Experimental Studies on the Effects of Merging and Deference Behaviour on Stair- Floor Landings.

By

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Abstract

This study provides an investigation into egress behaviour via stairways to increase understanding and further investigate the factors, which impede safe occupant movement. Fire evacuation drills of three different buildings were monitored by video cameras positioned throughout the stairwells. The purpose of the evacuation drills was to enable the analysis of the behaviour of the occupants, the merging process and the speed of movement.

Studies in Human Egress Behaviour have become increasingly important in fire safety engineering research. The focus of the study is the merging process of the occupants and their behaviour at the stair-floor interface (landing). An investigation was made into the merging and deference behaviour that occurred on the stair-floor landings. Results demonstrated that occupants on higher floors are at an increased risk due to stoppage because of merging and deference behaviour. An investigation of the stair floor geometry and entrances onto landings was undertaken. In addition, further research is required to investigate the capabilities of advanced computer egress models to accurately predict merging and deference behavior.

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Chapter 1: Introduction

Deference behaviour can have a negative or positive impact on the overall evacuation of a building. Its occurrence can dictate how an evacuation will unfold. MacLennan [74] has observed from evacuation drills a significant amount of disturbance of the continuity of flow when one flow stopped and another started at a merging region. Merging is more efficient when an exit route is utilized to complete capacity. In evacuations, at the merging region i.e. the stair-floor landing, the sharing of access occurs between the Floor Flow and Stair Flow resulting in breaks in the egress flow causing a significant impact on capacity. The merging process and subsequent deference behaviour of the occupants frequently occurs in evacuating high rise buildings.

Building codes base stair and exit widths on the estimated occupancy loading for a floor regardless of the entire building population. These widths are also based on phased evacuation procedures [127]. If simultaneous evacuation were employed then congestion could occur on each floor at the staircase entry points. Observational studies on evacuation drills have given researchers a realistic approach to help create a better understanding of the factors which can impede efficient evacuation from high rise buildings.

The effects of human behaviour during the evacuation of a building are investigated in this study in order to understand the fire safety requirements of occupants and buildings. Fire safety engineering is moving towards a performance-based design it is therefore necessary that research be continued to understand the role that human behaviour has on stairs during a building evacuation. Due to a limited amount of experimental data available to better understand the area of merging and deference behaviour, there is a need for research to be carried out in the this area [80]. In addition to this, researchers such as Fahy [34] have reported that computer evacuation models have limited data to improve the capabilities of current computer evacuation models. *"This data can be used in the development and refinement of evacuation models and in the use of such models*," Fahy, F., (2002) Pg 1 [34]. This study aims to provide useful experimental data with the intention to aid in the development of computer evacuation models.

Video-recorded observations of building evacuation drills are suitable as they provide the researcher with the visuals of what people actually did during the evacuation. They also provide information on how people prepare to evacuate, crowd movement such as queuing, flows through doorways and stairs, travel speeds, merging and deference behaviour. It would be preferable to observe real fire incidents however real data is not always freely available for analysis.

This study is presented into seven chapters. Chapter two discusses the research that has already been undertaken into human behaviour in fire and computer evacuation modelling. It provides a general review of literature on human behaviour in fires and highlights the importance of further research in this area. The purpose of this chapter is to give the reader adequate background on what is currently known about merging and deference behaviour.

This chapter also provides an overview of current computer evacuation models. It outlines the process in which two current computer evacuation models attempt to predict merging and deference behaviour. Chapter three presents the research methodology approach. It details the research design and the methodology used to conduct this research. The data collection method, measurement techniques and the analytical approach is detailed in this chapter.

Chapter's four to six present a detailed description of the analysis of five evacuation drills. The analysis includes the investigation of the factors, which can impede the safe and rapid movement of occupants during an emergency evacuation. Finally, chapter seven brings together the key findings, the contributions this research has made and provides suggestions for further research.

Chapter 2: Literature Review

2.1 Human Behaviour during Evacuation

Human behaviour in fire is a scientific field that identifies facts, concepts and relationships established though systematic observation and experimentation [87]. The field of human behaviour in fire is relatively new compared to other areas of fire research. Over the last two decades it has become more dynamic with the contributions of international research as presented in the proceedings from the first to the fourth symposiums in human behaviour in fire [13]. It is paramount that further research is undertaken to aid in the understanding of human behaviour in fire. It is of great importance that fire safety engineers have a good understanding of the concepts of human behaviour to determine the occupant's likely response during a fire emergency. It is therefore, vital that research is continued to further develop this field. Compliance with fire safety requirements and the provisions for adequate means for safe evacuation are crucial in any building, however, the success of these provisions, greatly depends on the behaviour of building occupants at the time of a fire emergency [87]. Fire disasters such as the MGM hotel, Dupont Casino and the Beverly Hills Super Club fires have all marked the importance of understanding the phenomenon of human behaviour in fire during an evacuation [78].

The earliest studies of Human Behaviour in the United States were documented in the first edition of the National Fire Protection Association's Building Exits Code in 1927. Early human behaviour studies comprised of the capacity counts of the velocity of pedestrian movement for the New York City design of the Hudson Terminal building in 1909 [13]. Evacuation studies involving federal government office buildings with both 'normal' exiting flows and 'fire drill' exiting flows were conducted in the early 1930s and published in 1935 [13]. In the United Kingdom, evacuation studies were conducted by the London transit board [13] analysing evacuation times and the movement of crowds in buildings.

2.2 Phased Development of Human Behaviour in Fire

In 1998, at the conference of the first international symposium on human behaviour in fire, Pauls [78] presented a paper on the development of Human Behaviour in fire where the development was split into four phases. Pauls [78] stated that the first phase began in 1956 with the report by John Bryan [13] of an investigation of the human behaviour in the fire at the Arundel Park Hall in Brooklyn, Maryland, USA. Woods [123], followed with a study on the Behaviour of people in fires" in 1972, analysing the behaviour of more than 2,000 persons in nearly 1000 fires. Pauls [81] during 1969 carried out a study on response to emergencies in buildings", which built upon early studies of psychological and social responses of people in large-scale natural disasters. During 1969-1974, work began on detailed documentation of occupant behaviour in evacuation drills in large office buildings in Canada including the documentation of the NBS (The National Bureau of Standards) Technical Note 818, Occupant Behaviour in fires by Ruben and Cohen [99]. Pauls [78], reported that the first international meeting to discuss research on fire related human behaviour took place on the 2nd May 1975, at NBS. Pauls [78] stated that the second phase of the development in human behaviour in fire involved major programmes of research and international seminars in 1977. Researchers came together from North America and Europe to contribute to the study of human behaviour in fire. Also in 1977, Best [6] documented a report on the tragic fire at the Beverly Hills Super Club in Kentucky. During the development of phase two, the first book in the area of Human Behaviour "Fires and Human Behaviour" edited by Canter [21] was published. The second phase also marked the publication of the first bibliography on human behaviour in fire by John Byran in 1978 [106]. Bryan [13] also carried out a report on drawing implications for codes and standards of the "Project People" studies. During the 1970s in the United States, the National Bureau of Standards was the primary source for the funding research in the field of Human behaviour. As a result, these studies involved the examination and development of methods used for the investigation of occupant behavioural response in fire emergencies in the United States and United Kingdom [78].

Pauls [78] stated that the third phase of development introduced valuable work by Bryan [16] on behavioural response to fire and smoke, which is documented in the SFPE handbook of Fire Protection Engineering. Major fire disasters, in particular the Summerland fire in 1973 on the Isle of Man, the MGM Grand Hotel fire on the Las Vegas strip in 1980 and the Kings Cross underground station fire in London in 1987 all highlighted the field of human behaviour in fire [78]. The third phase also introduced studies by Shields [108] with research on evacuation from building fires for the disabled. Proulx [83] presented research on how to prevent panic in an underground emergency and a study of evacuation timing in apartment buildings. Fahy [32] compared predicted occupant response with actual occupant response recorded in trial evacuations of a hotel with disabled occupants using an evacuation model EXITT89 for high-rise buildings. Their work continued into the fourth phase. Since the 1980s fire research started to focus more on computer modelling, therefore, funding had been directed to the computer models concerned with simulating human evacuation behaviour [106].

Pauls [78] stated that the fourth phase of development in human behaviour in fire began with the first international symposium on human behaviour in fire held in Belfast, Ireland in 1988 [109]. Seventy four papers were presented at the conference and twenty three countries were represented. Shields [109] briefly discussed a compilation of 17 papers all of whom were presented in the proceedings of the first international symposium on human behaviour. In addition Shields [109] compiled a list outlining the history of human behaviour research up until 2001.Other interesting studies included work by Clerico [28] in his investment of a multidisciplinary study on the problem of evacuation from buildings generated by an outbreak of fire. His work also included a calculation method for different building classifications paying particular attention to public buildings, taking into account the different occupancy types in each building.

Gwynne [45] presented a review describing the three different modelling approaches adapted in computer-based analysis and critically reviewed the inherent capabilities of each approach. Galea [50], utilized the Stapelfeldt evacuation data for the validation of Building Evacuation Model. Although lack of credible data was identified in the observed evacuation data set, agreement between the BuildingExodus predictions and the observed evacuations were reported. The third international symposium on human behaviour in fire presented by Shields [107] included forty-four papers. Among the forty-four papers included work by Pauls [80] outlining the requirement for more 'human performance data'. Taylor and Pepperdine [118], conducted research analysing human behaviour and how public safety campaigns affect human behaviour before and during fires. Blake [8] presented a paper on an analysis of the survivors' experiences of the World Trade Centre evacuation on September 11th 2001.

Sekizawa [103] discussed what populations were most vulnerable to fires and identified key issues as well as suggested policies for improving the fire safety of these identified vulnerable populations. Hoskin [58] presented an analysis of emergency egress and occupant characteristics of stadiums based on research on fire protection and evacuation procedures of stadium venues in New Zealand and discussed how crowd management can improve evacuation procedures. Ebihara [31] discussed the growing demand for elevator use in evacuations in high-rise buildings and developed a model to simulate elevator operation for calculating evacuation time by elevators. A paper by Sekizawa [104], described the results found from an investigation carried out by the "Study Group on Evacuation behaviour in the Hiroshima Motomachi High-rise Apartments." The study was conducted by a questionnaire survey and interviews and concluded a 'delay time to start' evacuation. Occupants ignored the perception of smoke and only began their evacuation when instructed by other occupants and fire safety personnel.

Olsson [75] investigated human behaviour and movement by observing the evacuation of three university buildings. Total evacuation, pre-movement time lags and non-direct evacuation behaviour were analysed and simulated using Simulex, a computer evacuation modelling software program. Results found that individuals with pre-recorded PA (a public address system) information were faster in the completion of pre-movement activities than those in siren alarm evacuations.

During the fourth symposium on human behaviour in fire in 2009 almost seventy papers were presented. Three major world trade centre evacuation research studies were discussed and reviewed. The symposium discussed the most current issues associated with fire safety design and evacuation issues associate with tall buildings. A number of papers were presented in the area of evacuation by means of stairs and or escalators. Among these papers included a study by Boyce [9] were experimental studies were carried out to investigate merging behaviour in a staircase. Boyce [9] reported that there was a need for more experimental studies to investigate the area of merging. A study carried out by Melly [72] investigated the egress behaviour on stairs during video-recorded evacuation drills. The paper presented initial findings of the evacuation drills investigating the merging process and deference behaviour. A number of variables that can affect the merging process were highlighted one of which was the location of the entrance onto the stair-floor landing. Melly [72] reports that the occurrence of deference behaviour can have a negative effect on a building evacuation.

2.3 Behavioural Actions

Understanding the basic concepts of human behaviour in fire is vital to determine occupants' likely reaction to a fire emergency. Buildings accommodate a variety of occupants with different characteristics, i.e. some will be able to escape in most incidents, some will have great difficulty and others will remain and risk fighting the fire. This type of behaviour is influenced by psychological, physiological and circumstantial factors such as previous involvement in fire incidents

Withey [121] developed a model defining the examination of psychological and physical processes an individual uses to decide if a fire alarm or cue is really a threat. Bryan [16] reported that six steps of the decision making process are crucial in the perception of fire. The six steps are as follows: "Recognition, Validation, Definition, Evaluation, Commitment and Reassessment" [16].

2.3.1 Recognition

The recognition process happens when an individual perceives cues as an indication of a fire threat. However, these cues can be ambiguous and sometimes do not indicate the severity of the threat [70]. People often associate alarm signals with systems tests or unannounced fire drills and not real fires. Delayed threat recognition is a very important issue in fire protection engineering [16]. The fire disaster at the Dupont Hotel and Casino in San Juan, Puerto Rico in 1986 sets an example of delayed recognition where occupants remained in the casino and *"gambling activities apparently continued"* even after explosions were perceived [63]. The ambiguous nature of the fire cues, and the unstructured nature of many public and social groups require the appearance of significant amounts of smoke, or sudden and threatening flames before most individuals without specialized fire prevention instruction or prior fire incident experiences perceive a threatening fire to be present [16].

2.3.2 Validation

The process of validation consists of attempts by the individual to determine the danger of the cue by seeking reassurance that the threat is low [70]. In this process individuals seek confirmation or reassurance about the perceived cues. Seeking information validates the character of a fire incident. When the received cues are ambiguous, the individual will often try to seek additional information. Occupants tend to ask themselves validating questions do they smell smoke and should they evacuate. [70].

2.3.3 Definition

The definition process consists of an individual's attempt to relate information concerning the threat to some contextual variable, as well as the severity of the fire, the magnitude of deprivation of the threat and the time context [16]. This process helps the individual relate the threat to their own situation. The individual will determine a course of action on how much smoke they see or how much heat they feel.

2.3.4 Evaluation

The evaluation process often happens very quickly, within seconds, and under great stress and threat. An important part of this process is the individual's perception of the time available for evacuation or time available to seek refuge [46]. Sime [111] also indicates the perceived time available depends on the information communicated to the occupants regarding the location and development of the fire. The variables of the physical location of the fire origin may be crucial in the evaluation process. These variables may be:

1. The physical location of the individual in relation to the means of egress,
2. The location of other members of the population at risk,
3. The physically perceived untenable effects of the fire, and
4. The overt behavioural response of other individuals in the population [16].

During the evaluation process the individual may decide whether to use 'flight or fight' to reduce their threat. The individual may decide to evacuate the building (flight) or attempt to extinguish the fire (fight) [70]. During this process, the individual can also be very susceptible to the actions of other members of the population at risk [70]. The behavioural responses observed in the evaluation process can influence other occupants, which can result in either adaptive or non-adaptive behaviour [70].

2.3.5 Commitment

The process of commitment involves the techniques carried out by the individual to formulate the behavioural response in the evaluation process. Therefore, if the individual does not act on the decision made during evaluation the individual immediately becomes involved in the cognitive process of reassessment and commitment [16]. People are often very committed to what they are currently doing which might be standing in a line at the supermarket, watching TV, completing a task at work etc. when they perceive their first cues of fire. Because of commitment, people may be engrossed in an activity and will continue what they are doing despite warnings of danger (93).

2.3.6 Reassessment

Reassessment can be the most stressful stage of the decision making process for an individual because of the failure of previous attempts to achieve the formulated response strategy to the fire incident [16]. Due to the possibility of successive failures, the individual will become more anxious and frustrated and therefore decisions become less rational, and the likelihood of fatality or injury increases [70].

Withey [121], suggested that three processes define fire-related human behaviour: recognition/interpretation/verification, behaviour (action/no action), and outcomes (evaluation and long-range effects). Bickman [7] introduced a similar model consisting of four-stages: a physical event (fire), detection of cues, definition of situation, and coping behaviour. Quarantelli [97] considered the concept of panic while, Proulx [83] researched the effect of stress on the decision-making process and the importance of communicating information has on reducing stress in a fire incident.

2.3.7 The Decision Making Process

The development of all of these models used to evaluate the adaptive characteristics of human behaviour in fire and the decision making process are crucially important to fire safety engineering design. Fire protection systems installed in buildings can often carry false expectations regarding how occupants actually behave during fires. From several evacuation observational studies, it has been found that occupants tend to ignore the sound of fire alarms in public buildings such as airports and shopping centres [88]. In most cases, the occupants carry on with their activities showing commitment as one of the steps in the decision making process by Withey [121]. The implementation of human behavioural actions into fire engineering design is important to avoid these problems.

2.4 Socio-psychological Concepts

Another process to aid in the understanding of how people act in fire is to view the behavioural actions under four socio-psychological concepts. These concepts are Avoidance, Commitment, Affiliation and Role [70]. People feel that they can protect themselves by denying unpleasant situations [125]. Psychological denial is very common during the first moments of a fire, when people find reassuring and benign explanations for the cues they see, smell and hear [125]. In most cases people do not believe the information they are given by alarm systems. Avoidance justifies the reason why people delay recognizing the threat and spends a long time ignoring the situation involved [70]. People are often very committed to what they are currently doing which might be standing in a line at the supermarket, watching TV, completing a task at work etc. when they perceive their first cues of fire. Because of commitment, people may be engrossed in an activity and will continue what they are doing despite warnings of danger [125]. Many people for example, will continue to enter a building despite the warning of flashing fire-warning lights [70].

One of the primary causes of delayed start of evacuation is Affiliation [125]. In Most cases one starts to evacuate until everyone in the group (family members or friends) are ready. Once a group has started to evacuate, the slowest member determines the speed of the movement for the entire group [125]. "*Affiliation is such a strong concept that it over rides threat*", Meacham, B.J., (1999), p. 307 [70].

Occupants who feel responsible for other occupants often do not evacuate a building without those occupants regardless of the threat involved, e.g. parents will not start to evacuate without their children, and people wait for co-workers. A visitor in a building is usually more passive during an emergency than residents or employees of that building. Visitors are likely to spend more time on the threat, recognition and validation because they are unfamiliar with the building [70]. Occupants will seek instructions from supervisors, fire safety wardens and others in authority.

2.5 Non-adaptive Behaviour

Non-adaptive behaviour can involve occupants helping others evacuate a building, occupants re-entering a building, occupants moving through smoke and in some situations actions to help stop the spread of smoke, heat and or flames in the event of a fire incident. It is considered that non-adaptive behaviour represents a small proportion of human behaviour in fire incidents even under life threatening conditions [42]. If the result of non-adaptive behaviour is successful, the outcome can be considered as adaptive behaviour e.g. the success of an occupant extinguishing a fire.

2.5.1 'Panic' Behaviour

The most highlighted non-adaptive behavioural response in fire mostly used in the reporting of fire disasters by media is the concept of 'panic'. Newspaper reporters tend to use this description for its drama following fire incidents Although the concept of 'panic' has continuously been used in media there is little evidence of panic in human behaviour response to fire incidents in the past. It has been reported by Sime [111], Keating [61] and Quarantelli [97] that the likelihood of panic behaviour in fire emergencies is considered a 'myth' by social scientists.

"The following conditions must be presented simultaneously to trigger panic: The victim perceives an immediate threat of entrapment in a confined space, Escape routes appear to be rapidly closing, Flight seems to be the only way to survive and no one is available to help" Heide, E.A, (2004) p. 342 (53).

People mostly utilize rational decision making during a fire emergency, even when the behaviour is unsuccessful on the outcome of a fire, at that time of the fire incident, the decisions made can be rational when all factors were considered. The word panic is often used by the public to describe being frightened, nervous or anxious. Wood (123) investigated the behaviour of two thousand people in nine hundred and fifty two building fire incidents. Results from interviews and questionnaires found that there were three general types of reactions: concern with evacuating oneself or with others as a group, concern with containing the fire and possibility fighting the fire and concern with warning others and notifying the fire brigade (123).

Overall, the occupants showed evidence of rational adaptive behaviour with no evidence of irrational behaviour such as panic. The notion that people caught in a fire will panic has long been rejected by psychologists. Panic has rarely been observed as a human response to danger from fire. In fact, most people appear to apply rational decision-making relative to their understanding of the event at the time of a fire [83]. However, this type of behaviour can have a significant effect on the outcome of an evacuation and should not be totally neglected (42).

2.5.2 Re-entry Behaviour.

Re-entry behaviour has been most prominent in residential fires, where occupants after completing an evacuation safely will turn around and re-enter the building. In most cases the occupant is fully aware of the extent of the fire within the building. Byran (16) found in the examination of the interviews of 584 participants involved in 335 residential fire incidents that 27% of the participants attempted re–entry. The reasons for re-entry were to fight the fire, seek information about the fire, notify others and to save personal belongings. Wood (124) carried out an examination of 952 fire incidents where he found that 43% of the occupants attempted re- entry. The collected data was mostly from domestic fire incidents, with 17% from factories, 11 percent in multi-occupancy dwellings, 7% in shops and 4% in other institutions. Re- entry behaviour can hinder efficient evacuation of others.

2.5.3 Movement through Smoke

It was found that occupants were prepared to travel considerable distances through smoke, which can be influenced by fire fighting behaviour, a familiar exit route and travel distance and the alerting of others [120]. "*Smoke filled environment is hazardous with respect to the heat conditions and the toxicity and irritancy of the fire effluents.*" Heskestad, A.W., (1998), p.631 [39].

Occupants have moved through smoke for distances of over twenty meters with limited visibility of less than 4 meters to achieve evacuation [16]. The lack of visibility greatly reduces efficient evacuation movement. An experiment carried out by Janse [59], found that the participants of a study where capability of walking through a smoke filled corridor without breathing for twenty seconds covering a distance of thirty meters.

2.6 Factors that Affect Occupant Behaviour

Another technique used to understand occupant behaviour in fire is the consideration of the following three elements [87]: occupant characteristics, building characteristics and the fire characteristics. Occupant characteristics are vital in predicting their likely response to a fire and hence their likely egress. Factors such as age and mobility will affect the speed of movement. Gender is a strong characteristic in predicting response in a residential fire, as it has been reported by Proulx [87] that men are more likely to fight the fire and women are more likely to call the fire department. Occupants with past experience or training in fire evacuations obviously behave differently [87].

In building regulations and codes, buildings are classified by their purpose. It cannot be assumed that occupants in different buildings such as a cinema, museum or airport all of which are classified assembly building will respond to a fire in the same behavioural manner. Each of these buildings has different architectural features, some more complex than others. It is important to consider the overall building layout and design to predict occupant movement [87]. The third element is the fire characteristics, which obviously has a huge impact on occupant response. The smell of smoke or the sight of flames can be the different cues perceived by occupants. The sight of flames will initiate a different response to the smell of smoke [87].

2.7 Movement Characteristics

It is essential to be able to predict occupant response time. It is estimated using three fundamental characteristics: density, speed and flow. Density is the number of persons occupying a unit of floor area (person/m^2) [22]. Speed is simply the speed of travel covered in a unit of time (e.g. 1.0m^2/s). Flow is the number of people passing a given point in a unit of time (e.g. 2.0 persons/s). The three characteristics are related by the following equation [84]:

Flow= Speed x Density x Width Equation (1)

Occupant movement depends on the space available between occupants. When density is measured less than 0.5 persons/m^2 people are able to move along walkways at about 1.25m/s. At greater densities the speed of movement decreases to a shuffling speed with a possible standstill e.g. density at 4 persons/m^2 . The main factors that determine the speed of movement of a crowd are likely to be the occupant characteristics such as age. At low densities the main factors that determine speed are likely to be occupant profile, knowledge and experience and grouping. For example, a family group is likely to move at the speed of its slowest member, being a child or a senior person [90].

The speed of movement on stairs is lower. At low densities, able bodied persons can average a speed of 1.1m/s along a stair slope in comparison to a horizontal speed of 0.8m/s. In an office building the optimum flow conditions observed on a 1120mm wide escape stairs are as follows [90]:

1) Each person would occupy slightly less than two treads,

2) There would be a descent of one store every 15 seconds and,

3) One person per second would pass a fixed point [90].

Fruin [35] used six levels of service (A-F) for walkways, stairways, and queuing. The highest standard with the least chance of congestion is Level A. Level F provides the lowest likelihood of congestion [90]. It is important to distinguish flow time from the movement time. The flow time is the time taken for people to pass through one part of the egress route. The movement time is the time taken to go from a point of origin to a remote place of safety. Evacuation time is more difficult to control and predict than flow time [90]. The total evacuation time has two phases, the 'time to start' phase also known as the pre-movement time and the 'movement' phase, the time required to travel to a place of safety.

It cannot be assumed that occupants in a building will immediately start to evacuate upon hearing a fire alarm signal. Even with the perception of smoke, occupants are reluctant to start evacuation. The pre-movement time and is broken down into recognition and response time [73]. The pre–movement time can be studied in two ways, during evacuation drills and interview studies [88]. Proulx [84] studied two high-rise apartment building fires in Canada, where six fatalities occurred in the stairwells in one building and one fatality in the room of origin in the other building. The high- rise apartment building fire with six fatalities occurred at night in the winter time. It was reported in the occupant accounts of the incident that the fire alarms were not audible in many of the apartments and evacuees were notified about the fire by others. Occupants who attempted to evacuate estimated their time to start evacuation at 10 to 30 min. The occupants of the second building heard the fire alarm as there was a sounder in each of the apartments. Occupants reported they waited for instructions from the voice communication system and estimated that they took 5 minutes before starting to evacuate after receiving the evacuation order.

Sekizawa [104] carried out a research survey and an analysis of 77 respondents from occupants of a twenty-storey apartment building fire, which occurred in Hiroshima City, Japan in 1996. The fire started on the ninth floor apartment and spread to the 20^{th} floor within 30 minutes through the balconies via external flame spread. Seventy two percent of respondents were 60 years and over, and the gender split was 1:3 males to females. At the time of the fire 40% were watching TV. Only 10% perceived the fire from the fire alarm sounding, while for 26% it was the siren of fire engines and 55% were notified by neighbours. Most were very slow to begin evacuation. In this fire 47% used the elevators to evacuate, 42% the stairs and 7% a combination of both.

Gwynne [44] conducted an unannounced evacuation of a university facility. It was found that the pre-movement times ranged from approximately 10 to 200 seconds. Fifty four percent of individuals carried out two actions prior to commencing to evacuate, 28% completed one or no actions and 18% completed three or more. The range of pre-movement actions found included; immediate evacuation etc.

It was found that the student population required staff prompting before they commenced evacuation therefore, the pre-movement time for the students was dependent on the time taken for the staff to notify the students. Shields et al [110] conducted an unannounced evacuation drill of a Marks & Spencer's retail store. The evacuation drill used video cameras to record the behaviour and movement of the customers and staff. It was observed that the floor staff responded fast to the fire alarm by prompting the customer's movement to evacuate. The staff switched from regular business to evacuation mode, shut down tills within almost 30 seconds and directed customers towards their nearest exits. The average time for the customers to start evacuation was 25s to 55s. The efficient and effective staff response to the fire alarm resulted in the evacuation of 500 customers in two minutes.

2.8 Occupant and Building Characteristics

Occupants require to be able to evacuate a building before untenability occurs. On activation of a fire alarm, there should be adequate time for occupants to reach a safe place of refuge before untenability occurs. If a time delay to start evacuation occurs then the overall available time to escape decreases. A key strategy of reducing the time delay to start evacuation is by delivering to the occupants the information about the emergency as early as possible to initiate movement. Following and alarm activation movement can be prompted by voice communication messages, staff instruction or a change in environment. A number of such characteristics that could have an impact on the time delay to start evacuation have been identified and discussed in BS DD240 [91]. The most salient building and occupant characteristics are as follows [90]:

2.8.1 Types of Warning System

The fire alarm signal is the most common warning system however; the signal can sometimes be the least effective due to false alarms, test alarms and fire drills. Voice communication systems with informative live messages can prompt a fast response. The voice communication system used in conjunction with a closed-circuit TV would assist an officer to provide precise information of the information regarding fire threat and instructions for evacuation to the occupants.

2.8.2 Building Layout and Wayfinding

For fast efficient evacuation, it is vital a building has well planned way-finding system. If wayfinding is poor in a building, the occupants will spend more time trying to obtain information on appropriate exit routes. In most cases, escape routes are located in an area that is not in everyday use therefore proper escape signage necessary [73].

