reliance on local building codes. Building design issues associated with emergencies require support from dynamic data that capture typical patterns that characterise a certain type of function. This type of data can also guide the designer, architect and engineers to analyse their own design case and produce mitigation solutions to potential emergency events on their own building design.

The aim of this research was to highlight the improvement of the design of the built environment in order to better cope with extreme events by observing the evacuation process in real life cases and by using crowd modelling and simulation techniques to test various evacuation scenarios. This paper reviewed building codes associated with emergencies as well as crowd modelling and simulation approaches; and highlighted how computer modelling and simulation tools can enhance building design by facilitating the analysis of building design requirements related to crowd behaviour during evacuation to improve building design guidance.

Design factors for a safe emergency evacuation were identified in Observation Case Studies conducted in three office buildings. Perceived distance to exits and familiarity of building occupants with the exits were found to be the most influential factors in exit preference during emergency evacuations. The Observation Case Studies showed how the exit preferences of people change during the evacuation process. Although prescriptive approaches using balanced exit usage have been shown historically to be safe, many buildings are now being designed on a performance with regard to exit time. Therefore scenarios were designed to test evacuation time using crowd modelling approach. The Simulation Case Studies showed why building design needs to consider the influence of exit preferences during emergency evacuations in real life. The real life behaviour in exit preference was compared with the design information found in the current building regulations and guidance. NFPA 101 and PD 7974 were used for the case studies as the information sources where data on the characteristics of building occupants can be found [31,33]. It was observed that the information found in current building codes and standards were of a static type that neglects the real life conditions and behaviours during the evacuation process. The information found in the building guidance was based on the assumption that exit use was equally balanced during the evacuation process. However, in real life, there are factors that influence the exit preference and use; therefore emergency exits are not used equally during evacuations. This conflict emphasized the need to consider dynamic information that can guide the designers and engineers to analyse and reflect changing real life conditions in their designs. The comparison of the scenarios simulating the balanced and imbalanced use of exits highlighted the fact that the imbalanced use of exits increases the evacuation time. It is observed that imbalanced use of exits increases the evacuation time 20% when compared to the equally balanced use of exits; which is a high increase that has to be considered in design decisions. Moreover, the information found in current building design codes and standards needs to be revised to allow for real life cases rather than assumed scenarios results.

As the techniques and tools for crowd simulation research are improved to incorporate more realistic human behaviour, it is possible to explore and analyse different types of buildings for various extreme events and emergency situations. The theories on human behaviour during emergencies claim various collective group behaviours from panic to rational acts [36]. The study of group behaviours during emergencies is a complex process because it can vary in different cases depending on type of the emergency event, characteristic of the building and characteristics of the group such as the size of the group, their familiarity with the building, and varieties in gender, abilities and age. There is still the lack of integrated approaches that consolidating behavioural factors with the development of crowd simulation models. It is also worth investigating strengths and weakness of the emergency teams, and respects the needs and requirements of the fire fighters and rescue teams because there may be access and evacuation difficulties for rescue operations. Moreover, providing accessibility to all, not only the majority of the population makes the design process for emergencies more complex because special requirements have to be included to meet the needs of various disabilities in design solutions. Design guidance for providing safety for building occupants, disabled people and rescue personnel during fire can be found in some of the building codes and standards (such as Approved document B: Fire Safety for fire fighting; Disability Discrimination Act 1995, BS8300, BS 5588, Guide to Safety at Sports Grounds 1997, Building Regulations PART M 2004, The Football Trust National Guide to Facilities for Disabled Football Supporters and A Guide to Grounds for Disabled Football Supporters) and these can be tested and compared with real life cases and various simulation scenarios.

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