2.8.3 Visual Access

Some buildings such as open plan offices provide visual access to occupants who can observe the behaviour of others. This can be an important source of information and can improve the perceptions of cues for many occupants. The location of the nearest exit and the installation of strobe lights are also effective means of visual access.

2.8.4 Focal Point

Focal point relates to buildings such as cinemas, theatres and nightclubs where occupants focus their attention to the screen and stage. To stop the focal point in these types of environments, the lights should resume, music should be turned off to turn the occupant's attention to the fire situation.

2.8.5 Training

It is mostly institutions, schools, universities and some work places that provide evacuation training to their staff. Training is an effective part of an efficient rapid evacuation, which was observed in the previously discussed evacuation study conducted by shields et al [110]. The response time of occupants can greatly depend on the occupant's status within the building and the behaviour and instruction given by the staff and wardens therefore, it is crucial that training is provided to staff and wardens.

2.8.6 Frequency of False Alarms

The frequency of false alarms in a building can greatly influence the pre-movement time. A fire alarm will not always initiate a fast response for evacuation movement, however, the fire alarm is still a good way to warn or alert the occupants of the fire situation. It is important to minimise the likelihood of false alarms to prevent delays in time to start movement.

2.8.7 Familiarity

Familiarity and experience with the building can have a major impact on an occupant's choice of evacuation route. People who work in a building and who have been trained with evacuation drills are familiar with the emergency exits therefore they are more likely to start evacuation rapidly.

2.8.8 Responsibility

Occupants of a single-family house are more likely to respond immediately to a smoke alarm because they know they are responsible for it. In public building or some places of work occupants or visitors don't feel responsible if the fire alarms sounds. They wait for instruction from a member of staff. For example in a hotel, a non-staff member may lack a sense of responsibility for the building and its system and may not respond to the alarm. In a store customers are unlikely to be familiar with the building and its systems and if not directly threatened will continue with shopping activity and ignore responsibility [20].

2.8.9 Social affiliation

Occupants who emotional ties with e.g. a family member may attempt to gather as a family group. This may take time especially if the members are not all together as a group at the start of the fire incident.

2.8.10 Alertness and Limitation

The degree of alertness among occupants depends on the type of building occupancy. In a hotel or a residential building the occupants require a longer time to respond to a fire alarm as they may be asleep. The limitations of occupants may vary and will extend the response time. These limitations could be physical, intellectual, and perceptual and could be due to the consumption of alcohol or drugs.

2.9 Calculating Movement Time

In general, when designing for life safety the aim is to ensure that the required safe egress time (RSET) is shorter than the available safe egress time (ASET) [74]. Occupants should be able to leave a building or part of a building to a safe place before untenable conditions occur. The inhalation of smoke and toxic gases can impair movement, and may cause incapacitation. The (RSET) time line is subdivided into a number of intervals (74):

$$RSET = t_d + t_a + t_o + t_i + t_e \qquad \text{Equation (2)}$$

Where t_d is the detection time from ignition to detection; t_a time from detection to notification of the occupants of a fire occurrence; t_o is the time from notification until occupants decide to take action; t_i is the time from decision to take action until evacuation starts and t_e is the time from the start of evacuation until it is completed. Time interval t_d

the detection time from ignition and t_a the time from detection to notifying the occupants are influenced by fire detection and alarm characteristics therefore these values would be a constant for different fire scenarios.

$$t_e = t_p + t_m \qquad \text{Equation (3)}$$

The time to escape is defined as the sum of the pre-movement time and the movement time as shown in equation 3.

2.10 Elements of Movement Time

Milinskii (9), Fruin (8), and Pauls (10) developed compatible methods for predicting the flow of movement of groups of occupants in emergencies. The methods established are based on the speed of movement and the population density of the groups of occupants. These methods assume that (74);

1. All persons will evacuate at the same time,
2. Occupant flow will not involve any interruptions caused by decisions of the individuals involved.
3. All or most of the persons involved are free of disabilities that would significantly impede their ability to keep up with the movement of a group."(74).

The approach is often referred to as a hydraulic model of emergency egress and is termed modelled evacuation time (74). Actual evacuation is the time required for the occupants to leave a building and will exceed the modelled evacuation time. The difference between modelled evacuation time and actual evacuation time can be expressed in terms of an apparent evacuation efficiency using the relationship (74).

$$t_e = t_{me} e \qquad \text{Equation (4)}$$

Where t_{me} is the modelled evacuation time in seconds and e is the apparent evacuation efficiency, which is a function of elements that interfere with the assumed hydraulic evacuation flow. Typical examples of efficiency elements, which can reduce evacuation efficiency, are:

1. Delays caused by egress management activities of wardens or others directing the evacuation,
2. Time delays involved in stopping and restarting of flows at merging points,
3. Delays, self-instituted by individuals that retard their start or slow their progress and,
4. Inefficient balance in the use of exit facilities, where some emergency routes are overtaxed while others are underutilized (74).

2.11 Horizontal Movement

As mentioned previously a number of researchers have carried out work on crowd movement research (refer to section 2.7). Fruin (35) studied the flow of pedestrians, which included the size, and shape of occupants' bodies, queuing, and the flow speed in relation to escape route widths in estimating speed of movement on horizontal terrains and on stairs. Fruin generated levels of service (A-F) for walkways, stairways, and queuing (refer to section 2.7).

Based on the work of Fruin (35), Predtechenskii and Milinskii (82) and Pauls (81) MacLennan and Nelson (74) produced a descriptive system of movement. In their work they calculated a "region of interest" within population densities of 0.54 persons/m^2 and 3.8 persons/m^2. When the population density was less than 0.54 persons/m^2 people could maintain a speed of movement determined by their physical capability however, when the population density was above 3.8 persons/m^2, movement would cease.

2.12 Movement on Stairs

Due to the physical dimensions involved in stairways, movement is more difficult than on a horizontal surface. Dimensions such as the angle of the stair, the height of the risers, the depth of the treads and the location of handrails all have a significant effect on the occupant's speed of movement. Population densities change between a room/space to a stair enclosure, which may result in bottlenecks. The occurrence of merging between the occupants on the stairs and the floors entering the stairs below also have an impact on the speed of movement on the stairs (74).

Fruin [35] examined the movement of 700 people across an indoor stairway with the following dimensions; 177.8mm riser, 285.75mm tread and pitch of 32 degrees and an outdoor stairway with the following dimensions; 152.4 mm riser, 304.8mm tread and a pitch of 27 degrees. The following results were generated by the studies: the outdoor stair achieved the fastest speeds, the lower risers in the outdoor stair achieves higher speeds also on both the incline and decline movement and it also showed that males were always faster than females. Fruin also produced a level of service for stairwells, which assumes that the occupant speed is dependent on population density.

Pauls (74) claimed that people keep personal space between each other and argued that people move shoulder to shoulder. Pauls further developed the "*edge gap*" into an effective width model. He carried out twenty-nine drill evacuations of tall buildings where he calculated the flow rates on stairways incorporating the edge effect as being 300mm. He found that a population density of 0.5p/m^2 achieved a horizontal movement of 1.25m/s and a stair movement of 1.1m/s which is the same as 0.8 m/s horizontal movement. Pauls (74) calculated the optimal density, speed and flow rate to be 2.0 p/m^2, a speed of 0.5 m/s on stairs and a flow of 1.18 p/m.s of effective stair width. If the density grew to a rate of four and five p/m^2 then little or no movement would occur.

The effective width developed by Pauls [74], 'We', takes into account the lateral swaying of people during movement through an exit route. It is the clear width of the exit route less the boundary layers [74]. The clear width is measured from wall to wall. Once the edge effects are subtracted from the boundary, e.g. in a stairway, 150mm is taken from each wall boundary and 90mm in from each handrail centreline.

2.12.1 Calculating Travel Speed

The travel speed on level or ramped areas, where the population density is less than 0.54 persons/m^2, has been estimated as 1.2 m/s. Where the population density exceeds 3.8 persons/m^2 movement is likely to cease. Speed of travel on a horizontal surface can be calculated as follows [74]:

$$S = k - akD \qquad \text{Equation (5)}$$

Where:

S= speed along the line of travel (m/s);

D = density (persons/m^2);

k = constant depending on size of riser and tread;

a = 0.266 for speed in m/s and density in persons/m^2.

Where k is a constant dependent on the type of terrain, for corridors, ramps and doorways it is 1.4 and a = 0.266.

The maximum speed of travel on stairways will depend on the population density and the stairway tread and riser dimensions. It is calculated as follows [74]:

$$S_t = k\,(1.0 - 0.266\ D_{tread}) \qquad \text{Equation (6)}$$

Where S_t is the speed of travel (m/s), k is a constant for evacuation speed obtained from table 3-14.2 (4), and Dtread is the population density on treads (persons/m^2). Paul's data compiled a number of studies [74] of uncontrolled total evacuations of tall buildings.

2.13 Evacuation Studies

Chow [23] carried out a study on an evacuation in a super tall (72 storeys) residential complex in Hong Kong. The lower seven levels were shopping malls and car parks. Using empirical equations for crowd movement along staircases to calculate the total evacuation time, Chow [23] found that the evacuation time for the 65 levels of residential could not be faster than 24 minutes even under a low occupant loading. The shopping mall required 20 minutes for evacuation. According to chow [23], these times are not acceptable for evacuation and argues that full simultaneous evacuation is favourable to the public over phased evacuation especially after the World Trade Centre incident. This would require more staircases to be provided to these super tall buildings. Chow [23] recommended appropriate fire safety management and training to the staff in the mall on how to evacuate occupants.

Pauls [90] began by observing as many evacuation drills as possible in tall office buildings, being careful to record many aspects of each exercise in detail, and then developing relations that best described what was actually observed. Altogether 29 drills were observed in buildings ranging from eight to 21 stories traditional uncontrolled total evacuation procedures were used.

In 1995, Proulx [84] designed an experiment to observe evacuation time and occupant movement in four apartment buildings using video cameras located throughout the buildings. The buildings were characterized as mixed occupancy housing, as they included seniors, children and people with disabilities. The 6-7 storey high buildings comprised of between 80 and 130 apartments and accommodated an average of 150 occupants. The buildings were located in four different cities to study the different evacuation strategies used by local fire departments. The results were analyzed regarding the behaviour of the people, the occupant's time to start to evacuate and the occupant's total time to evacuate and reach a place of safety. The results found that the time to evacuate related back to the time to start evacuation (the pre-movement time), occupants who started late had a longer evacuation time. The time delay to start evacuation was due to various pre-movement actions observed in the different buildings.

The observations also showed that there were few significant time differences between the age groups of the occupants. In two of the buildings Proulx [84] reports that the seniors moved faster in starting their evacuation but when they reached the corridors and stairs they moved slower, however, they still reached safety in approximately the same average time as the other age groups. It was also found that occupants who moved in groups were slower due to the movement being formed by the slowest member of the group i.e. a young child, or an elderly senior.

2.14 Merging and Deference Behaviour

While observing evacuations of high-rise buildings, it is common for researchers to find the occurrence of deference behaviour on the stair-floor landing [72]. Deference behaviour occurs during the merging of the incoming stair flow from higher floors above merging with the floor flow entering into the staircase. It describes how the occupants of the stair flow who are already on the stair give way to the occupants entering the stairwell from their floor and vice versa. Many studies have been carried out on the evacuation from high-rise buildings and human behaviour while evacuating [74, 90], however little work has been carried out to date on the type of human behaviour that occurs on stairs during an evacuation.

Merging plays an important factor during evacuation as it can dictate the speed of movement on the stairs and hence can control the speed at which a floor can empty into a stair. Deference behaviour can have a negative or positive impact on the overall evacuation of a building. Its occurrence can dictate how an evacuation will unfold. MacLennan [74] has observed from evacuation drills a significant amount of disturbance of the continuity of flow when one flow stopped and another started at a merging region. Merging is more efficient when an exit route is utilized to complete capacity. In evacuations, however, there is normally the sharing of access at merging regions resulting in breaks in the egress flow causing a significant impact on capacity. The merging process and subsequent deference behaviour of the occupants frequently occurs in evacuating high-rise buildings. Building codes base stair and exit widths on the estimated occupancy loading for a floor regardless of the entire building population. These widths are also based on phased evacuation procedures [127]. If simultaneous evacuation were employed then congestion would occur on each floor at the staircase entry points. Observational studies on evacuation drills have given researchers a realistic approach to help create a better understanding of the factors, which can impede efficient evacuation from high-rise buildings.

To date some degree of work has been conducted in the area of merging and its subsequent occupant behaviour. Takeichi et al [116] conducted experiments to identify the impact of merging in a staircase during an evacuation and the effects of merging in relation to various crowd densities, direction of merge and whether the door joining a hallway to a staircase was opened or closed. The relationship between the ease of merging and the staircase population density demonstrated that merging is easier when the density is lower. When the density on the stairs increased, the floor flow rate onto the landing decreased. When the door entering the landing was located adjacent to the incoming stair the floor flow rate was greater than when the door was located opposite to the incoming stair flow. It was found that when merging occurred the flow opposing stair traffic was about 15-20% lower than the flow when merging occurs in the same direction as the stair flow. Another experiment revealed that the floor flow rate entering the landing was 30% lower than when the door is initially opened therefore, Takeichi et al [116] reports that it is easier to merge when the door is initially open. The experiments only involved twenty-seven test subjects and gave only short periods of merging. However, the results of the experiments demonstrated that the geometrical layout of the stair –floor interface and the density of the stair flow were significant in understanding the merging process. A modelled study by Galea et al [37] found that the speed at which a floor can be emptied onto a stair can be improved by connecting the floor to the landing adjacent to the incoming stair rather than opposite the stair. They reported that configuring the stairs in this way, while reducing the floor emptying time resulted in a corresponding decrease in the descent flow rate of those already on the stairs. They suggest that in high-rise buildings, floors should be connected to the landing on the opposite side to the incoming stair. They also noted that experimental data is required to verify modelling predictions in this area.

Pauls [90] outlined that he observed merging and deference behaviour in a number of early Canadian evacuation studies in the 1960s and 1970s where a 2:1 merging ratio was found. He noted that this type of behaviour could drastically affect the ability of evacuees from more endangered upper floors from getting away from a fire. He highlights that the occurrence of the merging process and deference behaviour warrants careful attention. Once more, Pauls [80] found the occurrence of deference behaviour where the occupants from the stair flow met with the floor flow occupants attempting to enter the exit stairs. He discovered that the stair flow deferred to the floor flow on many occasions. Not only did this behaviour lead to a shuffling speed but more importantly to complete stoppages increasing the evacuation time of the occupants in the higher floors above and for the occupants who are already in the stairs. Boyce [9] presented results of three evacuation studies where she investigated merging flows and behaviour on stairs. The findings showed evidence of different merge patterns throughout the merge periods in each evacuation study. The study also highlighted the potential impact of the location of the floor entrances relative to the stair, door and stair widths and population characteristics on merge patterns. Boyce [9] suggested a need for repeated studies in a range of occupancies to investigate a number of variables that can affect merging.

2.15 Computer Evacuation Modelling

Crowd movement has been of interest across a number of disciplines especially fire safety engineering and it is an essential design feature in providing a safe environment. Evacuation models are both an important means of calculating crowd movement and the evaluation of building design. Mathematical modelling is used to predict the number of evacuation routes available within a building and in the identification of the flow of occupants through these routes.

Computer evacuation models provide a more realistic and possibly a more reliable calculation than traditional hand calculation methods. They provide a visual representation of the evacuation process. The calculation methods in the SFPE handbook only focus on the elements of the construction throughout the building and calculate the flow time of occupants to pass a point. i.e. calculating the time, it takes the occupants to travel from a point inside the building to the exit (outside) [64]. The use of computer evacuation models achieves a more realistic calculation of the evacuation process through a building. There are currently a wide range of evacuation models available, which differ in complexity and have their own unique capabilities [45]. Another benefit from using these models over recent years is the amount of time saved. Prior to computer evacuation models, designers would allocate significant time in performing tedious engineering hand calculations to assess a life safety design.

2.16 Development

For over thirty years, crowd movement and human behavior have been modeled. Predtechenskii and Milinksii [82] and Fruin [35] carried out early studies on the movement of people in non-emergency conditions. Computer evacuation modeling is one of the important means of investigating an evacuation from a building [124]. Evacuation modeling falls into two categories; Ball Bearing Models (movement models) and Movement and Behavior Models. Ball Bearing Models assume that people will evacuate immediately and treat the occupants as unthinking objects. The direction and speed of evacuation is determined by population densities and exit capacity, etc. In contrast, Movement Models consider physical characteristics of the enclosure, and treat the occupant as an active agent who will respond to stimuli such as fire hazards, exit preference and individual behaviour. The Movement Models have been developed based on human behavior research and crowd movement studies [45].

2.17 Types of Evacuation Models

A number of reviews of evacuation models have been carried out, one of the more recent carried out by Santos and Benignos [101] where they conducted a critical review of evacuation simulation models identifying their capabilities and limitations from the perspective of human evacuation behaviour. Kuligowski [64] in 2004 conducted a review on twenty-eight of egress models, which were classified by their level of sophistication. Gwynne [45] classified twenty-two evacuation models based on optimization, simulation and risk assessment. Kuligwski's [64] review provides information on the purpose, availability, modeling method, model structure and perspective, methods for simulating movement and behavior, output, use of fire data use of visualization and AutoCAD drawings of twenty-eight models. The review categorized the models based on their level of sophistication in the following order, Movement Models, Partial Behavioral Models and Behavioral Models. The results found in the models of each of the three categories vary. Kuligwski's [64] review may prove very useful in picking an appropriate model for a specific project.

2.17.1 Movement Models

Movement models concentrate solely on the movement of occupants travelling from one element e.g. one room in the building to another room [64]. The output from this type of model includes the total evacuation time, the flow through openings and the location of bottlenecks. There are two methods used in computer models to represent the enclosure of where the evacuation takes place. They are the fine and the coarse networks. The structure of Movement models are represented by a coarse network and use a global perspective of occupants. Examples of this type of model include WAYOUT [119] and STEPS [115].

2.17.2 Partial Behavioural Models

Partial behavioural models predominantly calculate crowd movement through a building but can also simulate an occupant's behaviour [64].These models combine a coarse and fine network to represent the structure. In addition, they use a combination of global and individual perspectives to view the occupants. The user inputs the occupant's characteristics, pre-evacuation times, etc. order to relate the effect of Human Behavior during an evacuation. Examples of this type of model are EXIT89 [32] and GridFlow [4].

2.17.3 Behavioural Models

The behavioural type models are identified as the most advanced type of evacuation model using a more sophisticated simulation technique. Several of these models can include occupant decision making and the actions of occupants during an evacuation [64]. The structure of the model is represented by a combination of fine and continuous network and incorporates an individual perspective of the occupants [77]. Evaluating the probability of a particular action being performed by occupants can be carried out. Examples of this type of model are buildingEXODUS [46, 47, 50, 51].

2.18 The Structure of Computer Evacuation Models.

There are two methods used in computer models to represent the enclosure of where the evacuation takes place. They are the fine and the coarse networks [64]. The floor space is divided into sub regions with each sub region connected to its neighbours. The nodes, which make up the space available to an occupant, make it possible to accurately represent the geometry and any obstacles present [64]. It also enables accurate location of each individual at any time during the evacuation. In a fine network arrangement, the entire floor space of an enclosure is covered in tiles and nodes. Some examples of models that use this network are Simulex 0.2 m x 0.2m square nodes and Exodus 0.5 m x 0.5m square nodes [45]. Each node can represent a room or a corridor. A model that incorporates a coarse network allows the occupants to move from room to room rather than from one area inside a room to another. Therefore, the exact position or location of an occupant cannot be represented [45]. Fine networks better represent an enclosure more than a coarse networks.

Similar to the representation of the enclosure the population is represented in two approaches: an individual and a global perspective [64]. The model user inputs the personal attributes into the model. These attributes are used in the measurement of movement and decision making of that individual. This process allows the model to represent a diverse population. The global perspective represents a group of occupants during an evacuation. Rather than distinguishing the individual, they form a homogeneous group excluding different characteristics [45]. This approach lacks the representation of the relationship between an occupant and the effects of toxic gases during an evacuation.

Human behaviour is complex to simulate in a computer evacuation model. Many models have attempted to include a number of aspects of human behaviour. As a result, models have been separated into five behavioural systems [64, 45]:

1. No Behavioural Rules.
2. Functional Analogy Behaviour.
3. Implicit Behaviour.
4. Rule Based Behavioural System.
5. Artificial Intelligence Based Behavioural System.

2.18.1 No Behavioural Rules

The models that fall under this category do not apply behavioural rules and concentrate solely on the physical movement of the population and the physical representation of the geometry for example EVACNET [64].

2.18.2 Functional Analogy Behaviour

The models in this category use a series of equations to control the response of the entire population. It is possible to represent the population as individuals however; all the individuals are still affected in the same deterministic manner [45]. An example of this type of model is the Takahashi Model [64]. The Takahashi model regards the occupants as a homogeneous liquid employing the hydraulic approach and assumes an egress constant speed throughout the evacuation.

2.18.3 Implicit Behaviour

These models represent behavioural rules using complicated physical methods. Many of these models such as EXIT89 [32] and WAYOUT [119] are based on the input of secondary data featuring psychological and sociological influences and rely on the validity and accuracy of the secondary data [45].

2.18.4 Rule Based Behavioural System

A rule based behavioural system such as buildingEXODUS [46, 47] allows the model to take the decision for the occupants based on a pre-defined set of rules. The pre-defined rules can be activated at a specific situation. There are three types of interactions during an evacuation they are [45]:

- people-people i.e. interaction with other occupants,
- people-structure i.e. interaction with the enclosing structure and
- People- environment i.e. interaction with fire effected atmosphere.

These interactions may take place on psychological, sociological and physiological levels. Several models have attempted to incorporate all the behavioural interactions however; no model fully addresses all types of interactions [45].

2.18.5 Artificial Intelligence Based Behavioural System

This type of system involves the individual occupant mimicking human intelligence in relation to the enclosure. This system has been incorporated into some behavioural models such as EGRESS [64] and VEGAS [64]. It provides a more precise representation of the decision making process however, a disadvantage of this type of system is that it takes away an element of the user control.

2.19 Validating Computer Evacuation Models

Validation of computer models is carried out to challenge the capabilities of the model .A limitation of computer evacuation models is the lack of experimental data to aid in the validation of these models [50]. The predictions of an evacuation model rely predominantly on the data inputted into the model.

"No degree of successful validation will prove an evacuation model correct however confidence in technique is established the more frequently it is shown to be correct in a wide range of applications", Galea, E.R [38], 1998 p. 415.

There are four forms of validation that an evacuation model should undergo. They are:

- Component testing to ensure that the component performs as intended i.e. can an occupant travel 10m in 5 seconds if their travel speed is 2m/s [38,50].
- Functional validation to investigate whether a model has the ability to exhibit the range of capabilities required i.e. compliance with prescriptive building codes. Functional validation investigates whether a model has the ability to exhibit the range of capabilities required for example compliance with prescriptive code. Functional validation is required to set out in a comprehensible manner providing

a full range of model capabilities, inherent assumptions and provide a guide for the correct application of these capabilities. In addition, all the information should be available in a technical manual [38, 50].

- Qualitative validation is performed to demonstrate that capabilities of the model perform accordingly and produce realistic patterns and results. It examines whether the behavioural capabilities of the model are capably of outputting realistic behaviours [38, 50].
- Quantitative validation compares the model predictions with reliable experimental data and demonstrates that the model is capable of reproducing measured behaviour. There are two main types of quantitative validation; the use of historic data where the model developer has the knowledge of the experimental results, and blind predications where the developer has no access to results prior to performing predictions [38, 50]. *"It should not be considered as a once and forgotten task and should be dealt with in a systematic and graduated approach"* , Galea[38] 1998, p. 414.

A limitation with computer evacuation modeling as stated in several studies is the lack of suitable evacuation data available. Evacuation data is required in particular to assist in further validation of the current computer evacuation models.

2.20 Examples of Evacuation Models

There are many computer evacuation models currently available and they all vary in complexity. The following section provides a description of two types of computer evacuation models that claim to have the ability to predict merging and deference behaviour.

2.20.1 GridFlow

GridFlow is a partial behaviour model, which calculates egress times by representing individual occupants in building spaces on a grid network [4]. The model combines the pre-movement and movement behaviour for a performance based design. The model relies on the density of the population to control the movement of the population and uses pre-movement times distribution observed by Purser [4]. The occupants are labeled with FED[1] susceptibility and their travel speeds are affected according to the FIC[2] due to irritant smoke, as defined by the user. The structure of the model is based on a continuous space using a fine network approach. The distance map is made up of 0.5 by 0.5m grid cells. Each individual or group can have a set of characteristics such as xy coordinates of each occupant in time with the simulation, starting position in the simulation, destination and exit, pre-movement time, unimpeded walking speed and FED susceptibility. The occupants move toward the exits under the constraints of the Nelson and Mowrer chapter of the SFPE handbook [74].

[1] : Fractional Effective Dose.
[2] : Fractional Irritant Concentration.

The individual movement is represented either in 2-D or in 3-D. Grid flow offers multiple options for how merging flows are simulated. GridFlow uses two methods to simulate merging flow. The first option is the free flow option where the flows are controlled by the personal movement algorithms. The second option called the controlled flow option applies rules to deal with the competition between flows. The two inlet flows on a stair, the stair flow and the floor flow reach full capacity the model will balance the outlet flow to a shared 50:50 merge ratio between the two flows [64].

The output from this model includes details about the population at every logging interval after each simulation run. The output data can be exported from the model into an Excel spreadsheet. AutoCAD drawings can be imported into the model however; the floor plan can be drawn within Grid Flow using a graphical user interface (GUI). The user specifies the links on the floor plan that lead to outside or another space within the building and is prompted to input the width of the link and the maximum flow through the link. A special feature of this model is its ability of simulating counter flow, manual exit blocks and obstacles, fire conditions that affect behaviour and the ability to define groups [64].

GridFlow has undergone many simulation runs of various buildings for the purpose of validation. The validation process consists of component testing, functional validation, qualitative testing, and quantitative verification. Within this computer model, human behaviour has also been validated by using movement data to simulate a scenario and comparing the model's evacuation behaviour and time to the observed evacuation and SFPE Handbook data [74].

2.20.2 BuildingEXODUS

BuildingEXODUS is a behavioural model, which simulates the evacuation of large numbers of people in a range of different enclosures [64]. The model is made up of five interacting sub models; occupant, behaviour, movement, toxicity and hazard sub models. The sub models share different attribute values. Each sub model relates to another submodel e.g., the movement model controls the movement of individual occupants from their current location to their destination. Input both from the occupant and behaviour sub models is required in order for the movement model to function. The behaviour sub model determines the occupant's response to a particular situation based on the individuals personal attributes and in turn transfers the decision to the movement sub model. BuildingExodus is a fine network system where the spatial set up is spanned by a two dimensional spatial grid mapping out exits, internal compartments and obstacles. Each floor is allocated a separate window for analysis purposes during execution of the simulation. A series of 0.5m x 0.5m nodes are input. The nodes may also be numbered as a function of proximity to exits. Each occupant is assigned a node and only one occupant can occupy a node at a time. Arcs connect the nodes together on the floor and Individuals use the arcs that connect the nodes together to travel from node to node throughout the building [77].

The model has undergone many forms of qualitative and quantitative validation studies. However, most of the studies have been carried out on Air Exodus [50]. The developers state that air exodus and Building exodus are based onto the same principles. The validation of Air Exodus was based on the comparison of model results and experimental data [51].

2.21 Predicting Merging and Deference Behaviour

There is a limited amount of research on how the merging process and deference behaviour on stairs can be represented using computer evacuation models. The merging process and deference behaviour can have a huge impact on the evacuation of a building. It is therefore important that the merging process and deference behaviour be satisfactorily represented in current computer evacuation modeling software [37]

Purser [96] examined how the computer evacuation model GridFlow simulates merging behaviour on stair landings during a building evacuation. A series of experimental evacuations were carried out in five different buildings with different exit and stair widths by Boyce [9]. The experimental evacuations were carried out to obtain validation data for the simulation model focusing primarily on the maximum specific flows, occupant densities and merge ratios on stairs. The study found that the maximum exit and stair flow rates obtained in the experiments were close to what was obtained in GridFlow. The maximum densities on the stairs compared well to the grid flow simulations. The experimental data also validated the 50:50 merge ratios that were found in GridFlow. Overall GridFlow was found to give a good replication of actual evacuation flow performance [96]. The main purpose of the evacuation experiments was to obtain data on specific evacuation parameters such as the merging process on stairs and the behaviour associated with this process. In addition specific flows at storey exits and densities on stairs were also investigated. The evacuation experiments were carried out in order to provide validation data for these evacuation parameters and to examine evacuation flow dynamics in real buildings with different storey exits and stair dimensions and different building layouts.

Galea [37] carried out a study to examine how the buildingEXODUS software predicts the merging process on a stair-floor interface and compared the results with trends found in existing experimental data of evacuation drills. As explained previously (refer to section 3.7.2) only one occupant can occupy a node (space) at any one time. However, there is often a case where two or more occupants will want to occupy a specific node or space. Therefore, the model uses conflict resolution to overcome the conflict for space between two or more occupants. The conflict resolution will firstly examine the time it took each occupant to arrive at the node in question. The drive attribute of each individual competing for the space is compared. The drive attribute represents the motivation of the occupants in question to win possession of the space or node. After evaluating the drive attribute of each occupant in question the drive with the highest drive will wins the possession of the node or space. However, if the drive is too close then the winner is randomly selected [77].

Galea [37] used two numerical test cases produced by the software to examine the nature of merging on the stair floor landings. Trends found in the second study of the interaction at the floor-stair interface were compared with trends from evacuation experiments of evacuation drills such as Takeichi [116]. The stairs in the numerical test represented a dogleg stair. Within the test two stair floor configurations were examined. The first configuration consisted of the door located adjacent to the stair flow and the second test the door from the floor is located to the opposite side of the incoming stair. Four tests were carried out using the two different stair geometries and two populations. The floor population was maintained to have an average density of four people/m^2 in the corridor to provide a steady supply of people trying to enter the stairs. The stair population was set up on the upper landing of the incoming stair population made up of various drive attribute set to a random population. The study revealed that the trends found in the experimental data were predicted successfully in the computer evacuation model buildingEXODUS [37].

2.22 Conclusions

The field of human behaviour in fire has progressed over the last two decades. The first international conference on human behaviour in fire was held in 1998. Fire disasters such as the kings cross underground fire and the more recent 9/11 world trade centre disaster highlighted the need for research to continue in the area of human behaviour in fire. A good understanding of the factors that can affect occupant behaviour in a fire is crucial. The psychological, physiological and the circumstantial factors require to be understood before commencing research into human behaviour in fire. Research into human behaviour during building evacuations has been ongoing for several years. An occupant's evacuation from a building is split into two phases, a pre-movement phase and a movement phase. Several studies have been carried out on the pre-movement phase. The movement phase involves the study of horizontal movement and vertical movement i.e. the movement on stairs. Studies carried out in the past on egress behaviour focused mostly on evacuation timing and occupant movement. It is common for researchers when studying building evacuations on stairs to find the occurrence of merging and deference behaviour.

Merging plays an important factor during evacuation as it can dictate the speed of movement on the stairs and hence can control the speed at which a floor can empty into a stair. There is a limited amount of experimental data available to provide a better understanding of the area of merging and deference behaviour and how this behaviour has an impact on an overall evacuation from a high-rise building. Pauls [80] has suggested for research to be undertaken in the area of deference behaviour.

Evacuation models can predict the location of the occupants as they move through a building. Together these models can provide a better understanding of the risk that an occupant may be exposed to during a building evacuation. The models vary in complexity but they share the same requirement that they rely on observation data of evacuation drills. A review of computer evacuation models split the models into three basic categories, movement, partial behaviour and behavioural models [64]. From an evaluation of the three categories, the behavioural models are the more advanced type of evacuation model. In addition to movement, this type of model incorporates occupant decision making and the actions carried out by occupants during an evacuation. A model that falls into this category is the buildingEXODUS evacuation model. Since the behavioural perspective of the buildingEXODUS model is rule based, it allows the user to input a pre-defined set of rules. The buildingEXODUS model may have the ability to accurately represent a broad range of human behaviour activity. This can be seen in the many validation studies carried out [47, 48]. Although there have been studies carried out for validation purposes there are limited studies on the occurrence of merging and deference behaviour on stair-floor landings and how the models treats this behaviour during a simulation. Fahy [34] provided a list of research needs to enhance evacuation models one of the needs listed was as follows: *"flows on different types of stairway configurations: what do we know about the use of space on stairs… the effect of the geometry of stairs"* Fahy, R. [34] (2002) p. 62.

A limitation in relation to computer evacuation modeling as stated in several studies is the lack of suitable evacuation data available. The data is required in particular to assist in further validation of the models in relation to their ability to accurately represent the merging process and deference behaviour on a stair -floor landing during a building evacuation. To enhance the effectiveness of current computer evacuation models further research is required using data that highlights the merging process and deference behaviour [37].

The main objectives of this study are to investigate the type of evacuation behaviour that occurs on stairs during a building evacuation and examine the type of behaviour resulting from the merging process i.e. deference behaviour. The main aim of this study is to examine how can such deference behaviour be altered or managed to make sure that the most endangered occupants are given priority in their evacuation [80]. The last main objective is to investigate whether different stair geometries have an impact on evacuation behaviour. The sub-objectives of this research are as follows:

- Investigate how occupants entering the stairs merge with the occupants who are already on the stairs; who has priority and what factors influence this priority?
- Investigate the merging process and merging trends with various crowd densities, directions of merge i.e. the flows that form from the stair and floor.
- Investigate whether the floor flow rate onto the stair decreases as the stair population density increases.

- Investigate different merge points on the landing and compare their floor flow rate to determine whether the location of the merge points have an impact on the merging process.
- Investigate whether the location of the door onto the landing has an impact on the merging process and explore whether the swing of the door has an impact on the merging process and precedence between the merging flows.
- Investigate the occurrence of stoppage on lower floors and how that stoppage proceeds up the stair to higher floors.

In order to achieve this, four different buildings were used to carry out the observations of evacuation drills. They consisted of two third level institutes, one office building and one public office building. The evacuation drill carried out in the public office building was not analysed in detail for this study. On initial examination of the observations it was found the there was a lack of suitable occupant capacity on the day of the evacuation. The five drills presented and analysed in this study were carried out in two third level institutes Drills C1, C2, C3 and D1 and an office building Drill L1.

Chapter 3: Research Methodology

3.1 Introduction

The two main approaches to research are qualitative and quantitative. This chapter describes the research design and the methodology employed to undertake this study. Qualitative research is used to gain insight into people's behaviours, value systems, concerns, motivations and culture or lifestyle [100]. Qualitative research was carried out to gain key insights into human behaviour on stairs during building evacuations via observation. Qualitative research gives the researcher the opportunity to observe record and interpret non-verbal communication, which is valuable during analysis. The greatest advantage of this method is that it permits the quantification of actual behaviours rather than reports of intended behaviour. Quantitative research seeks to deductively establish facts, make predictions and test hypotheses [52].

"Quantitative analysis can be described as fundamentally an exercise in statistics, which follows a logical deductive sequence. Two approaches have been identified '(1) using descriptive statistics to obtain an understanding of your data, or (2) testing hypotheses using statistical tests." Hair et al [52], 2007, p. 308

This research includes a qualitative data collection and both qualitative and quantitative data analyses. The data collected was in the form of video recordings of fire evacuation drills in a number of buildings. The data was qualitative in that it provided information on the human behaviour of the occupants during the evacuation drills. The qualitative data was then quantified in order to obtain floor flow rates, merging ratios, stair population densities and the speed of travel on the stairs. It was essential to use a tried and tested methodology to study the evacuation drills in order to ensure the success of the study. The methodology employed was used by the NRCC[3] for a number of residential and office building evacuation drill studies [93].

The type of buildings used to carry out the observations of the evacuation drills were two third level institutes and one office building. A total of five evacuation drills were observed. Drills C1, C2, C3 and D1 were carried out in a third level institute and Drill L1 in an office building. It was difficult to obtain permission to carry out the observations of evacuation drills in a number of desirable buildings due to insurance and security reasons. The buildings used in this study were not based on purpose group and occupancy type but on successfully obtaining consent from building management to observe their planned evacuation drills. This chapter details the method employed in collecting the data, the preparation work involved in organising the evacuation drills and the methods used to analyse the data.

3.2 Data Collection

Observational studies on evacuation drills have given researchers a realistic approach to help create a better understanding of the factors, which can impede efficient evacuation from high-rise buildings [72]. This enables analysis of the behaviour of the occupants, their speed of movement and the merging process. It would be preferable to observe real

[3] NRC: National Research Council Canada

emergency situations to study human behaviour in fire however, real fire data is not freely available for analysis. The human behaviour observed during a staged experiment or a fire evacuation drill can vary depending on the level of perceived risk. Evacuation drills can only provide a partial understanding of the type of egress behaviour on a stair [37]. False alarms and real fires do occur which cause building evacuations. Whether the alarm is due to a real fire or a fire drill for an evacuee these evacuations are real and the behaviour of the occupants depends on the estimated risk. The evacuation drills were field studies where there was limited control over the subjects and the environment. It was possible to control the time of the drill and the location of the recording equipment. The purpose of the study was communicated to owners/management via email prior to the evacuations.

3.3 Preparation Work

The plans of the building were reviewed prior to each drill to determine possible locations for the cameras. This was followed by a visit to each building to finalise the position of the cameras for each drill. Measurements of the stair and landing dimensions were recorded prior to each drill in order to calculate floor flow rates and stair population densities. Necessary measurements included the height of risers, length and width of the going and the floor landing dimensions.

Figure 3.1: Camera Location.

The observation equipment employed throughout the evacuation drills varied between six Sony handy cams, four Panasonic digital cameras and ten camera brackets. Figure 3.1 shows a picture of a camera mounted in the stairwell of Building C. The use of video cameras made it possible to observe and provide information on human behaviour and crowd movement during five building evacuations. The cameras were mounted to the walls in the stairwells and positioned to be capable of viewing occupants who were entering the landing from the floor entrance, the crowd movement on the landing and the stair flow occupants entering the landing from floors above.

The positioning of the cameras varied for all three buildings due to the physical layout of the stairs and landings. Each camera and video tape was labelled before the drill. The equipment was also tested prior to each drill. The battery life of the camera was checked; the sound level of each camera and a brief recording was carried out in each stairwell involving the movement of people on the stairs prior to each evacuation drill. A checklist was employed prior to each evacuation drill to ensure that all necessary steps were carried out before commencement of each evacuation drill. The camcorder used in the recording of data was attached to a personal computer. The raw video data from the video recordings was transfered onto the computer. The connection between the camcorder and the computer was made using a fire wire connection which enabled fast transfer of data. The program employed for capturing the data was Windows Movie Maker.

The results of the evacuation analyses provided information on human behaviour on stairs, the merging process and its effects, flow rates of people through doors and on stairways, effects of crowd density and crowd movement. The conclusions drawn from the analyses have the potential to be utilized during building design stage and can provide an additional source to assist in the validation and development of current computer evacuation models. The information such as the tracking of occupants from floor to floor was input to Microsoft Excel. All details including occupant identification, age ranges and times were also input into the Microsoft Excel in order to generate results. The video tapes were viewed individually to gather resulting data in order to identify the type of human behaviour, merge ratio, flow rates, stair population densities as well as the speed of movement in the stairwell during the evacuation. The data in Excel identified the floor from which the occupants began their evacuation from and the time when they left the building including evacuation behaviour on the stairs. All cameras clocks were synchronised to prevent any discrepancy between tapes. The time at which the alarm started on each tape allowed for confirmation of consistency when calculating the evacuation times etc. The recording of observed data from the video tapes and the estimation of occupant age was carried out by the researcher only to ensure consistency as recommended by Proulx [93].

The process of deciding the age for each occupant was based on the researcher's estimation and therefore it was subjective. The categories used for this study were taken from a study by Proulx [93]. The categories are shown in Table 3.1. The age categories relevant to the four evacuation drills carried out as part of this research are highlighted.

Age Category	**Age Range**
1	1-2 years
2	3-5 years
3	6-12 years
4	**13-19 years**
5	**20-39 years**
6	**40-64 years**
7	65+ years

Table 3.1: Age categories

3.4 Building C

Building C was a 'change of use' from an apartment building to a third level institute consisting of a ground floor and four upper floors. It comprised of classrooms, workshops and relating offices. There were two stairs, one located at the front (southeast) and one at the rear (northwest). Both students and staff occupied the building. Three evacuation drills were carried out in this building, two announced and one unannounced. The evacuation drills were observed using digital video cameras and questionnaires were distributed to the evacuees. Table 3.2 gives a breakdown of Building C's characteristics. Correct positioning of cameras was crucial in order to capture the behaviour and movement of the occupants.

	Building C (Cavan)
No. of Field Tests	3
Occupancy Type	3rd Level Institute (Educational)
No. of Floors	5 Accommodated
Stair Type/Arrangement	Half turn and Dog leg
No. of Stairs	2
Location of Stairs	Front (southeast) Rear (northwest)
Evacuation Strategy Employed	Simultaneous

Table 3.2: Building Characteristics.

Building C employed a simultaneous evacuation procedure. Three evacuation drills were carried out in Building C in Cavan, Ireland, C1 unannounced, C2 announced and C3 announced. Figure 3.2 (a) shows an external picture of Building C and (b) inside one of its stairwells (southeast front stairwell).

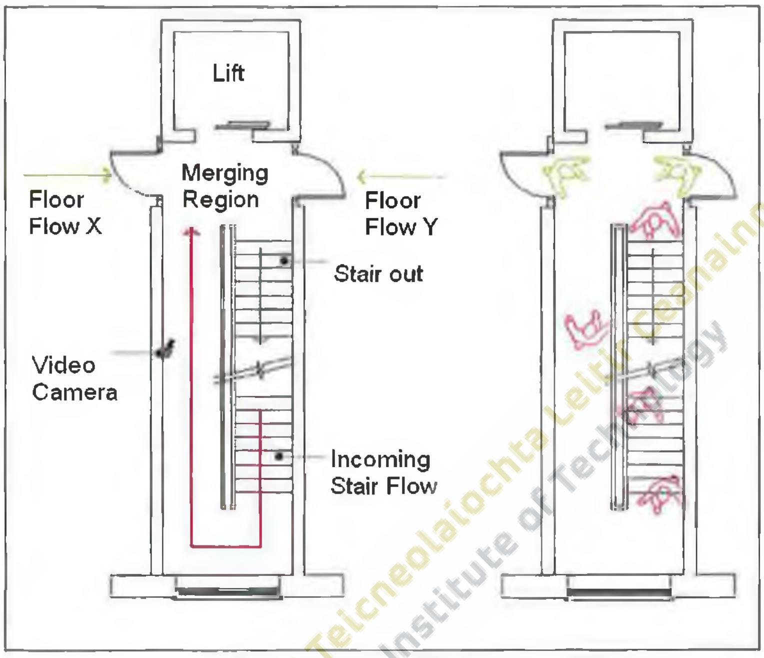
(a) Building C (b) Southeast Stairwell

Figure 3.2: Building C.

For the three evacuation drills, five cameras were mounted onto the walls in the front (southeast) stair angled appropriately to capture the movement and behaviour of the occupants as previously described. Figure 3.3 depicts a plan of the stair and floor configuration and the direction of the three flows of occupants in the stairwell. Weather conditions for all evacuation drills on the day were mild but cold.

The digital video cameras were installed and were started ten minutes before the alarm was sounded and ran continuously until the drill was completed. Wide-angle lenses were attached to the cameras to capture a wider view of the landings. Sound was also recorded through the camera, which allowed for observation of the overall atmosphere of the evacuation. The evacuation drills in Building C were conducted on Friday 13th February 2009 and 22nd March 2010. Throughout the drills, wardens were available on each floor to assist the occupants during the evacuation. The stairs to the rear (northwest) was blocked in the second and third Drills C2 and C3. The alarm sounded at 10.28 am for

Drill C1, 12.30 p.m for Drill C2 and 11.15 am for Drill C3. Upon hearing the fire alarm, the occupants were directed to the front stairs by the fire wardens on each floor.

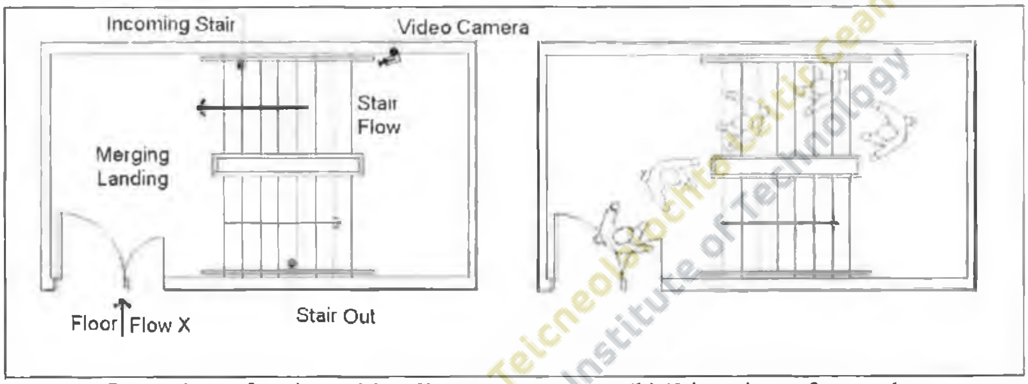


(a) Stair/Landing Configuration. (b) Crowd Flow.

Figure 3.3: Stair Configuration Building C.

3.5 Building L

Building L included two stairs one in the central core (south) and one at the rear (north) serving all floors. The occupants were the employees of the building. Eight cameras were mounted on the walls and angled to capture the movement of the occupants. Figure 3.4 (a) and (b) shows a plan view of the stair and floor configuration and the direction the two flows of crowd movement. Weather conditions on the morning of the drill were cold but dry. The cameras were installed in the north stairwell on floors, seven, nine, ten, eleven, twelve, thirteen, fourteen and floor fifteen. It was decided during the planning of the evacuation drill that only the top eight floors were to be observed due to the availability of eight cameras and brackets on the day. A camera was not mounted in the stair to observe the eight floor as it was not occupied on the day of the planned evacuation drill.



(a)Configuration of stair and landing. (b) Direction of crowd movement.

Figure 3.4: Stair Configuration Building L.

The planned evacuation procedure was as follows; the fire floor was floor nine therefore floors nine and ten evacuated immediately. After each ninety-second period, two floors at a time starting above the fire floor began to evacuate. That is, after ninety seconds floor eleven and twelve evacuated with floor fifteen and sixteen being the last floors above the fire floor to evacuate. Ninety seconds after floor, sixteen evacuated the floors below the fire floor i.e. seven and eight were then notified to evacuate. Every two floors below were notified at a ninety seconds periods with the first and ground floor being the final floors to evacuate. Again, the drill was unannounced. However, only the north stairs, see Figure

3.4, was observed by the video cameras. Unfortunately, during the course of the evacuation some occupants gained access to the second stairway. Table 3.3 gives a breakdown of Building L's characteristics.

	Building L(London)
No. of Field Tests	1
Occupancy Type	Office Staff
No. of Floors	16
Stair Type/Arrangement	Dog Leg
No. of Stairs	2
Location of Stairs	Central Core Rear (North)
Evacuation Strategy Employed	Phased

Table 3.3: Building Characteristics.

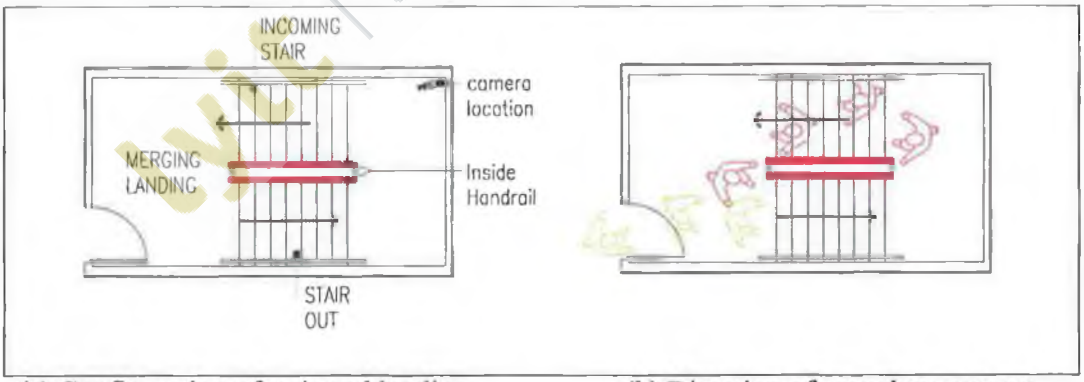
3.6 Building D

Building D is a three storey third level institute. The escape stair observed for the study was a 1.2-metre dogleg stair. The occupants were predominantly employees and students of the building however, there may have been visitors present on the day.

	Building D (Donegal)
No. of Field Tests	1
Occupancy Type	3rd Level Institute (Educational)
No. of Floors	3
Stair Type/Arrangement	Dog Leg
No. of Stairs	4
Location of Stairs	Central Core Rear (North)
Evacuation Strategy Employed	Simultaneous

Table 3.4: Building Characteristics.

Table 3.4 gives a breakdown of Building D's Characteristics. Three cameras were mounted onto the walls, one on each floor. The cameras were angled to capture the movement of the occupants. Figure 3.5 (a) and (b) shows a plan view of the stair and landing configuration and the direction of the two flows of crowd movement. i.e. the stair flow and the floor flow.



(a) Configuration of stair and landing. (b) Direction of crowd movement.

Figure 3.5: Stair Configuration Building D.

Weather conditions on the morning of the drill were cold but dry. The drill was unannounced. During Drill D1, three escape stairs were blocked making only one stair available for the occupants. This resulted in two hundred and twenty nine occupants using the stairs during the evacuation.

3.7 Data Analysis

Careful viewing of the video recordings was required to get quantitative and qualitative information on the information such as evacuation behaviour, merging ratios, flow rates, stair population density and speed of movement on stairs. Qualitative analysis was carried out to obtain information on the occurrence of evacuation behaviour on the stairs during each of the evacuation drills. Each floor was viewed individually to observe the occurrence of deference behaviour, to identify any possible trend of deference behaviour and to examine the impact of this type of behaviour on all of the building evacuation drills observed.

The use of digital video cameras made it possible to accurately calculate the speed of the occupants travelling down the stairs. It was possible to determine the time at which each occupant first appeared in the staircase and the time at which he or she reached the ground floor landing. The total time each occupant travelled within the staircase includes the time elapsed when occupants slowed down or stopped to allow newcomers into the stairwell as part of the merging process.

Drill	Average Age Category	Female %	Male %	Staff %	Students %	Apparent physical Limitations
C1	5	93	7	13	87	None
C2	5	92	8	9	91	None
C3	5	83	17	12	88	None
L1	5	82	18	All Staff	All Staff	None
D1	5	60	40	20	80	None

Table 3.5: Occupant Characteristics.

In Excel, each occupant was given an identification number. An age category was decided on using the categories in Table 3.1, the three categories used were categories 4, 5 and 6. Table 3.5 shows the percentage breakdown of female versus male occupants, staff versus students, apparent physical limitations and the average age range of the five evacuation drills.

3.8 Measurement Techniques

Flow rate is calculated as the quantity of people that pass a fixed point during an interval of time [90]. The flow rates were calculated by observing how many occupants passed a point i.e. through Floor Flow X and Floor Flow Y in Building C for an interval of time of twenty seconds. Twenty seconds was decided upon by the researcher and it was considered an adequate time to calculate this measurement. Twenty seconds allowed an adequate number of occupants to pass a point in order to calculate the flow rates. The flow rates included the flow rate through each landing entrance and the flow rate at the merge point. The stair flow rate was recorded when the occupants came of the last step onto the landing in each evacuation drill. The number of occupants that reached the landing (as they came of the last step) from the stair was recorded for an interval of time of twenty seconds as shown in Figure 3.6.

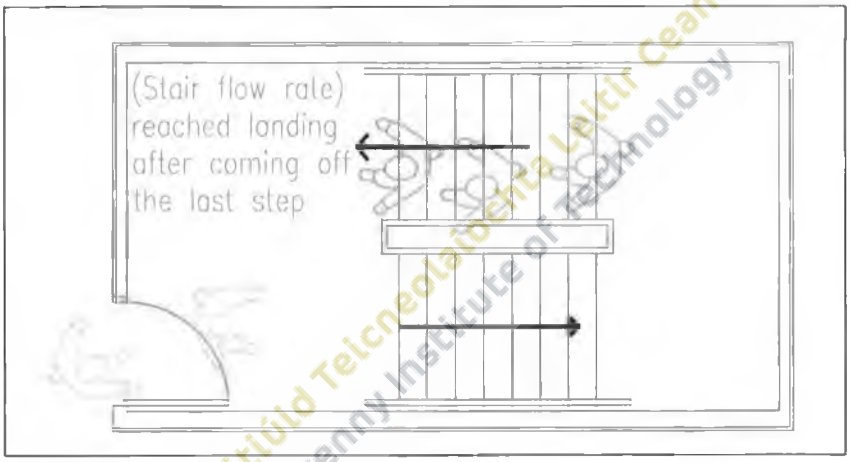


Table 3.6: Calculating the Stair Flow Rate.

Density is measure of the amount of people per unit area [90]. The stair population densities were obtained by calculating the number of occupants on the stairs and taking into account the dimensions of the stairs for an interval of twenty seconds. For example when eighteen people left the fourth floor for a time interval of twenty seconds and only ten people reached the third floor landing for the same time interval then the stair population density was eight people divided by the area of the stairs.

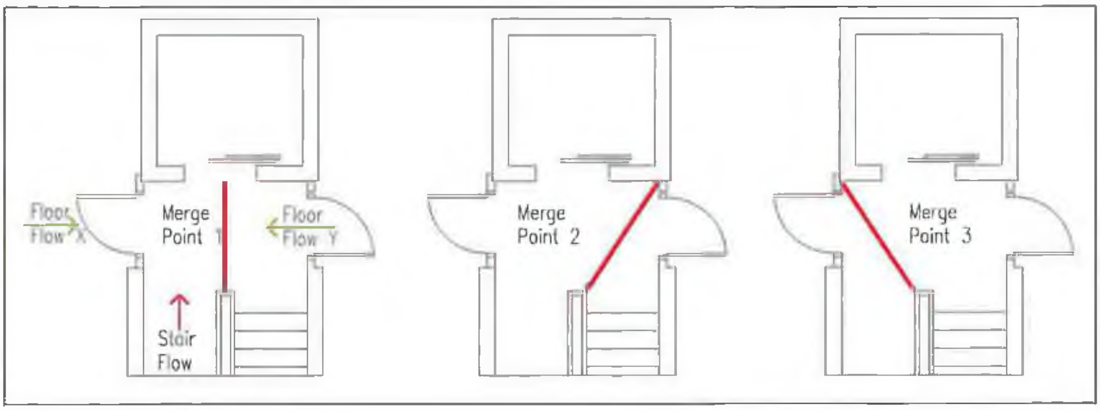


Figure 3.7: Merge points Drill C1, C2 and C3.

The merging process was quantified by calculating how many occupants passed a merge point from each flow, i.e. the floor flow and stair flow. The number of people merging from each flow was counted and ratios obtained and discussed in Chapters 4, 5 and 6. Figure 3.7 shows the three different merge points used during the evacuation drills of Building C.

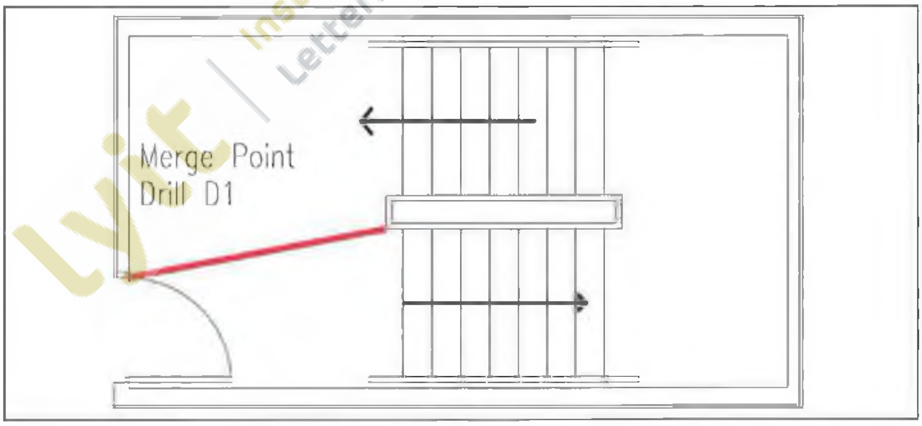


Figure 3.8: Merge Point Drill D1.

There was only one apparent merge point in Drill D1 because of the location of the entrance onto the landing on each floor. As can be seen in Figure 3.8 the entrance onto the landing is positioned opposite the outgoing stair and adjacent the incoming stair. The fact that the floor entrance was positioned directly opposite the outgoing stair allowed the occupants to move directly onto the outgoing stair without having to stop for the incoming stair flow. The merge point for this particular drill is shown in Figure 3.8.

3.9 Speed of Movement on Stairs

While viewing the video recordings it was possible to calculate the occupant's speed of travel on the stairs. The total time it took each person to travel from floor of origin to the final exit was calculated for the five evacuation drills. The time at which each occupant appeared on the stair landing was determined and the time that person reached the final exit. The movement of each occupant was observed from floor to floor including any time elapsed when the occupants stopped due to delay times because of deference behaviour and the merging process on the landings. To calculate the predicted speed of travel on the stairs, equation 6 (refer to section 2.12.1) is employed. Pauls [74] developed the equation where speed is defined as a function to the population density. The formula is based on the data from a study that Pauls [74] conducted which involved the observation of the evacuations of a number of tall office buildings

3.10 Summary

It was important to have a well-planned methodology that was flexible enough to deal with any unexpected situations that may have arisen due to the involvement of human factors in the research. The research design involved in this research used both a qualitative and a quantitative approach. The data collected was qualitative. The data was then quantified during the analysis. The methodology used for this research was successfully employed by the NRCC for a number of residential and office evacuation drill studies [93].

Chapter 4: Analysis of Building C

4.1 Introduction

As outlined in Chapter 3, three evacuation drills were undertaken in Building C. During evacuation Drill C2 all occupants on each of the floors used the front stair in the building and none of the occupants used the rear stairs as they were directed to do so by the fire marshals present during the drill. In drill C3, the same directions applied however, the fourth floor occupants continued to use the rear stair during the evacuation drill. As a result, the fourth floor occupants were omitted from some of the analysis. During evacuation Drill C1, the occupants used both stairs. Both a quantitative and qualitative analysis was carried out on the raw data collected from video recordings of the three evacuation drills in Building C. Drill C3 was a repeat study of Drill C2 and similar findings were established.

4.2 Merging during Drill C2

Significant merging occurred in Drill C2 due to a number of factors i.e. the availability of only one escape stair, the width of the stair and the large number of occupants creating a high population density on the stairs. Tables 4.1 to 4.11 describe the merging activity on each floor in Drill C2. Using a time interval of ten seconds the merge ratio was calculated by counting the number of occupants from the stair flow and the floor flow when passing a merge point on the landing before descending the outgoing stair.

Using the same time interval of ten seconds the flow rate was also calculated at each merge point and finally the tables include a brief summary of the type of behaviour observed during the merging activity. It was noticed that merging occurred at more than one merge point on the landing in Drill C2. Therefore, merging was calculated for three different merge points. The three merge points are illustrated in Figure 3.7 in the methodology chapter.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 1 (persons/sec)	Behaviour Observed
0-10	1	4	20:80	0.5	A Stair Flow occupant used the handrail to enter the outgoing stair by using her elbow to move onto stairs. The occupant was familiar with the other occupants.
10-20	1	2	33.34:66.66	0.7	The handrail was used again by the Stair Flow occupants to access the outgoing stair.
20-30	1	6	14.29:85.71	0.4	A Stair Flow occupant deferred to the Floor Flow. There was a build up of over 10 people behind that occupant from the Stair Flow.
30-40	1	5	16.66:83.34	0.6	The same occupant continued to defer to the Floor Flow. Some occupants from the Floor Flow joked with the Stair Flow occupant as he continued to defer to them.
40-50	1	4	20:80	0.4	Same as before.
50-60	2	3	40:60	0.6	The Stair Flow occupant began to merge into the Floor Flow, which allowed the rest of the Stair Flow occupants to continue their evacuation.
60-70	0	0		0	No movement. All flows at a standstill.
Total	**7**	**24**	**23:77**		

Table 4.1: Drill C2, Merge Point 1, 3rd Floor Merge Analysis.

Time Period (Secs)	**No. From Stair Flow (people)**	**No. From Floor Flow (people)**	**Merge Ratio Stairs: Floor (people)**	**Flow Rate at Merge Point 1 (persons/sec)**	**Behaviour Observed**
0-10	3	4	43:57	0.9	Merging was shared. Movement between the flows was efficient.
10-20	3	6	33.34:66.66	0.5	Stair occupants used the handrail to aid there movement into the landing and onto the outgoing stair.
20-30	4	4	50:50	0.7	Merging was shared between the Stair Flow and Floor Flow Y.
Total	**10**	**14**	**42:58**		

Table 4.2: Drill C2, Merge Point 1, 2nd Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 1 (persons/sec)	Behaviour Observed
0-10	0	6	0:100	0.5	The Stair Flow occupants deferred to the Floor Flow. The three girls who lead the stair flow conversed with each other as they deferred to the Floor Flow.
10-20	1	8	11.11:88.89	0.6	An occupant from the Stair Flow began to move onto the landing but the Floor Flow still took priority.
20-30	2	3	40:60	0.7	When the floor was almost empty the stair flow only merged with three from Floor Flow Y.
Total	**3**	**17**	**15:85**		

Table 4.3: Drill C2, Merge Point 1, 1st Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	2	6	25:75	0.5	Occupants from Floor Flow X quickly approached the outgoing stairs. Floor Flow Y were forced to stop entry and deferred to Floor Flow X as it continued to move fast.
10-20	0	8	00:100	0.4	Merging took place between the floor flows. One occupant from the stair flow moves onto the outgoing stair.
20-30	0	8	00:100	0.4	The second occupant from the Stair Flow continued and priority still lies with the Floor Flow X. One occupant from Flow Flow X deferred to four occupants from Floor Flow Y.
Total	**2**	**22**	**8:92**		

Table 4.4: Drill C2, Merge Point 2, 3rd Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	5	2	71:29	1	Floor Flow Y were first to enter the landing first. When Floor Flow X entered, Floor Flow Y slowed down and Floor Flow X and the Stair Flow took priority.
10-20	3	4	43:57	1.3	Floor Flow Y continued to defer to Floor Flow X and the Stair Flow.
20-25	0	0	00:00	0	Movement on the outgoing stair comes to a halt after becoming heavily congested.
25-35	4	2	66.66:33.33	0.6	Floor Flow Y empties.
Total	**12**	**8**	**60:40**		

Table 4.5: Drill C2, Merge Point 2, 2nd Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	0	6	00:100	0.5	Floor Flow Y are first to move into the landing.
10-20	0	4	00:100	0.6	Same as above.
20-30	2	3	40:60	0.7	The Stair Flow defer to the Floor Flow.
Total	**2**	**13**	**13:87**		

Table 4.6: Drill C2, Merge Point 2, 1st Floor Merge Analysis.

Time Period (Secs)	No. From Flow X (people)	No. From Flow Y (people)	Merge Ratio X:Y (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	9	4	69:31	0.9	Floor Flow X quickly approached the outgoing stairs. Floor Flow Y were forced to stop entry and deferred to Floor Flow X as it continued to move fast.
10-20	4	5	44:56	1	The Stair flow reached the landing. However merging is still taking place between the floor flows. Only one occupant from the Stair Flow passes the merge point.
20-30	4	4	50:50	0.9	Access was shared between both floor flows.
30-40	5	6	45:55	0.9	Merging between the floor flows was more efficient almost reaching a 50:50 merge.
40-50	3	1	75:25	0.4	Priority continued to lie with Floor Flow X.
Total	**25**	**20**	**56:44**		

Table 4.7: Drill C2, Merge Point 2, Floor Flow X & Y, 3rd Floor Merge Analysis.

Merge point two is shown in Figure 3.7 in chapter 4. The space on the landing was occupied by the Floor X and Y for this merge point. The merge ratio and flow rate was calculated for Floor X and Y. The sequence of merging activity for merge point 2 is shown is included in Tables 4.7, 4.8 and 4.9.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio X:Y (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	6	5	55:45	1	Floor Flow Y was first to move into the landing however, as soon as Floor Flow X entered it took priority.
10-20	4	3	57:43	1	Movement on the outgoing stair was congested and came to a halt for 5 sacs. When movement resumed Floor Flow X took priority again.
Total	**10**	**8**	**56:44**		

Table 4.8: Drill C2, Merge Point 2, Floor Flow X & Y, 2nd Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio X:Y (people)	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	9	5	64:36	1.1	Floor Flow Y were first to move onto the landing. However, as soon as Floor Flow X entered the landing took priority.
10-20	5	4	56:44	0.7	Merging was shared between the floor flows.
20-30	5	4	56:44	0.7	Merging was shared between the floor flows.
30-40	3	2	60:40	0.8	Priority lied with Floor Flow X.
Total	**22**	19	**54:46**		

Table 4.9: Drill C2, Merge Point 2, Floor Flow X & Y, 1st Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 3 (persons/sec)	Behaviour Observed
0-10	2	6	25:75	0.8	Merging took place between the stair and floor flows. Floor Flow X took priority while the Stair Flow deferred to them.
10-20	0	8	00:100	0.4	Congestion occurred on the landing. Movement was at a shuffling speed.
20-30	0	8	00:100	0.1	Two occupants from Floor Flow X deferred to Floor Flow Y. Little movement occurred at this merge point.
30-40	0	8	00:100	0.8	Movement became easier. The Floor Flow still has priority.
40-50	1	3	25:75	0.7	An occupant from the floor flow encouraged the occupant leading the Stair Flow to move past the merge point but does not defer to the occupant.
50-60	1	4	20:80	0.4	A second stair flow occupant followed through the merge point. Movement continued to be slow at a shuffling speed due to congestion on the stair below.
Total	**4**	**37**	**10:90**		

Table 4.10: Drill C2, Merge Point 3, 3rd Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor (people)	Flow Rate at Merge Point 3 (persons/sec)	Behaviour Observed
0-10	3	9	25:75	0.9	The Floor flow took priority.
10-20	4	7	36:64	0.5	The Floor Flow and Stair Flow shared access at this merge point.
Total	**7**	**16**	**30:70**		

Table 4.11: Drill C2, Merge Point 3, 2nd Floor Merge Analysis.

The following analysis of merging activity at each merge point was carried out to investigate a trend in the merge ratios and floor flow rates at the three different merge points in Drill C2. The analysis studies each merge point highlighting the overall merge ratios and average flow rate recorded for each floor.

The analysis of merge point one is as follows: Floor 3: Overall merge ratio is 23:77 between the Stair and Floor Flow with an average flow rate of 0.5 persons/second. Floor 2: overall merge ratio is 42:58 between the Stair and Floor Flow with an average flow rate of 0.7 persons/second. Floor 1: Overall merge ratio is 15:85(stair: floor) with an average flow rate of 0.6 persons/second. The flow rates of merge point one are graphically represented in Figure 5.1 for all three floors in Drill C2.

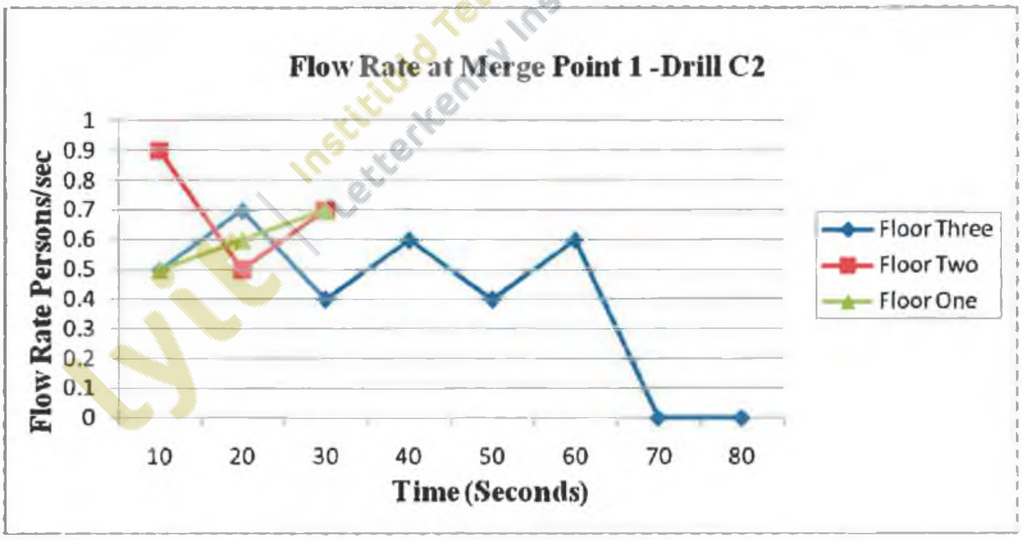


Figure 4.1: Flow Rate at Merge Point 1, Drill C2.

The analysis of merge point two is as follows: Floor 3: overall merge ratio is 8:92 with an average flow rate of 0.4. Floor 2: overall merge ratio is 60:40 with an average flow rate of 0.9 persons/second. Floor 1: overall merge ratio is 13:87 with an average flow rate of 0.6 persons/second. The flow rates of merge point tow (floor and stair flows) are graphically represented in Figure 5.2 for all three floors in Drill C2.

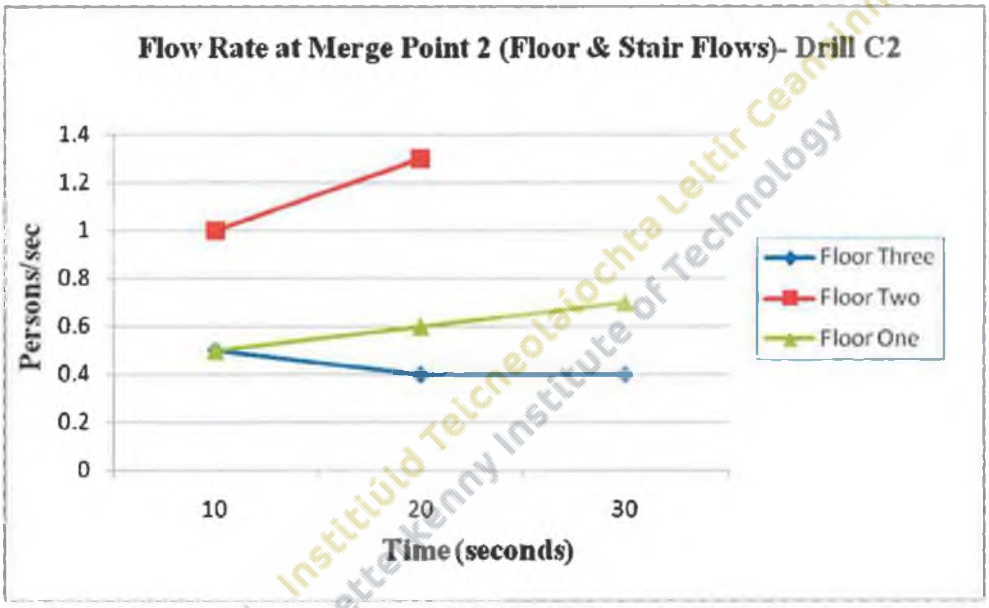


Figure 4.2: Flow Rate at Merge Point 2, Drill C2.

The analysis of merge point two between the Floor Flows **X** and **Y** is as follows. Floor 3: overall merge ratio is 56:44 with an average flow rate of 0.8 persons/second. Floor 2: overall merge ratio is 56:44 with an average flow rate of 1 person/second. Floor 1: overall merge ratio is 54:46 with an average flow rate of 0.8 person/second. The flow rates of merge point two (floor flows **X** and **Y**) are graphically represented in Figure 5.3 for all three floors in Drill C2.

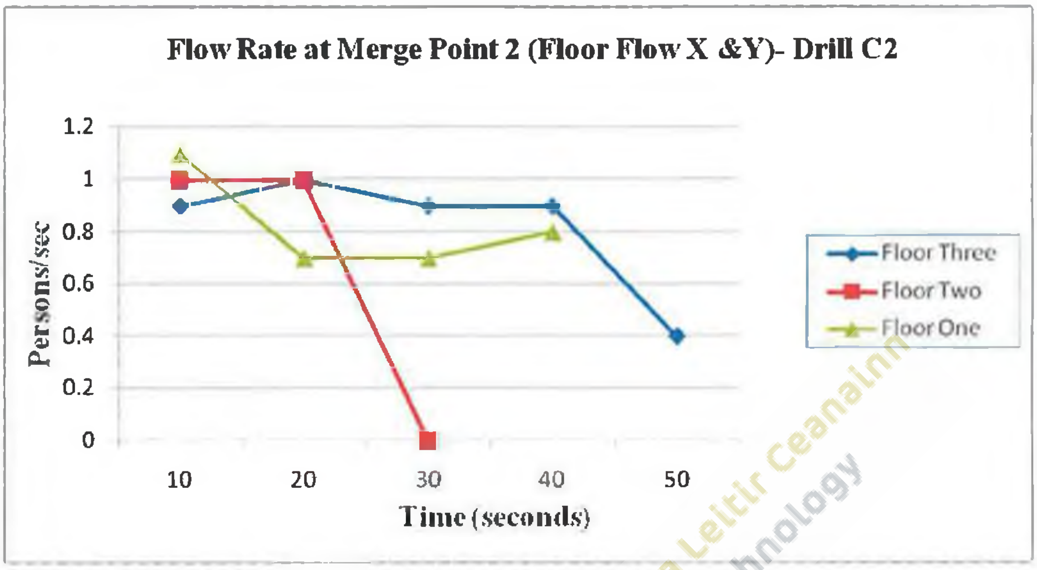


Figure 4.3: Flow Rate at Merge Point 2 (Floor Flow X and Y), Drill C2.

The analysis of merge point three is as follows: Floor 3: overall merge ratio is 10:90 with an average flow rate of 0.5 person/second. Floor 2: overall merge ratio is 30:70 with an average flow rate of 0.7 person/second. Floor 1: No merging took place between the stair and the floor flow. The flow rates of merge point three are graphically represented in Figure 5.4 for all three floors in Drill C2.

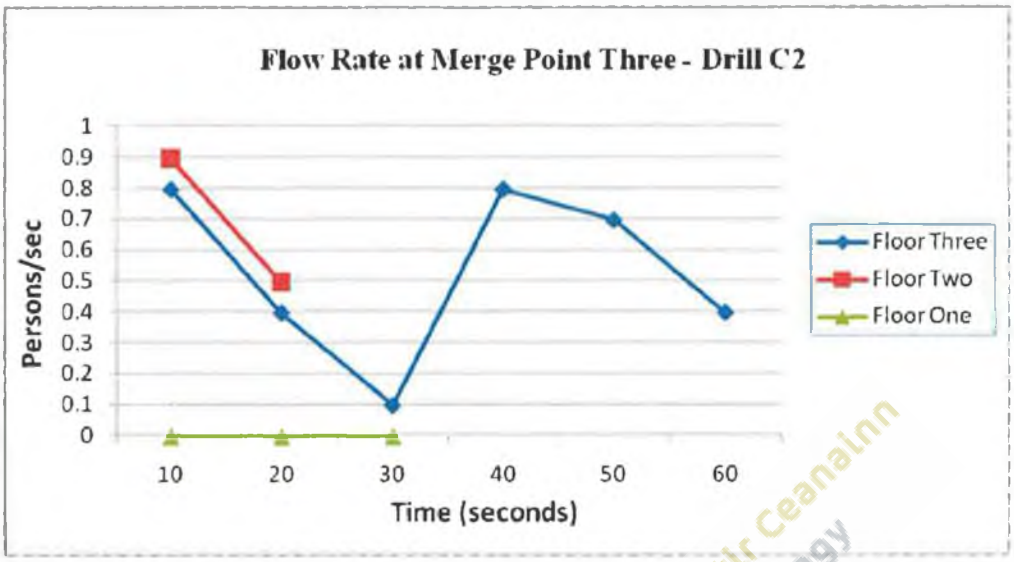


Figure 4.4: Flow Rate at Merge Point 3, Drill C2.

Table 4.12 gives a breakdown of the average floor rates at each merge point on the third floor. The table provided a comparison between each merge point. Merge point 2 shows the highest recorded average flow rate reaching a maximum of 1 persons/sec.

Floor 3	Flow Rate Merge Point 1 (persons/sec)	Flow Rate Merge Point 2 (persons/sec)	Flow Rate Merge Point 2 (Stair &floor)(persons/sec)	Flow Rate Merge Point 3 (persons/sec)
10-20	0.5	0.9	0.5	0.8
20-30	0.7	1	0.4	0.4
30-40	0.4	0.9	0.4	0.1
40-50	0.6	0.9	-	0.8
50-60	0.4	0.4	-	0.7
60-70	0.6	-	-	0.4
70-80	0	-	-	-

Table 4.12: Drill C2, Comparison of Flow Rates for each Merge Point on Floor 3.

The merge point involved the two floor flows X and Y. Merging at merge point 2 between the floor and stair flow on the third floor lasted for a short period. The lowest flow rate was found at merge point 1.

Floor 2	Flow Rate Merge Point 1 (persons/sec)	Flow Rate Merge Point 2 (persons/sec)	Flow Rate Merge Point 2 (Stair & floor) (persons/sec)	Flow Rate Merge Point 3 (persons/sec)
10-20	0.9	1	1	0.9
20-30	0.5	1	1.3	0.5
30-40	0.7	-	0	-
40-50	-	-	0.6	-

Table 4.13: Drill C2, Comparison of Flow Rates for each Merge Point on Floor 2.

Table 4.13 shows a comparison between the flow rates recorded at three merge points on the second floor in Drill C2. The highest flow rate was recorded at merge point 2 on the second floor. The lowest flow rate was recorded at both merge points 1 and 3. Table 4.14 shows a comparison between the flow rates recorded at three merge points on the first floor during Drill C2. The highest flow rate was recorded at merge point 2 on the first floor. The lowest flow rate was recorded at both merge points 1 and 2 (stair and floor flows) on the first floor. No merging occurred at merge point three on the first floor.

Floor 1	Flow Rate Merge Point 1 persons/sec	Flow Rate Merge Point 2(Flow X & Flow Y) (persons/sec)	Flow Rate Merge Point 2 (Stair & Flow) (persons/sec)	Flow Rate Merge Point 3 (persons/sec)
10-20	0.5	1.1	0.5	-
20-30	0.6	0.7	0.6	-
30-40	0.7	0.7	0.7	-
40-50	-	0.8	-	-

Table 4.14: Drill C2, Comparison of Flow Rates for each Merge Point on Floor 1.

The merge Tables 4.1- 4.11 describe the merging activity of the three merge points on all three floors in Drill C2. Tables 4.12 - 4.14 provide comparisons of each of the three merge points on all three floors. Figures 4.2 - 4.5 graphically represent the flow rates of all the three merge points on each floor. From a summary of the results from Tables 4.1–4.11, a trend was found in the relationship between the merge ratio and average flow rate at the three merge points. When the merging was 50:50 or close the flow rate was found to be high. When the merging was not shared and one flow had priority over the other, the flow rate was found to be lower i.e. merge point 2 on floor two the merge ratio was 56:44 and the flow rate was 1 person/sec. The results of Drill C2 highlighted that when a merge point is effectively shared i.e. 50:50 the flow rate at that point was faster. The comparisons of the flow rates of each merge point shown in Tables 4.12- 4.14 highlighted that the highest flow rate was found at merge point two between floor flows X and Y.

4.3 Merging during Drill C3.

As conditions of Drill C3 were similar to Drill C2, the same factors influenced the occurrence of merging. During Drill C3, the fourth floor occupants used an alternative escape route, which was the rear stairway. This stairway was blocked for all occupants but came available for the fourth floor occupants. As a result, the merging was recorded for floor one and two only. Also on floor two, the Floor Flows X and Y only merged for a short period. It was therefore difficult to observe the priority between the flows on these floors.

Tables 4.15 to 4.18 describe the merging activity on each floor in Drill C3. The same three merge points that were used in Drill C2 were also used in Drill C3, refer to Figure 3.7 in chapter 3.

Time Period (Secs)	**No. From Stair Flow (people)**	**No. From Floor Flow (people)**	**Merge Ratio Stairs: Floor**	**Flow Rate at Merge Point 1 (persons/sec)**	**Behaviour Observed**
0-10	4	4	50:50	0.7	Early sharing became apparent.
10-20	1	7	12.5:87.5	0.4	The Stair Flow deferred to the Floor flows.
20-30	3	5	37.5:62.5	0.5	The floor flows continued to take priority.
30-40	5	5	50:50	0.7	The Stair Flow only merged with the Floor Flow Y. This created a 50:50 merge.
40-50	3	3	50:50	0.7	The Stair Flow only merged with Floor Flow Y still 50:50 merge.
Total/Average Ratio	**8**	**14**	**36:64**		

Table 4.15: Drill C3, Merge Point 1, 1st Floor Merge Analysis.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor	Flow Rate at Merge Point 3 (persons/sec)	Behaviour Observed
0-10	4	4	50:50	0.7	Stair Flow and Floor Flow X began sharing a 50:50 merge.
10-20	1	7	12.5:87.5	0.4	The Stair Flow deferred to Floor Flow X.
20-30	3	5	37.5:62.5	0.5	The Floor Flow X continued to take priority.
Total/Average Ratio	**8**	**16**	**33:67**		

Table 4.16: Drill C3, Merge Point 3, 1st Floor Merge Analysis.

Merge point two on floor one is shown in Table 4.17. When the stair and floor entered onto the stair floor landing they competed for the space on the landing in order to proceed with their evacuation. The flows rates calculated at this merge point were for floor flows X and Y. The sequence of merging activity for this merge point is shown is included in Table 4.17.

Time Period (Secs)	No. from Flow X (people)	No. from Flow Y (people)	Merge Ratio X:Y	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	4	5	44.44:55.55	0.7	Floor Flow Y had a small priority over Floor Flow X.
10-20	2	3	40:60	0.5	As Floor Flow X deferred to Floor Flow Y, Floor Flow Y had priority.
20-30	2	6	25:75	0.5	One occupant from the Floor Flow X deferred to four from Floor Flow Y.
Total/Average Ratio	**8**	**14**	**36.36:63.64**		

Table 4.17: Drill C3, Merge Point 2, 1st Floor Merge Analysis.

Merge point two on floor two is shown in Figure 4.18. The flows rates calculated at this merge point were for Floor Flows X and Y The sequence of merging activity for this merge point is included in Table 4.18.

Time Period (Secs)	No. from Flow X(people)	No. from Flow Y (people)	Merge Ratio X:Y	Flow Rate at Merge Point 2 (persons/sec)	Behaviour Observed
0-10	3	2	60:40	0.5	Floor Flow X took priority over Floor Flow Y.
Total/Average Ratio	**3**	**2**	**60:40**		

Table 4.18: Drill C3, Merge Point 2, 2nd Floor Merge Analysis.

The following analysis of merging activity of each merge point was carried out to investigate a trend in the merge ratios and floor flow rates at the three different merge points in Drill C3. The analysis examines each merge point highlighting the overall merge ratios and average flow rate recorded for each floor. The analysis of Merge Point 1 is as follows: Floor 3: No merging took place between the stair and the floor flow. Floor 2: No merging took place between the stair and the floor flow. Floor 1: Overall merge ratio is 36:64 (stair: floor) with an average flow rate of 0.6 persons/second.

The analysis of Merge Point 2 between the Floor Flows X and Y is as follows: Floor 3: No merging took place on floor three. Floor 2: overall merge ratio is 60:40 with an average flow rate of 0.5 person/second. Floor 1: Overall merge ratio is 36:64 with an average flow rate of 0.6 person/second. The analysis of Merge Point 3 is as follows. Floor 3:.No merging took place on floor three. Floor 2: No merging took place at merge point three on floor two. Floor 1: Overall merge ratio is 33:64 with an average flow rate of 0.5 person/second.

An analysis of the results illustrated that there was a trend found in the relationship between the merge ratio and the average flow rate at the three merge points. When the merging was evenly shared between two competing flows then the flow rate of occupants at the same merge point was found to be high. This result concurred with the findings from evacuation Drill C2.

4.4 Floor Flow Rates during Drill C1 and C2

During Drill C1, the population density was much lower than in Drill C2 due to the lower capacity of occupants. Both stairs were made available during Drill C1 therefore, the floor and stair flow rates were much lower because of the low population density. The results of the floor and stair flow rates can be seen in Figures 4.6 and 4.7.

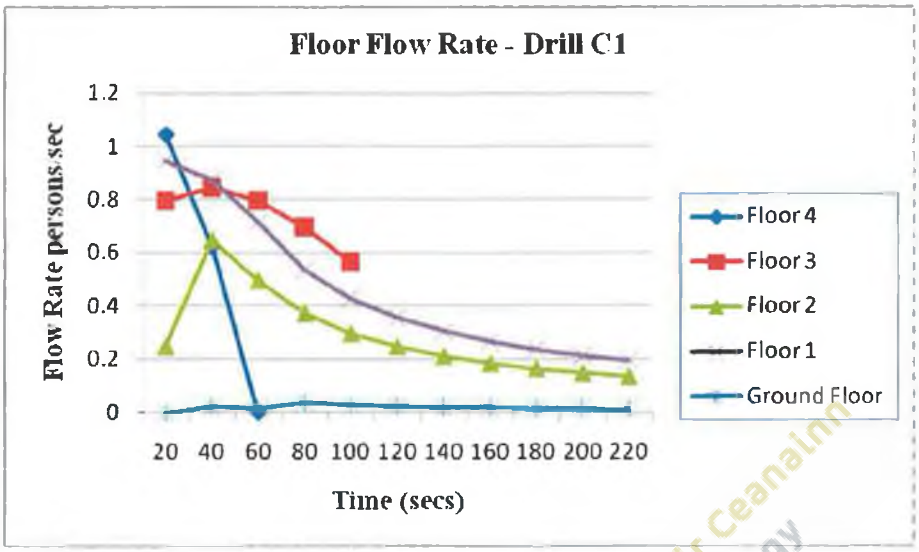


Figure 4.5: Floor Flow Rate- Drill C1.

The highest recorded floor flow rate occurred on floor four due to the occupants all evacuating on this floor simultaneously. The number of occupants on the fourth floor was low and as a result, the floor flow rate was calculated for a short period. There were only twenty one occupants on this floor and therefore the floor flow rate was only recorded on floor four for a short period. The next highest recorded floor flow rate was found at floor one. Floors one and two shows the same trend of flow throughout the drill this can be clearly seen in Figure 4.5.

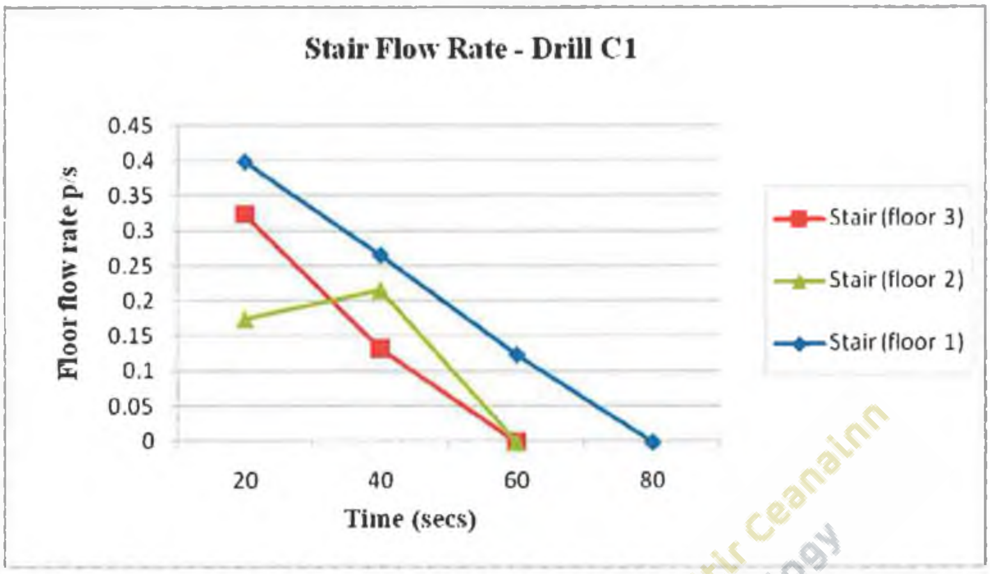


Figure 4.6: Stair Flow Rate – Drill C1.

Figure 4.6 shows that the stair flow was at its highest on floor one. This was expected, as there was no congestion or merging activity occurring on this landing during Drill C1. The occupants coming off the stairs were able to move freely onto the landing. Because of the two entrances from each floor there were three flows merging on the landing, two floor flows, Floor Flow X and Y and one Stair Flow. During Drill C1 there were no occupants evacuating from the third floor. The occupants on Floor one only evacuated from Floor Flow X. The priority between Floor Flow X and Y was compared on the second floor and it was found that Floor Flow X had priority.

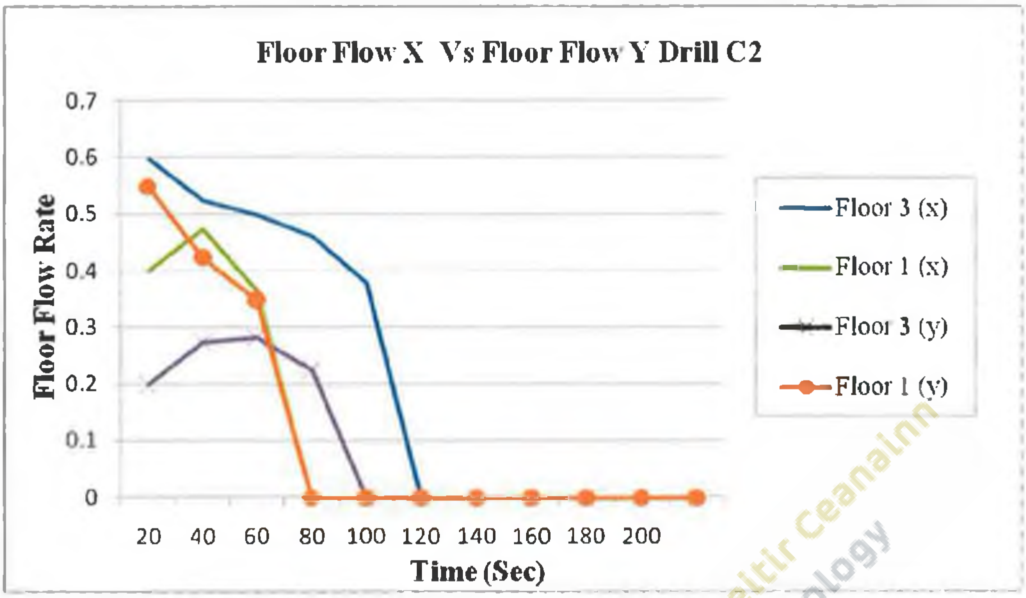


Figure 4.7: Floor Flow Rate X versus Floor Flow Y Drill C2.

Figure 4.7 shows the floor flow rate of two Floor Flows X and Y on floors one and three during Drill C2. The flow rates were recorded for floors one and three as these floors experienced the most merging activity during Drill C2. Because of the two entrances from each floor there were three flows merging on the landing, two floor flows, Floor Flow X and Y and one Stair Flow. Figure 3.3 in Chapter 3 illustrates the stair floor arrangement. In most cases the Floor Flow X took precedence over the Floor Flow Y however, it was observed that whichever floor entered the stair first began a faster flow rate. This occurred on floor one where Floor Flow Y entered the landing first and began a faster flow rate. However once Floor Flow X entered the landing this slowed down the flow rate for Floor Flow Y. It was therefore obvious that Floor Flow X was the stronger of the two floor flows throughout Drill C2.

The stair flow rate is shown in Figure 4.8. The results of the findings found that the stair flow rate was recorded at its highest coming off the stairs on floor three. The Stair Flow was only recorded for a short period due to the low population density on the stairs between floor three and two. This finding was a result of no congestion on the landing and stairs. The occupants were able to freely move on and off the stairs. The lowest recorded stair flow was recorded at floor one. This finding was a result of the larger numbers on the landing and stair.

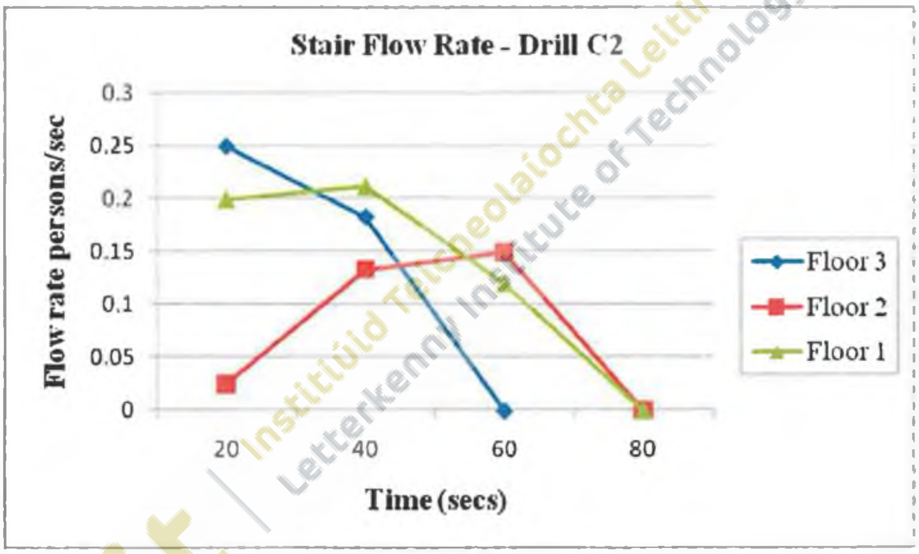


Figure 4.8 Stair Flow Rate - Drill C2.

Figure 4.9 shows the difference between the average Floor Flows X and Y for each floor landing during Drill C2. The results show the relationship between the location of the entrances onto the landing and the floor flow rate at that entrance. Floor Flow X took priority on all floors. The ground floor experienced insignificant evacuee numbers to determine a floor flow rate.

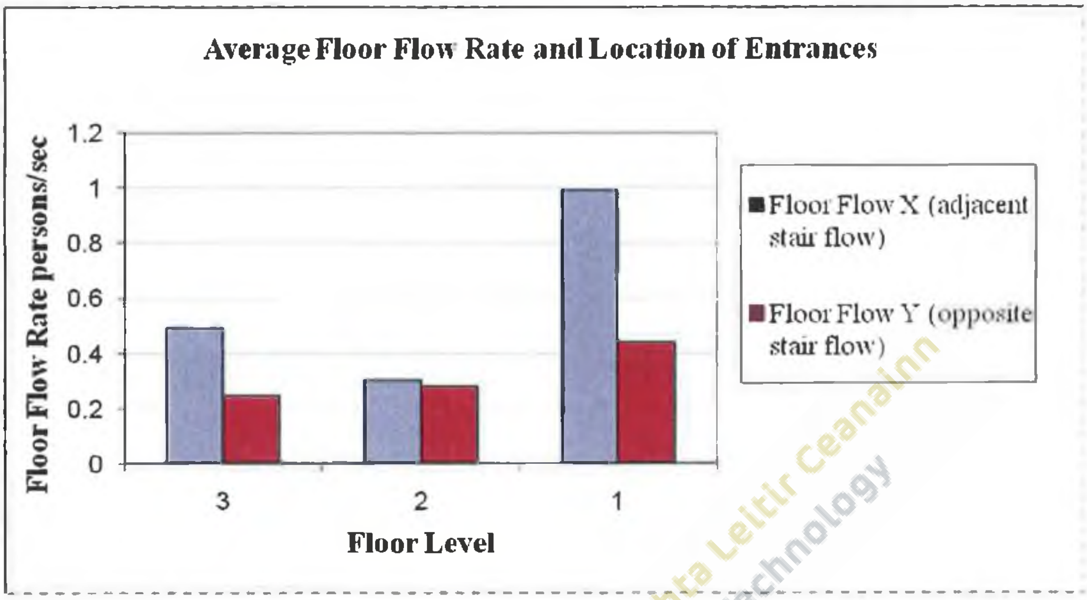


Figure 4.9: Average Floor Flow Rate and Location of Entrances Drill C2.

It can be said that the door positioned at Floor Flow X had a better location than the door positioned at Flow Y because the occupants of Floor Flow X had a faster flow rate over Floor Flow Y. When Floor Flow X entered into the stair first, it appeared to have an advantage over Floor Flow Y, which made it difficult for Floor Flow Y to enter into the stair when Floor Flow X had already developed a steady flow into the stair.

An incident of deference behaviour from Floor Flow X allowed a number of occupants to enter into the stair. An example of this occurred on floor three, where the occupants from Floor Flow Y attempted to enter the stair but discovered that the Floor Flow X had developed a steady flow into the stair.

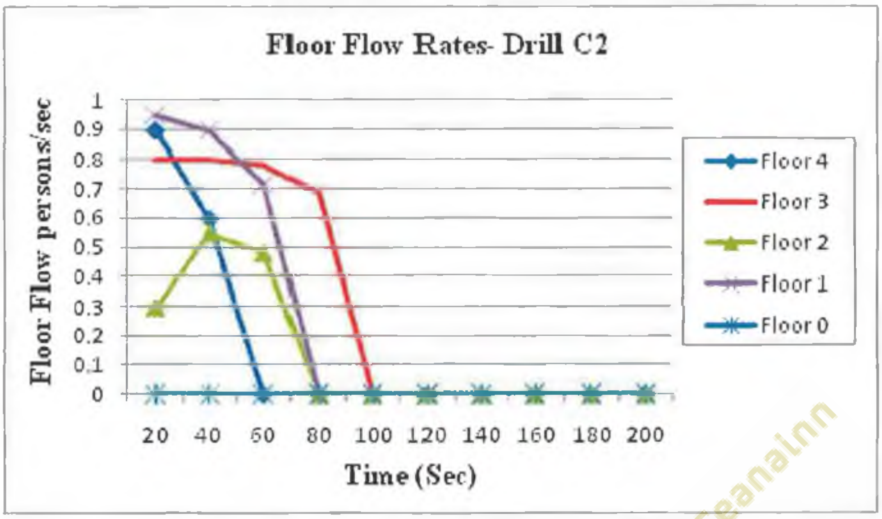


Figure 4.10: Floor Flow Rates Drill C2.

Figure 4.10 shows the floor flow rate combined for Floor Flow X and Y calculated for each floor landing. As the stair population density increased, it was obvious that the speed of movement on the stairs decreased.

4.5 Floor Flow Rates during Drill C3.

A comparison of Floor Flow X and Y was not made on floor three due to insignificant numbers in Floor Flow X therefore, the results show the comparison between floors one and two only. On floor one the first flow that entered the landing was Floor Flow X. This in turn, allowed Floor Flow X to begin a fast flow rate. When Floor Flow Y entered the stair, some merging began which in turn slowed down the Floor Flow X. Figure 4.11 shows how the priority remained with Floor Flow X on floor one and how it retained the fast flow rate during the evacuation Drill C3. Floor Flow X on the second floor began slowly but quickly became faster than Floor Flow Y. When both flows merged, it was difficult for Floor Flow Y to enter the stair as Floor Flow X had developed a steady flow. An example of this is shown in Figure 4.12 (b).

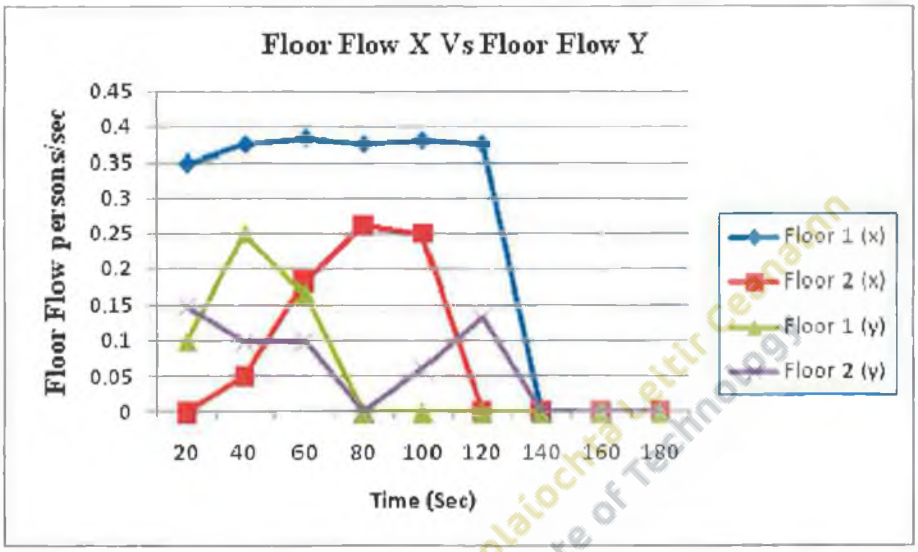


Figure 4.11: Floor Flow X Vs Floor Flow Y- Drill C3.

An occurrence of deference behaviour from Floor Flow X allowed a number of occupants from Floor Flow Y to enter the stair. One particular occasion of deference behaviour that occurred on floor, one allowed a number of occupants from Floor Flow Y to enter the stair. Figure 4.12 (a) shows this occurrence taking place when a young male from the Floor Flow X deferred to four young females from Floor Flow Y.

(a): Deference Behaviour on Floor one. **(b) Floor Flow X has priority.**

Figure 4.12: Deference Behaviour.

The stair flow rate was calculated on the landings of floors one and two as shown in Figure 4.13. The fastest flow rate was found with the third floor occupants where they began a fast flow rate of the stairs onto the landing on the second floor. There were only nine occupants on the third floor therefore egress only lasted for sixty seconds.

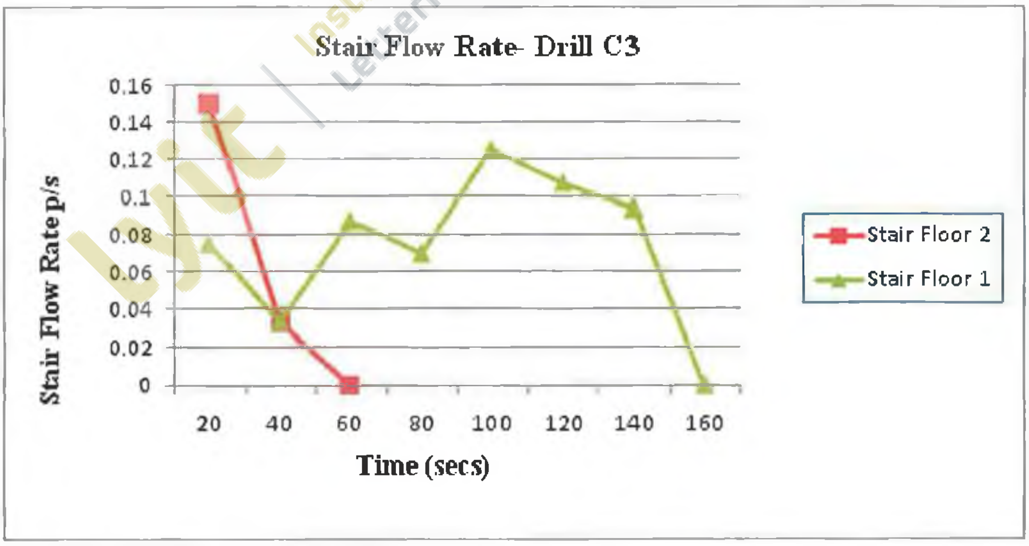


Figure 4.13: Stair Flow Rate – Drill C3.

The stair flow rate recorded on the landing of floor one reached its peak after one hundred seconds. There were higher numbers on the stairs, which included the third and second floor occupants combined. This in turn created a slower stair flow on the first floor landing. In addition, the occurrence of deference behaviour on the first floor delayed the stair flow rate for the third and second floor occupants.

Figure 4.14 shows the impact of the location of the entrances onto the stair during Drill C3. The results in the bar chart show the relationship between the location of the entrance onto the landing and the floor flow rate recorded at that entrance. The comparison between Flows X and Y were carried out on floors one and two only due to the lack of merging activity on floors three and four. Floor Flow X took priority over Floor Flow Y on floors one and two. It can be said that the door positioned at Floor Flow X has a location than the entrance at Flow Y when the occupants of Flow X had a faster flow rate over Floor Flow Y.

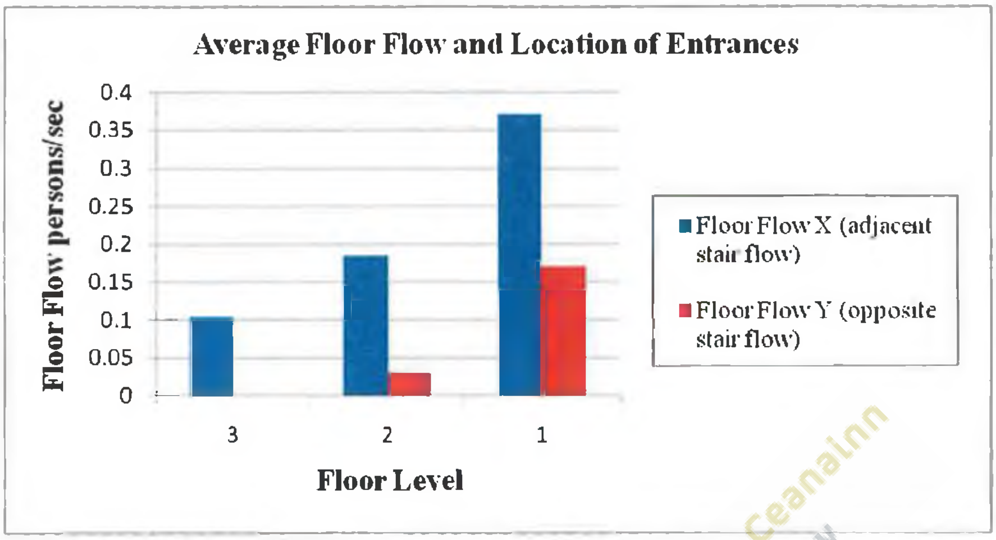


Figure 4.14: Average Floor Flow and Location of Entrances during Drill C3.

The results indicated that although the flow rate on the landing at Floor Flow X was high the occupants in the Stair Flow and on the floors above were experiencing a delayed evacuation as a result. This suggests that it may be favourable to have an entrance onto a stair-floor landing on the opposite side to an incoming stair flow. Positioning the entrance to the stair-floor landing to the opposite side of an incoming stair flow decreased the chances of one flow having a strong priority over the other flow during an evacuation hence creating a more evenly shared merging and a more efficient evacuation.

4.6 Stair Population Density during Drill C1 and C2.

Crowding in Drill C1 was not as high as in the announced Drill C2 where only one stair was available. Due to both stairs, being available for the evacuation Drill C1 there was a lower population density than the announced evacuation Drill C2. Figure 4.15 shows the stair population density recorded during Drill C1. The lower density resulted in smaller merging times and no stoppage time. (Refer to section 3.8 in chapter 3 for the method used to calculate the stair population density.)

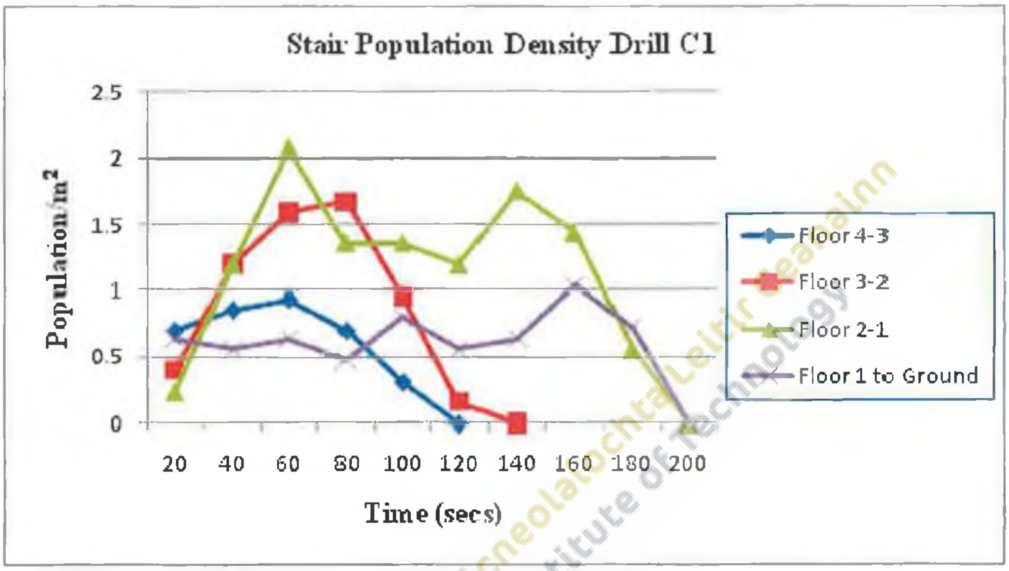


Figure 4.15: Stair Population Density Drill C1

Due to simultaneous evacuation and the discounting of one escape stair, the density on the stairs during Drill C2 was considerably higher than Drill C1. The stair population density between the first and ground floor and the second to first floor was high as a result of the deference behaviour observed on floor one. Figure 4.16 shows the stair population density between all floors for Drill C2.

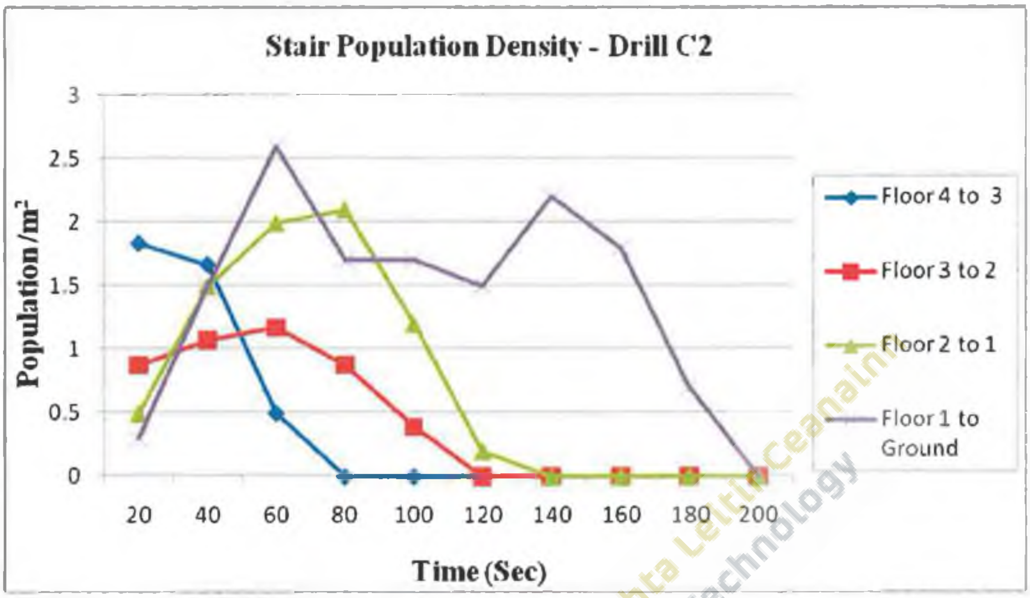


Figure 4.16: Stair Population Density Drill C2.

In Drill C2, it was found that when the stair population density increased the speed of movement on the stairs decreased and the floor flow rate onto the landing decreased.

4.7 Stair Population Density during Drill C3.

Due to simultaneous evacuation and the discounting of one escape stair, the density on the stairs during Drill C3 was considerably high. Figure 4.17 shows that the highest population density recorded for Drill C3 peaked at 2.64 peresons/m^2 after 80 seconds, which occurred on the stairs between floor two and floor one. The density reduced consistently over the remaining evacuation time. The density recorded from the first floor to the ground floor was similar to that of the second to first floor. It did not reach the same peak density of 2.64 persons/m^2. The stair population density was high between the second and first floor because of the deference behaviour that occurred on floor one. The density on the stairs between the first and ground floor was high due to a combination of the deference behaviour on floor one and the increased number of occupants evacuating from floor one. The stair population densities between floor four and three were recorded over a shorter period due to a small number of occupants on these floors.

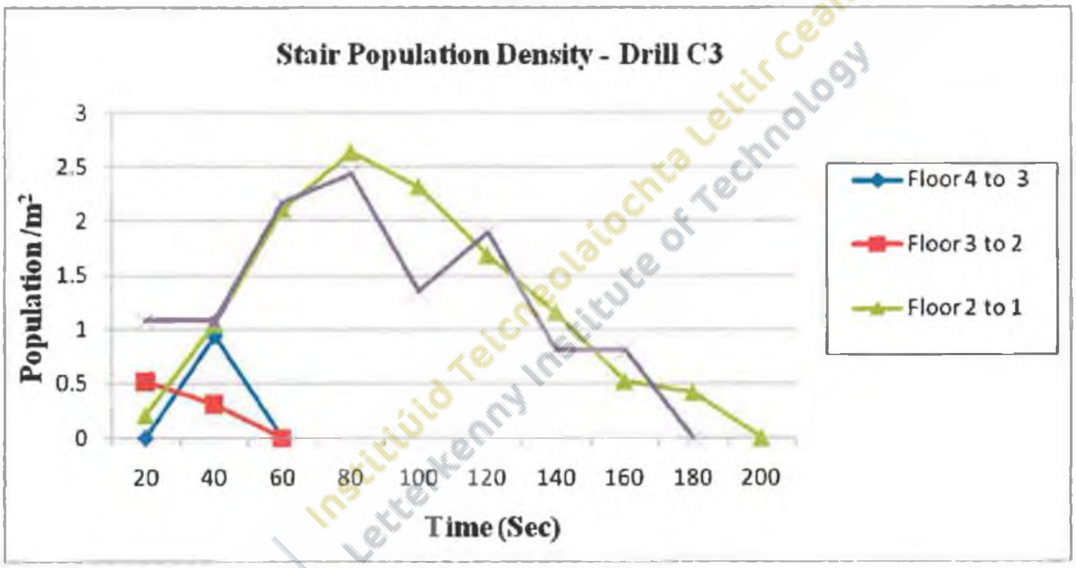


Figure 4.17: Stair Population Density Drill C3.

It was found that when the stair population density increased the speed of movement on the stairs decreased and the floor flow rate onto the corresponding landing decreased.

4.8 Speed of Movement during Drill C2.

Figure 4.18 shows the average evacuation time experienced by the occupants of each floor. The fourth floor occupants had obviously the highest evacuation time as expected. The average observed travel time between each floor was found by calculating the time it took each occupant of that floor to travel to the floor below between landing to landing and then obtaining the average.

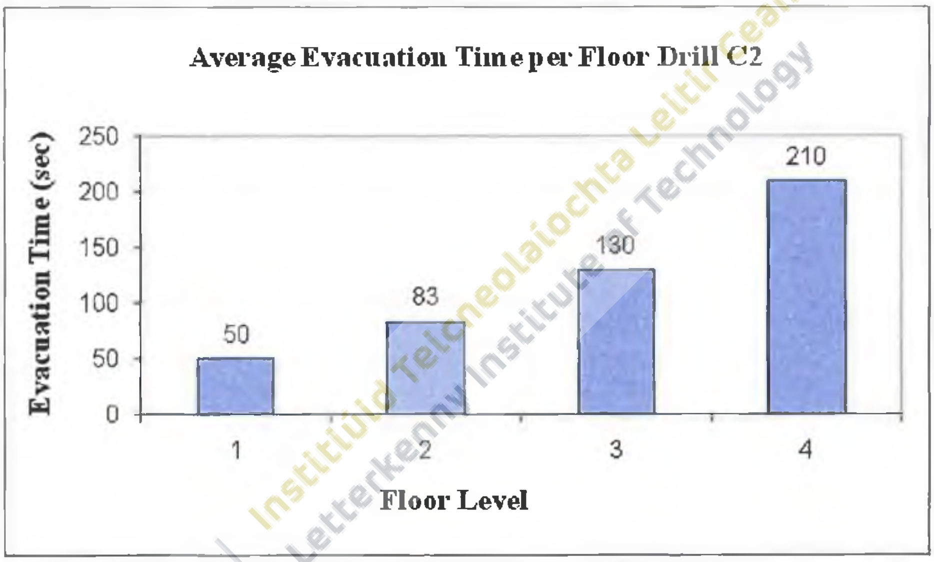


Figure 4.18: Average Evacuation Time per Floor Drill C2.

The average observed travel time is shown in Figure 4.19. The fastest time was found between the fourth and third floor because of no merging and no delay time. The slowest time was found between the third and second floor. The occupants were delayed due to merging and deference behaviour occurring on the lower floors, which in turn created a higher density on the stairs above.

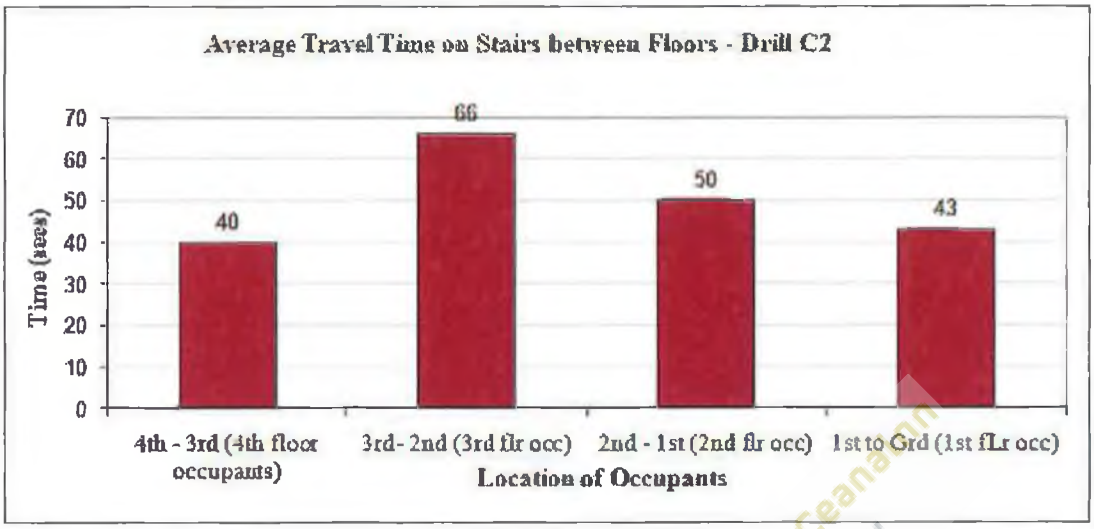


Figure 4.19: Average Travel Time on Stairs between Floor Drill C2.

Figure 4.20 shows the average travel time on the stairs between floors during the evacuation Drill C2 observed on the video recordings. The fastest speed of movement occurred between the fourth and third floor at 0.295m/s and the slowest speed of movement occurred between the first and ground floor at 0.107m/s. The speed of movement from the first to the ground floor was low because of the shorter travel distance. All other floors included the corridor distance of 7.24m. The speed of movement between the second and the first floor was high due to the deference behaviour that occurred on the first floor landing. The stair flow deferred to the first floor occupants. The speed of movement between the third and second floor was lower due to the higher density on the stairs below as a result of the occurrence of deference behaviour.

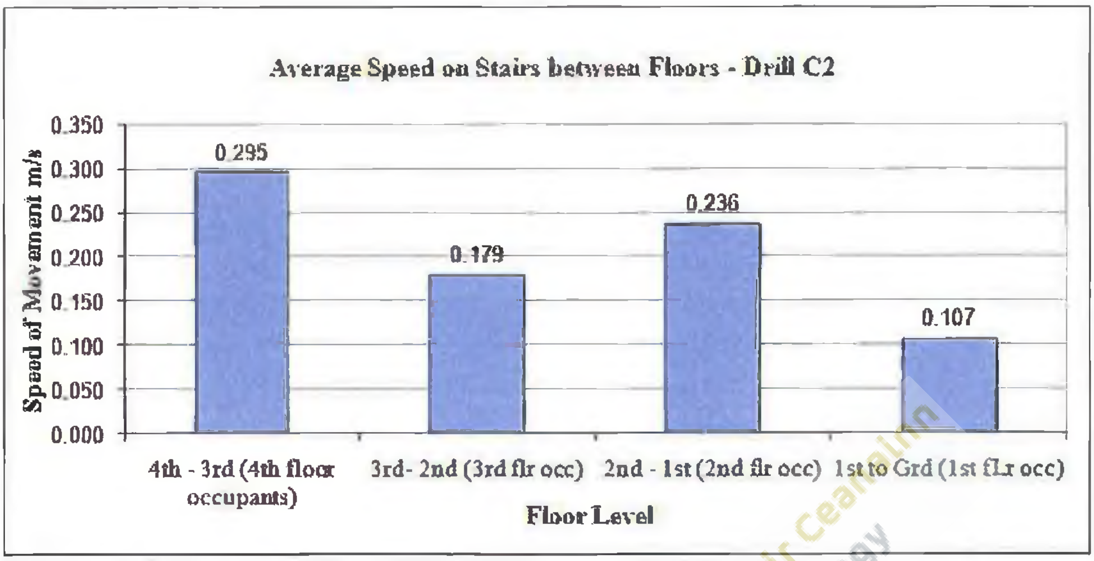


Figure 4.20: Average Speed on Stairs between Floors Drill C2.

Table 4.19 shows the observed speed and predicted speeds for drill C2. The predicted speed takes into account the density. Floors four and three in Drill C2 had a lower density therefore a higher predicated speed and Floors three to two in Drill C2 has an even higher population density therefore a higher predicated speed was calculated. The predicted speeds were all higher than the observed average speed found during the evacuation drills. Figure 4.21 shows a comparison between the observed mean speed and the predicted speed.

Stairwell	Floor	Density p/m2	Observed mean speed m/s	Calculated speed m/s S= 1 -0.266.Dpop
Drill C2	4-3	0.95	0.295	0.747
	3-2	1.31	0.178	0.652
	2-1	1.64	0.236	0.564
	1-Grd	2.29	0.106	0.391

Table 4.19: Observed Speed and Predicted speeds for Drill C2.

The results reveal that there was a huge difference between the observed speed and the predicted speed on all of the floors. The predicted speed found that the occupants moved at a faster speed than what was observed.

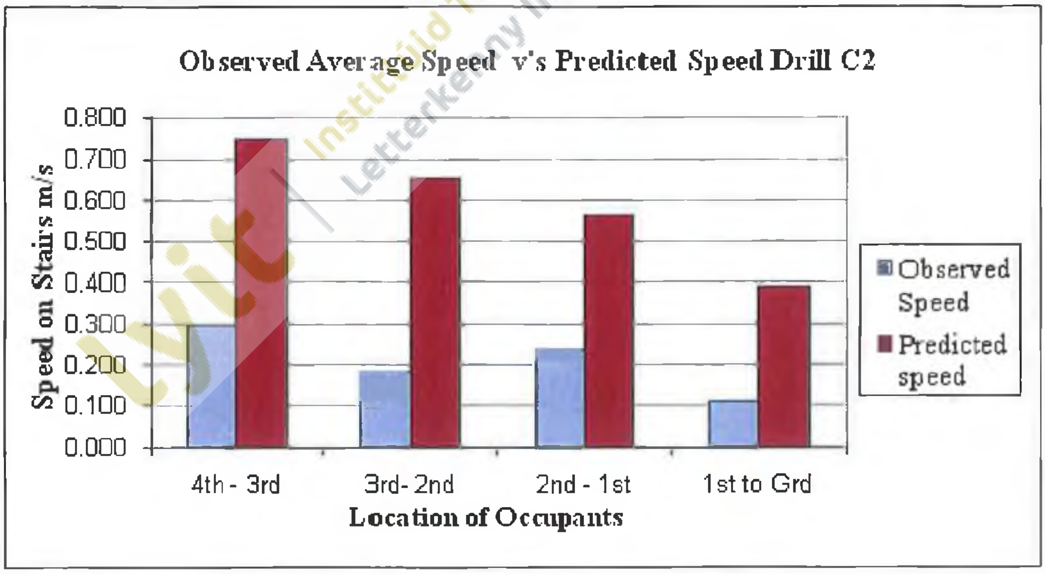


Figure 4.21: Observed Average Speed v's Predicted Speed, Drill C2.

The predicted speed was much greater than the observed average speed for Drill C2. Figure 4.21 shows the observed speed, which included the distance of travel and the time it took to travel that distance. The results of the predicted speed show the relationship between the density and the predicted speed as shown in Table 4.19. When the density was lower, the predicted speed of travel was much faster than the observed speed of travel.

4.9 Speed of Travel on the Stairs during Drill C3.

Figure 4.22 shows the average evacuation time experienced by the occupants of Floors one, two and three. The maximum evacuation time was recorded for an occupant on the third floor at 181 seconds. The minimum evacuation time was recorded for an occupant on the first floor at 18 seconds.

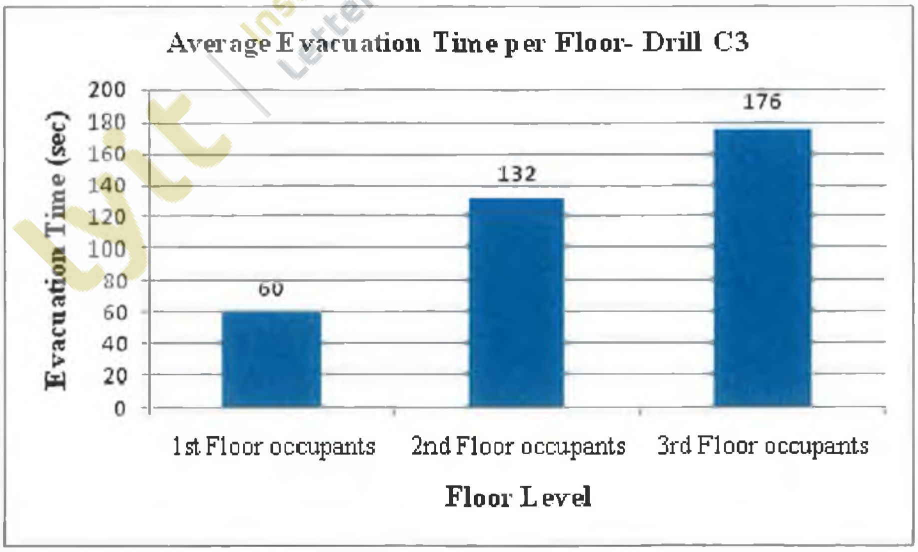


Figure 4.22: Average Evacuation Time per Floor Drill C3.

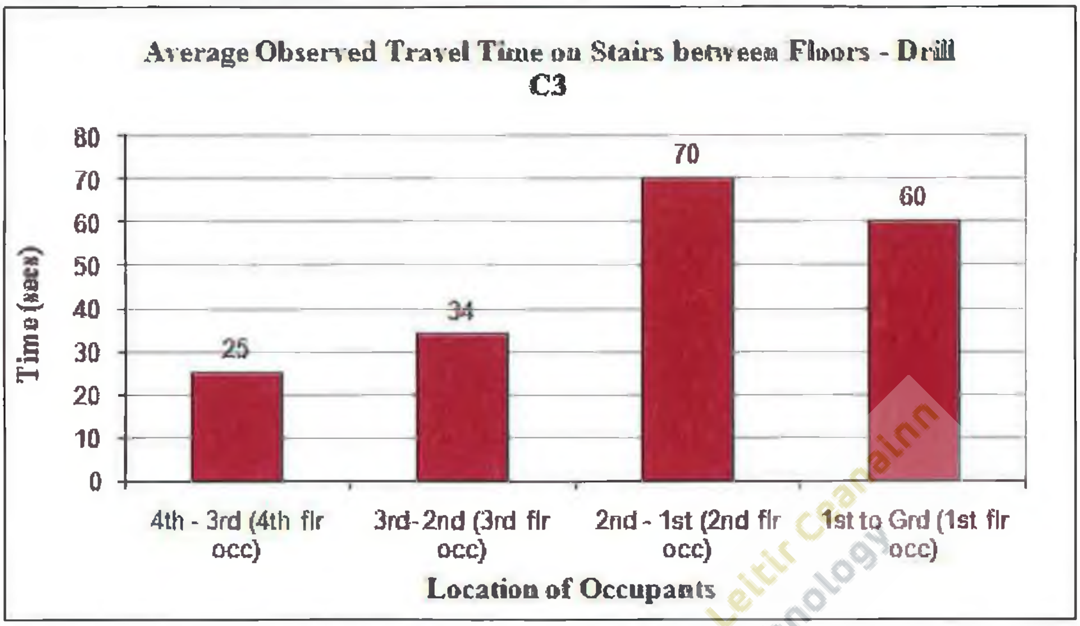


Figure 4.23: Average Observed Travel Time on Stairs between Floors Drill C3.

The results revealed that the second floor occupants recorded the slowest evacuation time due to the delays from merging and deference behaviour occurring on the lower floors. The delays created a higher population density on the stairs. Faster evacuation times were found between the fourth and third floor because of a lack of merging and no delay time. Figure 4.24 shows the average speed of movement on the stairs between each floor during the evacuation drill C3 as observed via the video recordings. The fastest speed of movement occurred between the fourth and third floor at 0.472m/s and the slowest speed of movement occurred between the first and ground floor at 0.077m/s. The average speed on the stairs from the second to the first floor and the first to the ground floor was low possibly due to a higher density and the occurrence of merging and deference behaviour. The high speed of movement between the third and second floor was possibly influenced by the low population density on the stairs.

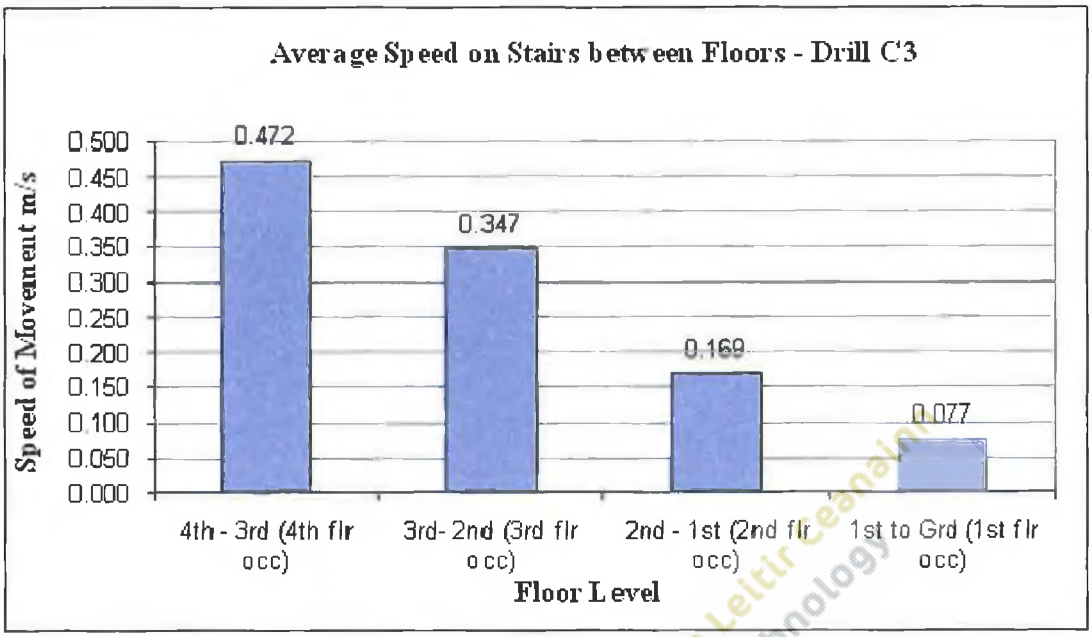


Figure 4.24: The Average Travel Speed on Stairs Drill C3.

Table 4.20 shows the calculated observed speed and predicted speeds for Drill C3. Floors four to three in Drill C3 had a lower density resulting in a higher predicted speed.

Stairwell	**Floor**	**Density p/m2**	**Observed mean speed m/s**	**Calculated speed m/s** S= 1-0.266.Dpop
Drill C3	4-3	0.19	0.472	0.949
	3-2	0.141	0.347	0.962
	2-1	1.214	0.169	0.678
	1-Grd	1.298	0.077	0.655

Table 4.20: Observed Speed and Predicted Speeds for Drill C3.

Figure 4.25 shows a comparison between the observed mean speed and the predicted speed.

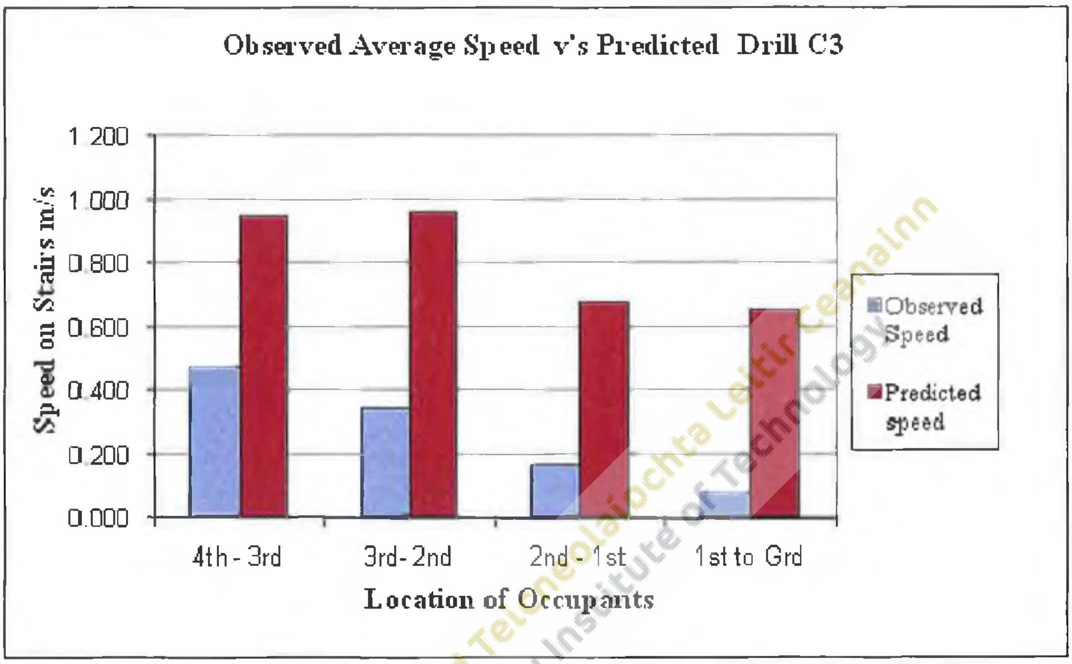


Figure 4.25: Observed Speed vs Predicted Speed Drill C3.

The results revealed that there was a huge difference between the observed speed and the predicted speed for all floors. The formula predicted that the occupants would move at a faster speed than that observed. This is an example of how engineering calculations do not take into account the kind of occupants' behaviour that can occur on the stairs during a building evacuation.

4.10 Delay Time during Drill C2.

The occurrence of merging and deference behaviour was found to have a negative impact on the flow of occupants on the stairs and landing during building C evacuations. The occurrence of merging and deference behaviour resulted in lengthy delays and stoppage times. The average delay time experienced by each floor during Drill C2 is shown in Figure 4.26. The fourth floor occupants experienced the greatest delay time while the first floor occupants experienced no delay time. The fourth floor occupants' evacuation was delayed as a result of two occasions of lengthy deference behaviour.

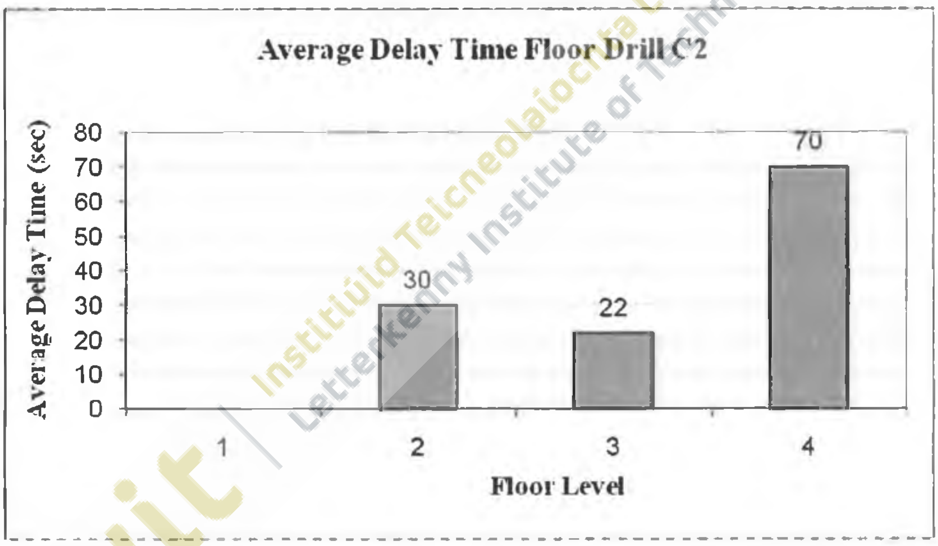


Figure 4.26: Average Delay Time Drill C2.

The first floor occupants experienced no delay time as the Stair Flow deferred to the Floor Flow on floor one allowing the entire floor occupants to evacuate. The maximum delay time during Drill C2 was recorded at one hundred and fifteen seconds and the minimum delay time was recorded at twenty five seconds. The time it took the first person to evacuate was twenty one seconds and the last person to evacuate was two hundred and ten seconds. On the third floor, a male occupant (age range, 13-19 years old) from the Stair Flow wearing a security uniform stopped at the landing and deferred to sixteen females entering the stair from the Floor Flow, before he began his descent. Figure 4.27 shows the resultant merging and stoppage time due to the occurrence of this deference behaviour. The graph shows the percentages of the Stair Flow and the Floor Flow that merged on the landing. At ten seconds, the incoming stair flow stopped and deferred to the Floor Flow on the third floor. The stoppage lasted for up to forty five minutes. The Stair Flow began to move but stopped again ten seconds later for a further ten seconds. A complete stoppage occurred because of the deference behaviour and lasted for almost forty seconds.

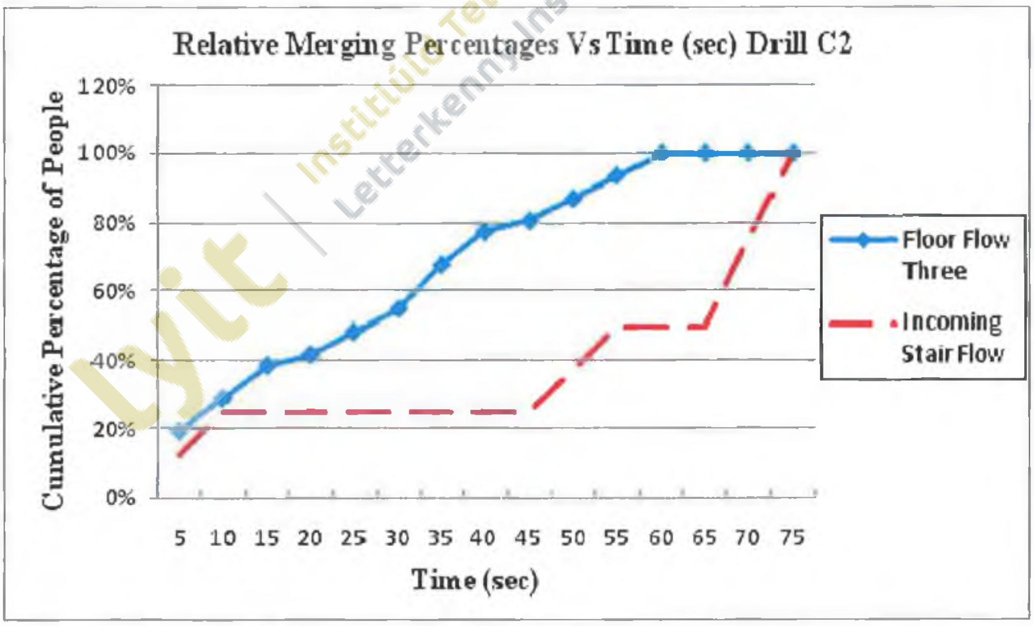


Figure 4.27: Relative Merging Percentages versus Time Drill C2 on Floor Three.

Merging on the second floor was found to have more evenly shared merge ratios. Floor Flow Y entered the stair first and it appeared to be easier for Floor Flow Y to develop a 50:50 merge with Floor Flow X. Figure 4.28 shows the percentage of the stair and floor flow that merged on the landing on the second floor.

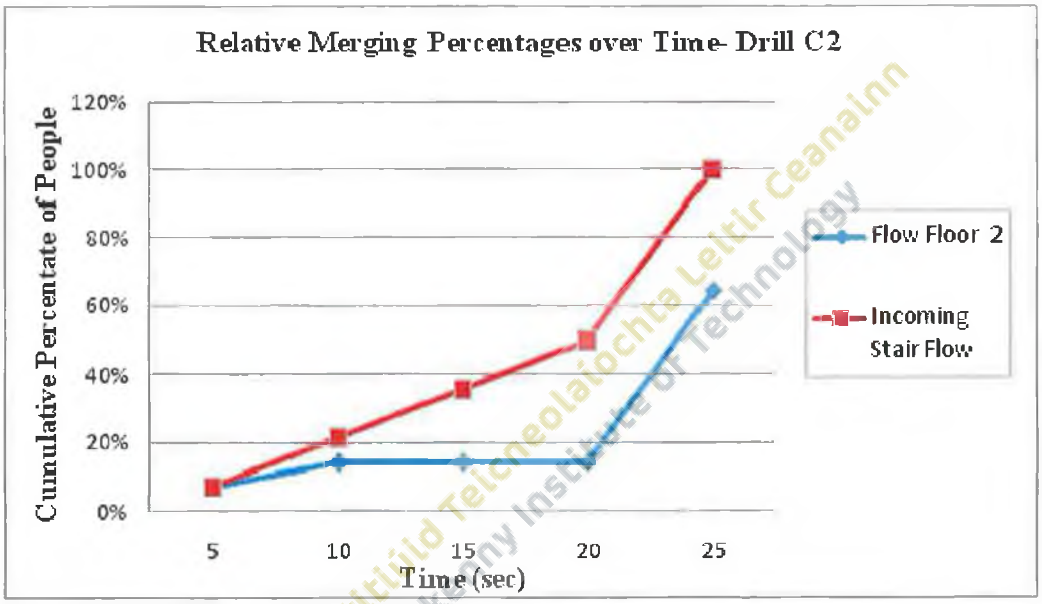


Figure 4.28: Relative Merging Percentages over Time Drill C2 on Floor Two.

The crowd movement slowed down considerably and then eventually it came to a halt due to deference behaviour which occurred on floor one. On floor one the Stair Flow deferred to the entire Floor Flows when three girls (age range, 13-19 years old) leading the Stair Flow, stopped at the first floor landing and waited until the entire floor emptied. This behaviour resulted in a complete stoppage on the floors above. Figure 4.29 shows how this behaviour affected the stair flow's evacuation.

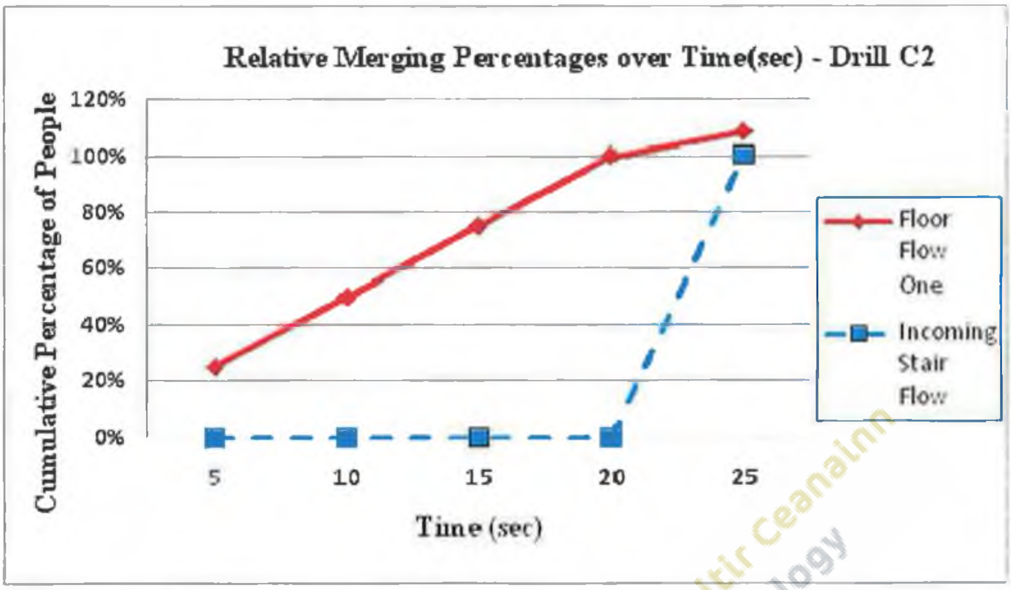


Figure 4.29: Relative Merging Percentages over Time Drill C2 on Floor one.

The delay time in Drill C2, which was experienced, by a number of the fourth floor occupants is represented graphically in Figure 4.30. Occupant one and two experienced little delay, as they were not affected by deference behaviour. They evacuated prior to the occurrence of deference behaviour.

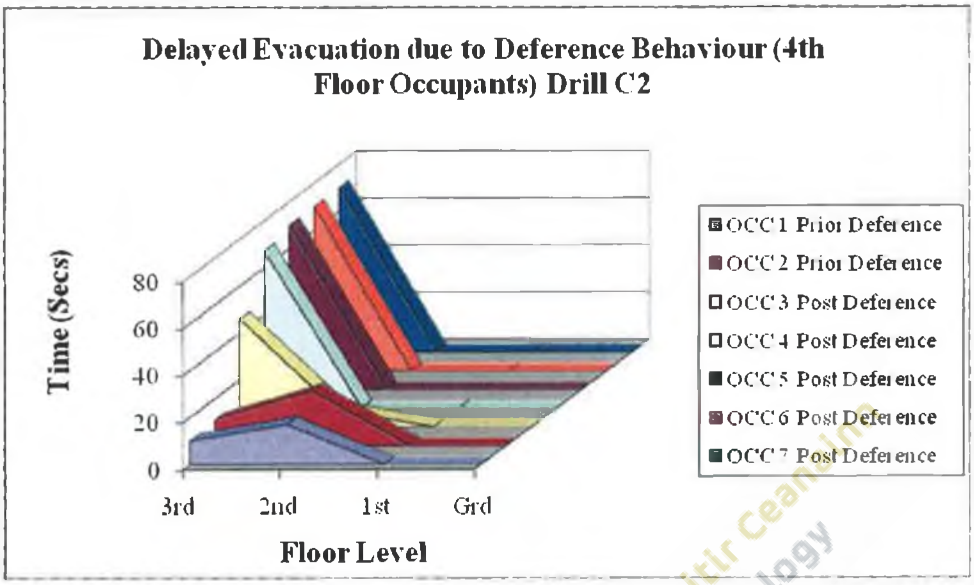


Figure 4.30: Delayed Evacuation due to Deference Behaviour Drill C2.

Occupant three, four, five, six and seven were all affected by deference behaviour. Figure 4.30 shows how one occasion of deference behaviour can affect the flow of occupants during a building evacuation.

4.11 Delay Time during Drill C3.

The delay time recorded does not include any delay for the fourth floor occupants as they used an alternative escape route. As previously explained this stairway was blocked for all occupants but came available for the fourth floor occupants during evacuation drill C3. Figure 4.31 shows the average delay time experienced by the occupants of each floor. The maximum delay time recorded for Drill C3 was experienced by the third and fourth occupants at 79 seconds.

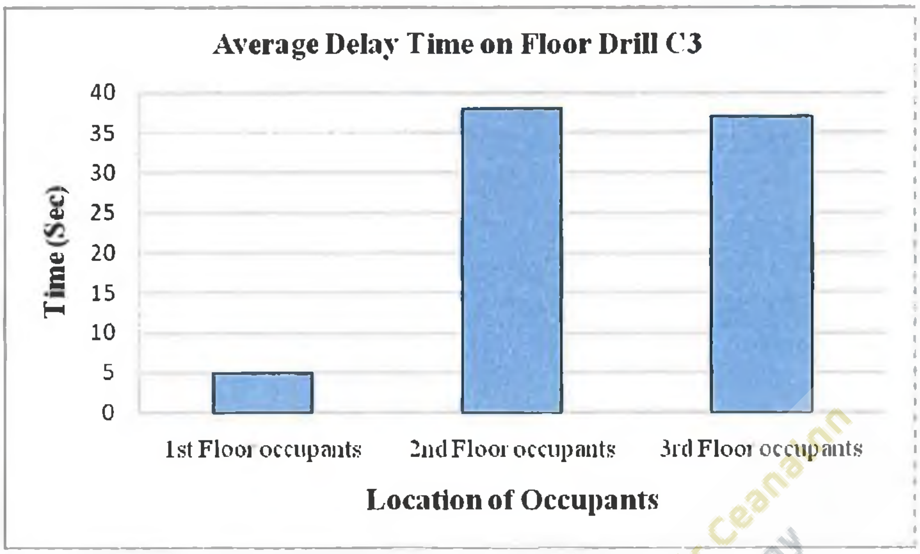


Figure 4.31: Average Delay Time Drill C3.

Figure 4.31 clearly shows that the second floor occupants experienced the greatest delay time while the first floor occupants experienced a very short delay time of five seconds. The second floor occupants experienced a high delay time due to deference behaviour occurring on the first floor.

On floor one a male occupant from the Stair Flow wearing a trainee security guard uniform stopped at the landing and deferred to five females entering the stair from the floor flow, before he began his descent. This is referred to as incident one for the purpose of the study. A complete stoppage occurred in the stair flow because of the deference behaviour, which continued for up to forty seconds. Figure 4.32 shows how the deference behaviour of incident one affects the occupants in the stair flow. The graph shows seven occupants from the second floor. The first two occupants (1 and 2) experienced a very short delay time from merging with the first floor occupants on the first floor landing.

Occupant three(Male, age range 20-39 years) deferred to the first floor occupants on the first floor landing and stopped for almost thirty seconds. Figure 4.36 shows how this incident of deference behaviour affected the remaining four occupants. The period of delay time lasted for almost forty seconds. The occupants he deferred to were both female and male and ranged from thirteen to nineteen and twenty to thirty nine years old.

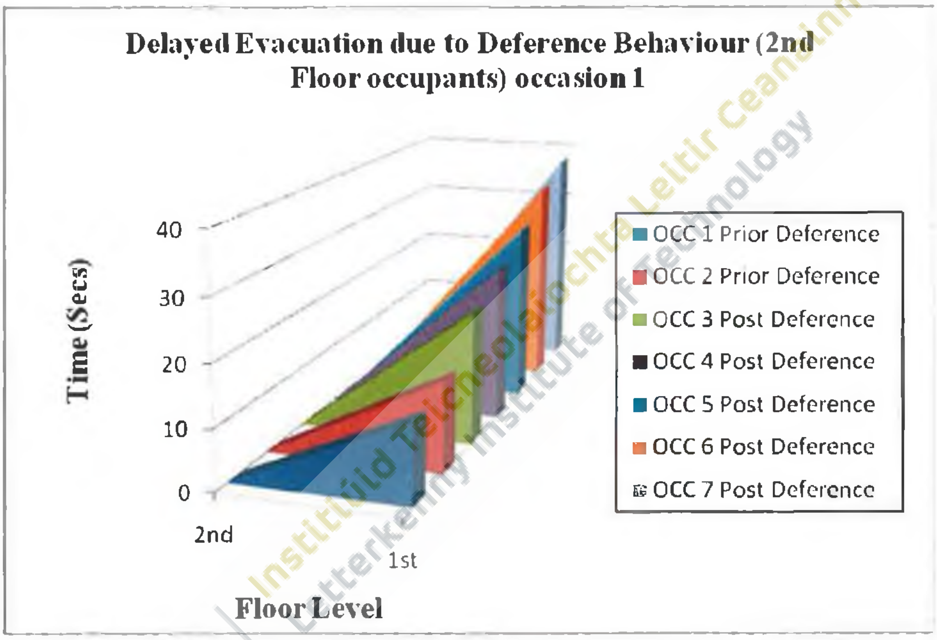


Figure 4.32: Deference Behaviour Incident 1, (Floor one).

Incident 2 involves Floor Floor X and Y on Floor one. A young male (age range twenty to thirty nine years old) from Floor Flow X deferred to three young females (age range thirteen to nineteen years old) from Floor Flow Y. Figure 4.33 shows how the deference behaviour of incident two affected the occupants in the floor flows. Occupants one and two evacuated prior to the deference behaviour on floor one and were therefore not impacted by this occurrence. Occupant's three to seven from Floor Flow X were impacted by this occurrence of deference behaviour for a period of almost twenty seconds.

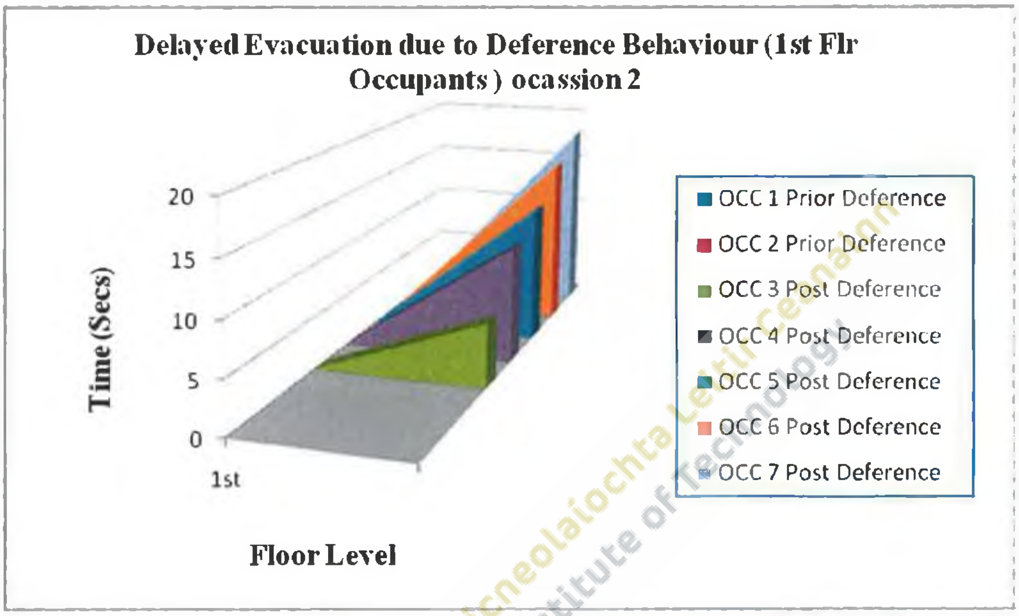


Figure 4.33: Deference Behaviour Incident 2, (Floor one)

Figure 4.34 shows how the deference behaviour of occasion three affected the occupants in the stair flow. Occasion 3 involved the stair flow deferring to the floor flow. There were two separate incidents of deference behaviour that occurred within a short time of each other. For this reason the two incidents have been combined. The first incident involved a female (age range of forty to sixty four years old) from the stair flow who deferred to three young occupants from Floor Flow Y. The second incident involved a young female (age range twenty to thirty nine years old) who deferred to two young occupants (age range twenty to thirty nine) from Floor Flow Y. Occupants one and two evacuated prior to the deference behaviour on floor one and were therefore not impacted by this occurrence. Occupants' three to seven from Floor Flow X are impacted by this occurrence of deference behaviour for a period of up to thirty seconds.

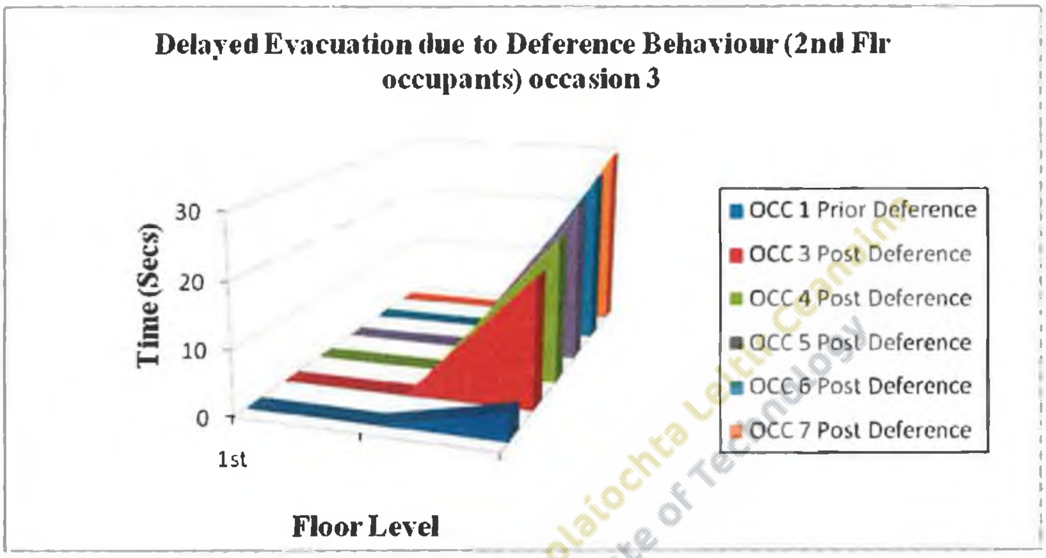


Figure 4.34: Deference Behaviour Incident 3, (Floor one)

The bar chart in Figure 4.35 illustrates the difference between the three incidents of deference behaviour that occurred on floor one during Drill C3. The delay time experienced during incident one was the greatest where a young male dressed in a trainee security guard uniform from the Stair Flow deferred to five young female occupants from the Floor Flow. It could be suggested that role play influenced this occurrence of deference behaviour i.e. the trainee security guard was playing a role of authority.

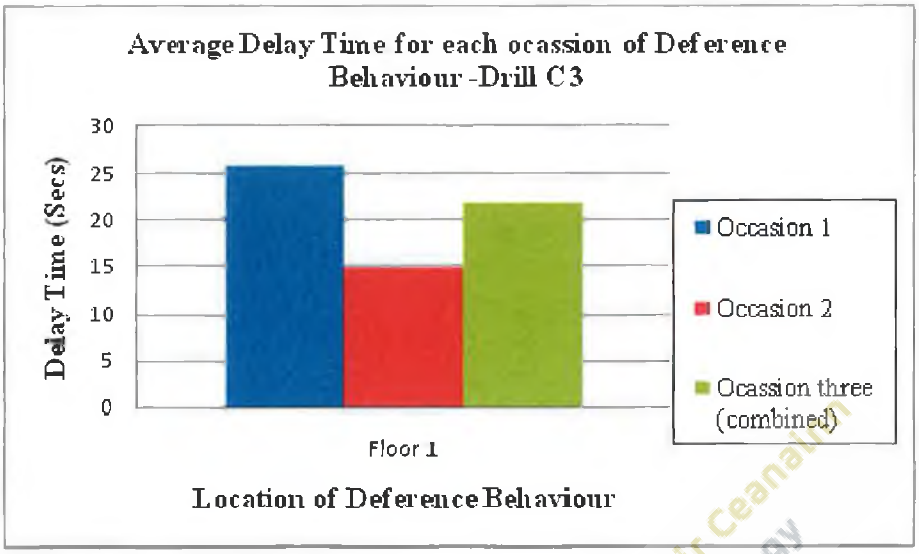


Figure 4.35: Average Delay time (deference behaviour) Drill C3

Table 4.21 below gives a breakdown of the three different incidents of deference behaviour in Drill C3. It also gives a description of the occupant characteristics of the occupants who stop and defer, the number of occupants deferred to and the average stoppage time that occurred due to this deference behaviour.

Location of Deference Behaviour	Occupants Characteristics	Flow (people)	No. Deferred to (people)	Flow Deferred to (people)	Average Stoppage Time (Sec)
Floor 1 Incident 1	20-39 yr old Male, trainee security guard.	Stair	5	Floor Flows X & Y	25
Floor 1 Incident 2	20-39 yr old Male, student.	Floor X	3	Floor Flow Y	15
Floor 1 Incident 3	40 – 64 yr old female, &20-39 yr old female student.	Stair	5	Floor Flow Y	18

Table 4.21: Description of Deference Behaviour during Drill C3.

The table highlights that the highest average stoppage time during drill C3 occurred as a result of deference behaviour on Floor one. It was interesting to find that an occurrence of deference behaviour found in Drill C3 had similar occupant characteristics with an occurrence found in Drill C2. Two out of three of the incidents of deference behaviour as shown in Table 4.21 highlight that the Stair Flow deferred to the Floor Flow. The second incident showed how Floor Flow X deferred to Floor Flow Y.

4.12 Comparisons between Drills, C1, C2 and C3.

Three drills C1, C2 and C3 were carried out in building C Drill C2 and C3 took place in the same building under the same conditions. They were both unannounced evacuation drills carried out by the building management team. The occupants in the building were both students and staff. Drill C3 was a repeated study of Drill C2 and similar conclusions have been drawn. During the evacuation of Drill C2 all occupants on each of the floors used the front stair in the building and none of the occupants used the rear stairs as they were directed to do so by the fire marshals present during the drill. The same directions applied during Drill C3 however, the fourth floor occupants continued to use the rear stair during the evacuation drill. As a result, the fourth floor occupants were omitted from some of the analysis. The stair population density was much lower in Drill C1 as both stairs were made available for escape. Therefore, Drill C1 recorded insignificant merging activity for analysis. The comparisons for merging activity were therefore made between Drill C2 and C3 in building C, as conditions were similar. In addition, the stoppage and delay time was insignificant for Drill C1 and has not been included in the comparative analysis.

4.12.1 Location of Entrances

In all three drills carried out in Building C the highest floor flow rates were recorded at Floor Flow X. The entrance at Floor Flow X is located adjacent the Stair Flow. Floor Flow X took priority over the Stair Flow during all drills in Building C except for one floor in Drill C1 where Floor Flow Y took priority over Floor Flow X on Floor two. The stair flow deferred to the Floor Flow X in all three drills in Building C and consequently it created a delay to the occupants on the floors above. The results of both Drill C2 and

C3 show that the floor flow rate of Floor Flow X was high and as a result the occupants on the stair flow experienced delays.

This finding suggests that it may be favourable to have an entrance onto a stair/landing on the opposite side to an incoming stair flow. Positioning the entrance to the stair/landing to the opposite side of an incoming stair flow decreased the chances of one flow having a strong priority over the other flow during an evacuation hence creating a more efficient evacuation.

4.12.2 Delay Time

There were considerable delays experienced by the occupants during Drills C2 and C3. The maximum delay time during Drill C2 was found to be 115 seconds experienced by the third and fourth floor occupants. The maximum delay time during Drill C3 was found to be one 79 seconds experience by the fourth floor occupants. The reason for these delays was the occurrence of merging and deference behaviour, which took place on the stair floor landings. The delays affected the Stair Floor mostly in Drill C2 and C3. The Floor Flows had priority during both drills and there were a number of incidents of deference behaviour by the Stair Flow during Drill C2 and C3 that caused these delay times. A description of the type of deference behaviour was described in Table 5.21. The different incidents of deference behaviour in both Drills C2 and C3 had the same negative impact on the occupants in the Stair Flow and the occupants in the higher floors. The deference behaviour that took place in both Drills C2 and C3 was carried out by the Stair

Flow occupants. The similar results highlight the possibility of role playing having been a contributing factor to the occurrence of the deference behaviour. During both drills the trainee security guards began their evacuation on the Fourth floor. Both incidents of deference behaviour, which occurred, affected the evacuation of the occupants in the Stair Flow and the occupants in the floor above.

4.12.3 Speed of Travel on Stairs

The observed speed of travel on the stairs was calculated for both Drills C2 and C3. The predicted speed of travel on the stairs was also calculated and comparisons were made between the observed and predicted speed of travel. The predicted speeds obtained resulted in higher speeds than what was observed.

4.13 Summary of Analysis of Building C

The findings from all drills carried out in Building C were very similar. However, Drill C1 had fewer occupants during the evacuation drill and less merging and delays occurred. Drills C2 and C3 had very similar findings. The merging results showed that the Stair Flow deferred to the Floor Flows on almost all floors. This observation does not concur with Pauls [5] who found that evacuees in the Stair Flow generally deferred to those entering from the Floor Flow. As there were two Floor Flows in Building C, it was found that one flow had priority over the other. The flow with the highest priority was Floor Flow X. A possible reason for this is the position of the entrances onto the landing. Floor

Flow Y was closest to the stair than Floor Flow X however, it was Floor Flow X that took priority during the evacuation. The location of the entrances seemed to have an impact on the merging process between flows. This observation of merging corresponded with findings from Takeichi et al [116] and Galea et al [37] i.e. that the location of the door opposite the Stair Flow can cause a lower floor flow rate. The study showed that the occupants' evacuation from Floor Flow Y did not begin to move until a space became free or an occupant from the opposing flows deferred to them.

Using three different merge points in Drills C2 and C3 highlighted that there was a relationship between the merge ratio and the flow rates at these merge points.

A description of factors associated with the three occurrences of deference behaviour showed that there was no definite trend found between incidents of deference behaviour. At this point, it cannot be concluded if gender or age had an impact on deference behaviour. However, one occasion of deference behaviour that occurred in Drill C3 also occurred in Drill C2 where a young male trainee security guard in uniform also leading the Stair Flow deferred to the Floor Flow. The fact that the same occurrence of deference behaviour took place in Drill C2 with similar conditions highlighted that it was possible the young male wearing a security uniform felt he was playing a role of authority.

Stoppage occurred on the upper floors in Drills C2 and C3 because of deference behaviour, which occurred on the first floor landing during Drill C2 and first and third floor landing during Drill C3. This had a significant negative impact on merging and deference behaviour i.e. it can put the occupants on the higher floors as was the case in Drill C3 were floors two and three were at a greater risk during evacuation.

The results also revealed that there was a significant difference between the observed speed and the predicted speed as shown in Tables 4.19 and 4.20. This is an example of how engineering calculations do not take into account the type of occupants' behaviour that can occur on the stairs during a building evacuation.

4.14 Conclusions

From the analysis of the results, it was found that the flow from the entrance adjacent to the stair flow took priority during the evacuation. The flow from the entrance opposite the Stair Flow created a more evenly merging process. In an ideal evacuation, it may be favourable to have an entrance positioned onto a stair landing opposite to the Stair Flow to create a 50:50 merge ratio, which in turn will prevent increased delay times for occupants on higher floors especially in high rise buildings. Even though the entrance adjacent to the stair flow created a high flow rate from that floor it also created a higher delay time to the occupants already on the stairs on floors above.

It cannot be assumed that only one merge point on a landing occurs on a landing in all building evacuations. In Building C merging was recorded for three merge points on the landing. Findings showed a trend in the merge and flow rate relationship.

It was difficult to identify the reasons behind the occurrences of deference behaviour and whether gender or age played a role. This is an area that perhaps requires further attention. A negative and worrying impact of lengthy periods of deference behaviour was the stoppage times that occurred. During the three evacuations in Building C the stoppage times that occurred as a result of deference behaviour caused the occupants on higher floors to experience delay time and in turn put their evacuation at a greater risk.

The comparison results between the observed and predicted speeds on the stairs were hugely different. This result highlighted that the engineering calculations i.e. the speed formula used did not accurately estimate the speed of travel on the stairs for the evacuations of Building C. It can be suggested that formulae used to calculate the speed on stars be revised to include the likelihood of deference behaviour and merging.

Chapter 5: Analysis of Building L

5.1 Introduction

In Building L a single evacuation was carried out. An analyses was undertaken on the data collected. The crowd movement was fluid and consistent on the eight floors observed. Short periods of merging were observed on floors, nine, eleven, twelve and floor seven. A phased evacuation procedure was employed for this drill.

5.2 Merging during Drill L1

No merging was observed on floors ten, thirteen, fourteen and fifteen due to a number of possible factors such as the phased evacuation procedure or the use of the south stair. The merging observed was evenly shared due to a low density population on the stairs. Table 5.2 shows the merging activity on the seventh floor during the evacuation Drill L1. When the Stair Flow and Floor Flow entered onto the stair floor landing, they competed for the space on the landing in order to proceed with their evacuation.

The flow rate was also calculated at the same merge point. The tables provided in this section include a brief analysis of the type of behaviour observed during the merging activity.

Time Period (Secs)	No. From Stair Flow (People)	No. From Floor Flow (People)	Merge Ratio Stairs: Floor (People)	Flow Rate at Merge Point (persons/sec)	Behaviour Observed
0-10	3	7	30:70	1	One occupant from the Stair Flow deferred to the Floor Flow occupants.
10-20	7	2	77.78:22.22	1	The Stair Flow began to take priority over the Floor Flow. The Floor Flow occupants are standing facing the Stair Flow.
20-30	5	3	62.5:37.5	0.9	The Stair Flow had priority. Two occupants of the Stair Flow were carrying laptops with monitors open which slowed down the flow rate at the merge point slightly.
30-40	6	3	66.67:33.33	1.1	The Stair Flow continued to have priority.
Total	**21**	**18**	**54:46**		

Table 5.1: Drill L1, 7th Floor Merge Analysis.

Table 5.1 shows the merging activity on the seventh floor during the evacuation Drill L1. The priority of merge belonged to the stair flow on this floor. A number of occupants from the stair flow were carrying laptops with the screens open. This type of behaviour showed a decrease in the occupant's movement on the stairs and landing as a result of carrying these items and it caused the flow rate at the merge point to slow down.

Time Period (Secs)	**No. From Stair Flow**	**No. From Floor Flow**	**Merge Ratio Stairs: Floor**	**Flow Rate at Merge Point (persons/sec)**	**Behaviour Observed**
0-10	6	2	75:25	0.6	Two occupants from the Floor Flow held the door open and merged with the Stair Flow.
10-20	3	1	75:25	0.6	The Stair Flow began to take priority over the Floor Flow.
Total	**9**	**3**	**75:25**		

Table 5.2: Drill L1, 9th Floor Merge Analysis.

Table 5.2 shows the merging activity on the ninth floor during the evacuation Drill L1. The table shows that the Stair Flow had priority over the Floor Flow on this floor.

Time Period (Secs)	No. From Stair Flow (people)	No. From Floor Flow (people)	Merge Ratio Stairs: Floor	Flow Rate at Merge Point (persons/sec)	Behaviour Observed
0-10	8	3	73:27	0.6	One occupant from the stair flow deferred to the Floor Flow occupants.
10-20	3	5	37.5:62.5	0.6	The Floor Flow began to take priority.
Total	**11**	**8**	**57:23**		

Table 5.3: Drill L1, 11th Floor Merge Analysis.

Table 5.3 shows the merging activity on the seventh floor during the evacuation Drill L1. Again, the Stair Flow had priority on this floor.

Time Period (Secs)	**No. From Stair Flow (people)**	**No. From Floor Flow (people)**	**Merge Ratio Stairs: Floor**	**Flow Rate at Merge Point (persons/sec)**	**Behaviour Observed**
0-10	3	2	60:40	0.9	The Stair and Floor Flow merge easily.
10-20	5	5	50:50	1	The Stair and Floor Flow merge easily.
Total	**8**	**7**	**53:47**		

Table 5.4: Drill L1, 12th Floor Merge Analysis.

Table 5.4 shows the merging activity on the twelfth floor during the evacuation Drill L1. The Stair and Floor Flow merge easily on this floor. There was only one entrance onto the landing positioned opposite the incoming Stair Flow in Building L, see Figure 3.4 in chapter 3. The swing of the door opened out onto the landing. This meant that the occupants from the Floor Flow had to hold the door open while making their evacuation. Findings from the results of Drill L1 showed that the Stair Flow took priority over the Floor Flow and does not concur with studies by Pauls as outlined earlier. The occupants of the Floor Flow could see that the Stair Flow were already on the stairs and had priority. In addition to this, the occupants on each floor may not have been familiar with each other due to different tenancies on each floor. However, the merging observed in Drill L1 were for short periods of time and may be considered as indicative.

5.3 Evacuation Behaviour

On floor seven during Drill L1 a male occupant from the Floor Flow deferred to four female occupants from the Stair Flow. Two females deferred to four female occupants from the incoming Stair Flow on the eleventh floor. From the short periods of merging activity as shown in Tables 5.1 to 5.4, the Stair Flow had priority over the Floor Flow. From analysis of the video recordings, it was seen that the occupants who entered the landing from the floor could see that the occupants from the floors above were already on the stairs. The Floor Flow deferred to the Stair Flow and allowed them to continue their descent.

Figure 5.1 (a) and (b) show other types of behaviour that occurred on the stairs during evacuation Drill L1. A number of occupants from the sixteenth floor carried their laptops with the screens open on the stairs while making their evacuation. Occupants from various floor carried mugs of hot beverages while others made phone calls and sent text messages while making their evacuation from Building L.

(a) Occupant Carrying Coffee Mug. (b) Occupant Carrying open Laptop.

Figure 5.1: Evacuation Behaviour Drill L1.

5.4 Stair population density

Figure 5.2 illustrates the stair population density for Drill L1 and it indicates that there was a high population density on floors fourteen to thirteen and thirteen to twelve reaching 4.1 population/m^2 after 340 seconds. Some crowding was observed on various floors however at no stage were there stoppages or long periods of merging. The crowd movement was fluid and consistent on the eight floors observed. This was possibly a result of the phased evacuation procedure.

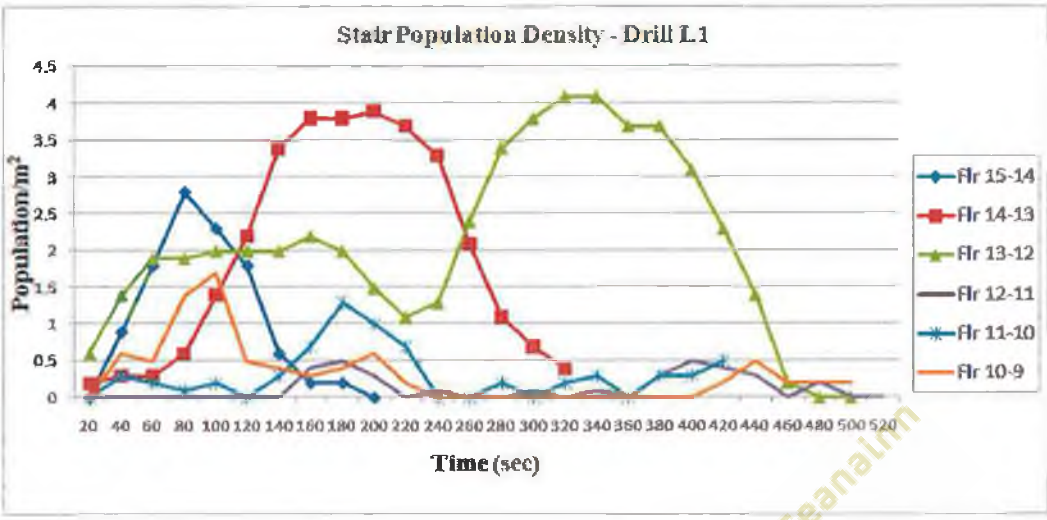


Figure 5.2: Stair Population Density Drill L1.

The Floor Flow rate as shown in Figure 5.3 was high on most floors during evacuation Drill L1 due to the phased evacuation procedure. The phased evacuation also resulted in the merging which allowed the occupants from the floor to move faster onto the landing.

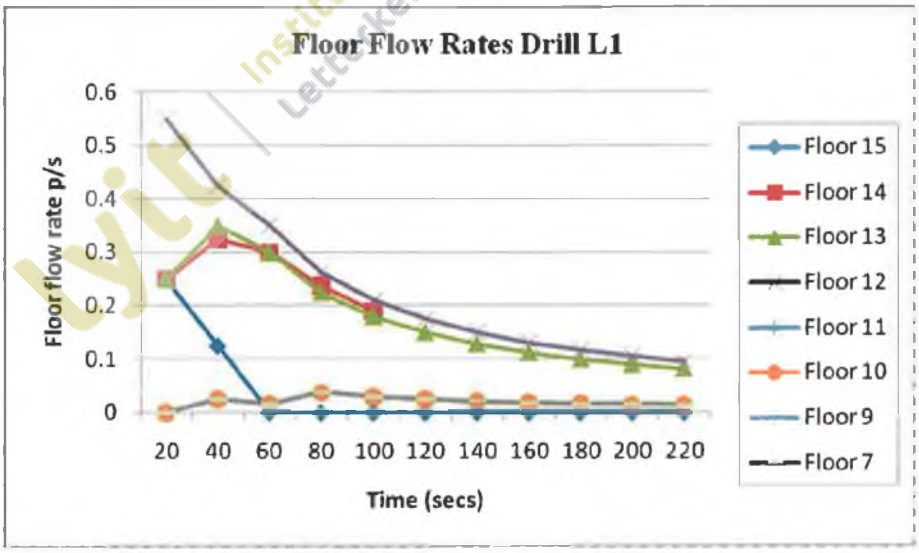


Figure 5.3: Floor Flow Rate Drill L1.

5.5 Speed of Movement

Table 5.5 shows the observed speed and predicted speeds for Drill L1.

Stairwell	**Floor**	**Density p/m2**	**Observed mean speed m/s**	**Calculated speed m/s S= 1.08- (0.266. 1.08.Dpop)**
Drill L1	16-15	0.65	0.426	0.894
	15-14	1.33	0.426	0.698
	14-13	2.47	0.426	0.371
	13-12	2.95	0.367	0.233
	12-11	0.35	0.384	0.979
	11-10	0.53	0.365	0.928
	10-9	0.67	0.349	0.888
	9-8		0.375	*

Table 5.5: Observed Speed and Predicted speeds for Drill L1.

* *The predicted speed was not calculated for floors 9 to seven as there was no camera positioned on floor eight.*

Figure 5.4 shows a comparison between the observed average speed and the predicted speed obtained for Drill L1. The bar chart clearly shows that there was a significant difference between both calculated speeds. Table 5.5 shows how the population densities varied for most of the floors. The results of the predicted speed show the relationship between the population density and the predicted speed. When the density was higher, the predicted speed of travel was slower and had a closer result to the observed speed as it can be seen for floors fourteen to thirteen and thirteen to twelve in Table 5.5. When the density was lower, the predicted speed of travel was much faster than the observed speed of travel.

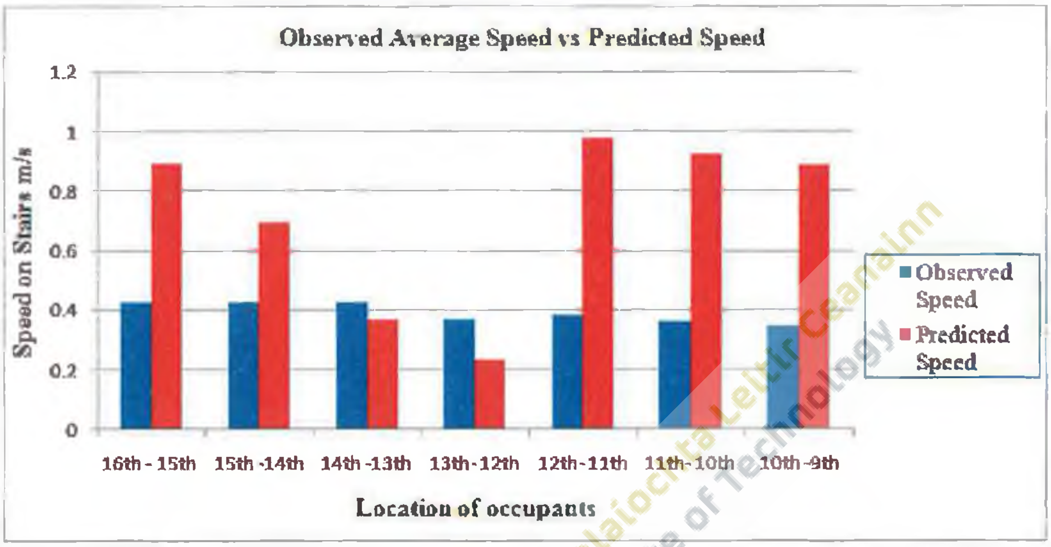


Figure 5.4: Comparison of Observed vs Predicted Speed Drill L1.

Figure 5.5 shows the merging percentages between the Floor Flow and the Stair Flow. It shows clearly that the Stair Flow has the highest percentage of occupants merging on the landing. The Floor Flow has a lower percentage of occupants merging with the Stair Flow and highlights a delay time. This delay time was a result of the Stair Flow having priority over the Floor Flow.

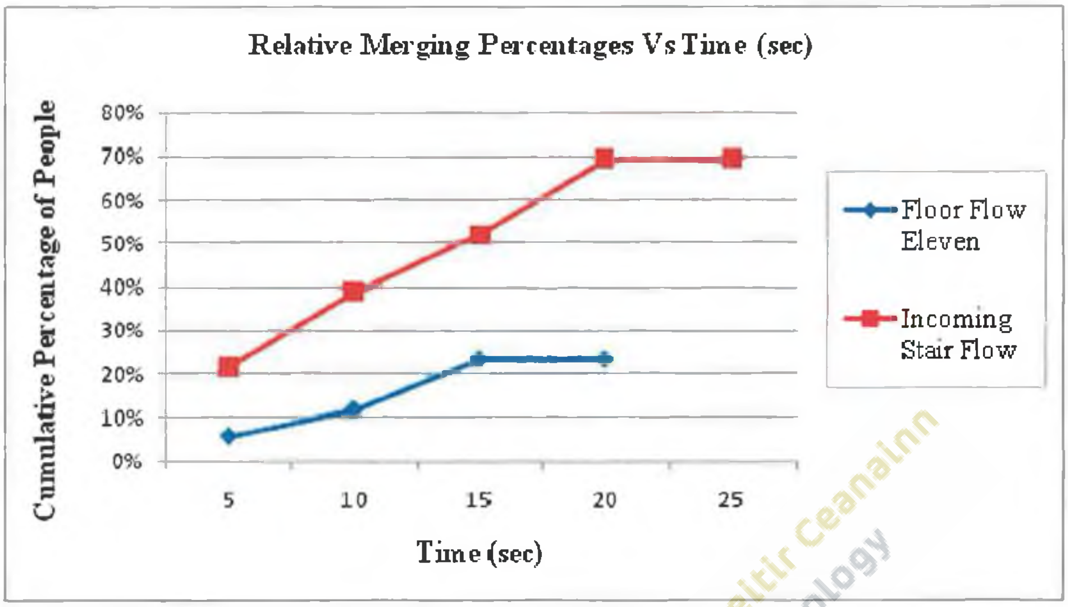


Figure 5.5: Relative Merging Percentages Vs Time, Drill L1.

Figure 5.6 shows the merging percentages between the Floor Flow and the Stair Flow. It shows clearly that the stair flow had the highest percentage of occupants merging on the landing. The Floor Flow had a lower percentage of occupants merging with the Stair Flow and highlighted a stoppage time. The stoppage time was a result of the Stair Flow having priority over the Floor Flow.

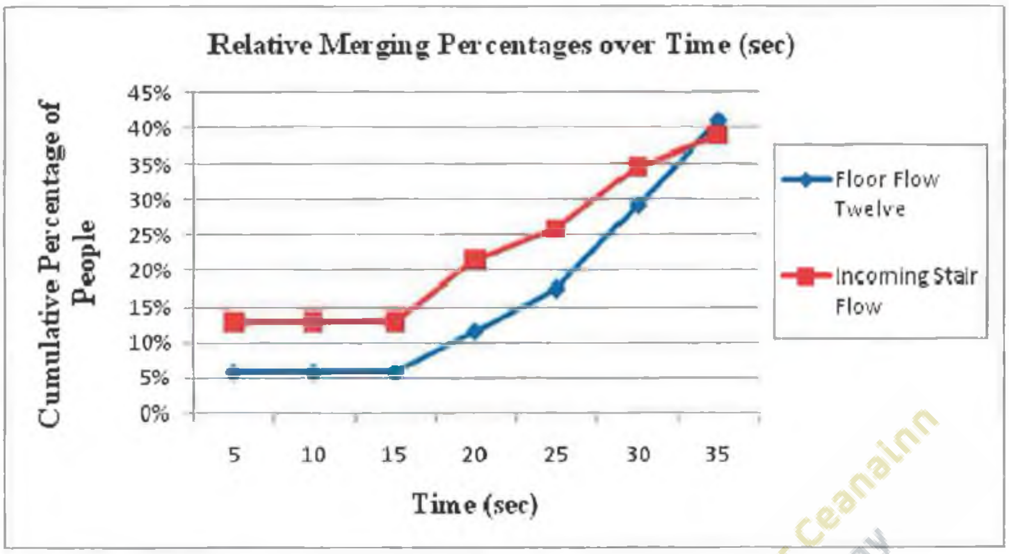


Figure 5.6: Relative Merging Percentages Vs Time, Drill L1.

5.6 Summary of Analysis of Building L.

Findings from the results of Drill L1 show that the Stair Flow took priority over the Floor Flow. The occupants of the Floor Flow in Building L could see that the Stair Flow had taken priority. A possible reason for this may be that the occupants were not as familiar with the different tenancies in the building.The results also revealed that there was a significant difference between the observed speed and the predicted speed as shown in Table 5.5. Again, the predicted speed calculated that the occupants would move at a faster speed than that observed.

5.7 Conclusions

Overall, the merging that occurred on the landings throughout the evacuation Drill L1, resulted in the Stair flow having priority over the Floor flow. It would have been interesting to investigate how a high-rise building similar to Building L would evacuate simultaneously. It would be expected that simultaneous evacuation would cause longer merging periods and this would have a huge affect to the occupants trying to enter the stairs above. The crowd movement observed was fluid and consistent on each floor because of the phased evacuation procedure employed for Drill L1.

Occupants from various floors carried mugs of hot beverages while others made phone calls and sent text massages on the stairs while making their evacuation. This type of behaviour on the stairs possibly resulted from a low level of perceived risk. It might be inferred that the occupants assumed it was a drill and continued with their morning coffee break. This type of behaviour can have a negative impact on an evacuation. It can cause slower movement on the stairs. The carrying of these items can cause obstruction to the occupants and possibly result in a fall. More space is required also for the occupants to carry these items down the stairs.

The predicted speeds calculated were much higher than the actual observed speeds. The results show that when the density was high the predicted speed was slower and had a closer result to the observed speed. When the density was lower, the predicted speed of travel was faster than the observed speed. This finding reinforces the findings of the other drills. It is not clear as to why the latter is the case in this instance, and it would be considered prudent to undertake further analysis on a larger sample size of evacuations to see if this trend is particular to the scenarios investigated.

Chapter 6: Analysis of Building D

6.1 Introduction

A single evacuation was carried out in Building D. An analysis was undertaken on the data collected. The evacuation procedure employed was simultaneous. Figure 3.6 in chapter 3 shows a plan view of layout of the stair and landing in Building D. Floors, one and two were observed during the evacuation drill in Building D.

6.2 Merging during Drill D1.

It should be noted that merging only occurred on floor one during Drill D1 as there were no occupants occupying the third floor at the time of the evacuation. The merge point used is shown in Figure 3.8 in the methodology chapter. Table 6.1 includes a brief summary of the type of behaviour observed during the merging activity.

Time Period (Secs)	No. From Stair Flow (People)	No. From Floor Flow (People)	Merge Ratio Stairs: Floor	Flow Rate (persons/sec)	Behaviour Observed
0-10	11	5	67:33	1.6	The Stair Flow took priority, as the flow rate from the Floor Flow was low.
10-20	3	8	27:73	1.1	The priority changed to the Floor Flow when it formed a steady flow from the entrance, which forced the Stair Flow to slow down.
20-30	3	8	27:73	1.1	The Floor Flow continued to take priority.
30-40	9	9	50:50	1.8	Both flows formed an almost evenly shared merge.
40-50	10	8	56:44	0.7	One occupant from the Floor Flow deferred to the Stair Flow, this in turn created a shared access on the landing between both flows.
50-60	7	6	54:46	0.9	Both flows shared almost a 50:50.
60-70	6	6	50:50	1.1	Both Flows shared 50:50.

Table 6.1: Drill D1, 1st Floor Merge Analysis.

Time Period (Secs)	**No. From Stair Flow (People)**	**No. From Floor Flow (People)**	**Merge Ratio Stairs: Floor**	**Flow Rate (persons/sec)**	**Behaviour Observed**
70-80	6	7	46:54	0.7	Both flows continued to share almost a 50:50 merge.
80-90	7	3	70:30	0.8	The Stair Flow began to form two flows into the landing and as a result, the Floor Flow was forced to only one flow entering the landing.
90-100	6	3	67:33	0.8	Priority continued to belong to the Stair Flow.
Total/Average Ratio	**58**	**63**	**48:52**	**1.06**	

Table 6.1 (Continued): Drill D1, 1st Floor Merge Analysis.

When merging began on floor one, the Stair Flow had priority because at this stage the Floor Flow did not form a steady flow onto the landing. As soon as the Floor Flow became steady, it took priority over the Stair Flow. One occupant from the Floor Flow on floor one deferred to the Stair Flow allowing the Stair Flow access to the landing. This in turn created a more evenly shared merge between the two flows. Towards the end of the merge period, the Stair Flow took priority when they formed two flows into the landing this resulted in the Floor Flow resorting to only one flow into the landing. During the evacuation of Drill D1, the overall priority belonged to the Floor Flow. The relationship between the merge ratios and the flow rate at the merge point were not evident in Drill D1. Unlike Drill C2 and C3 (Refer to section 4.2 in chapter 4), the results showed that when the ratio was recorded at 50:50 the flow rate at that merge point was lower than the more imbalanced merge points. This may have been a result of a wider stair and landing compared to the narrow stair in Building C.

6.3 Evacuation Behaviour

The Floor Flow began with a single line entering the stair landing however when the Floor Flow rate increased it formed a double line i.e. two people entered the landing at the same time. This is shown in Figure 6.1.

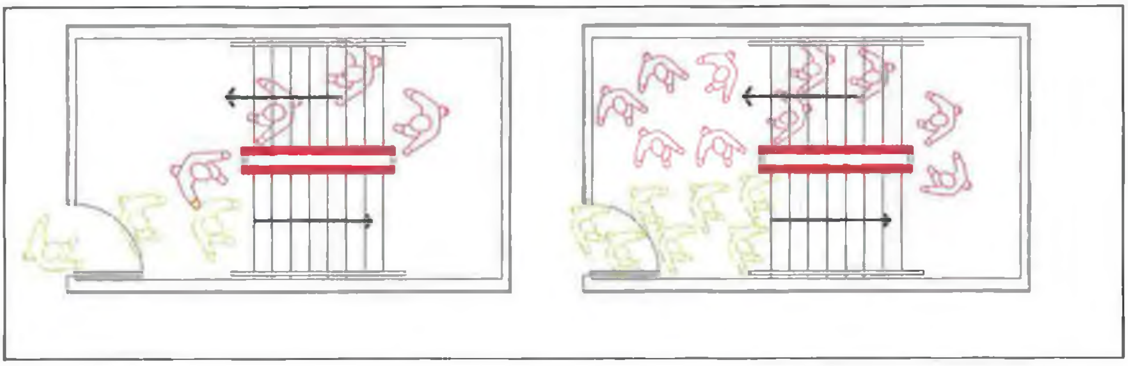


Figure 6.1: Direction of Crowd Movement, Drill D1.

One of the factors, which seemed to impede the Floor Flow, was the direction of the swing of the door entering onto the landing. The door swung in the direction of escape i.e. onto the landing and therefore it had to be held open by the occupants during their evacuation as shown in Figure 6.2 (b). This seemed to impede the timely egress of the evacuees.

(a) Two Flows from the Floor Flow. (b) Door held open.

Figure 6.2: Crowd Movement during Drill D1.

Before the stair population density increased, members of the Stair Flow had to stop when they reached the landing. It may be inferred that the occupants from the Stair Flow found it difficult to enter the landing as the Floor Flow had already occupied the landing with two flows as shown in Figure 6.2 (a). The Stair Flow had to wait until there was space to enter the stair. A number of occupants from the stair flow were forced to move towards the wall to attempt entry into the Floor Flow as depicted in Figure 6.3.

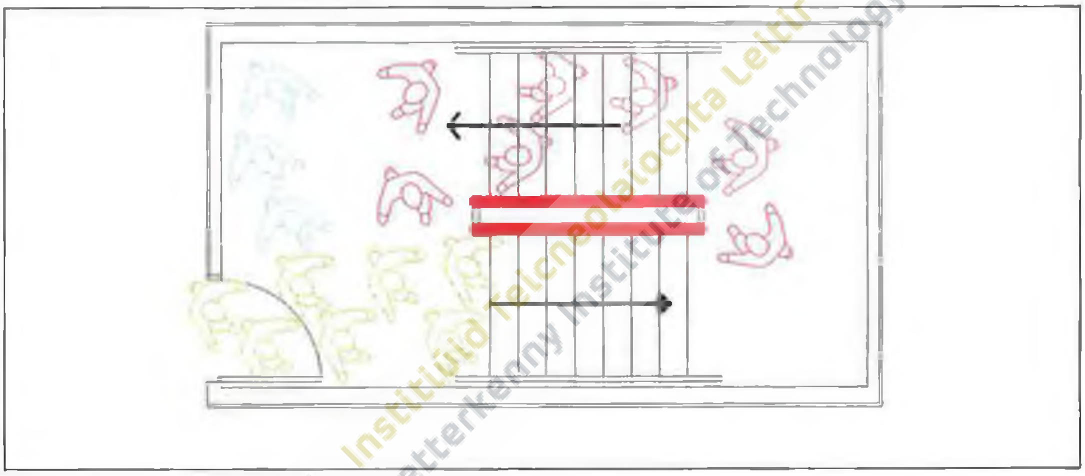


Figure 6.3: Stair Flow Movement onto Landing.

One male occupant who was a staff member from the Floor Flow deferred to an occupant who was also a staff member from the Stair Flow. The Stair Flow was both male and female. This allowed the Stair Flow to have access to the inner space of the landing in order to reach the outgoing stair. After the occurrence of deference behaviour, the Floor Flow continued to move however, they could only achieve one flow onto the landing because of merging with the Stair Flow. Soon after the occurrence of deference behaviour, the Floor Flow regained priority over the Stair Flow. The movement on the stairs slowed to a shuffling speed due to the congestion on both the stairs and the landing.

6.4 Stair Population Density

The Density on the stairs was very high during Drill D1. Figure 6.4 shows the highest and lowest stair population densities for Drill D1. The width of the stair and size of the landing was almost twice the size as the landing and stair in Building C. This allowed more people to enter the stairs increasing congestion which in turn caused a delay time. When movement recommenced it progressed into a shuffling speed on the stairs. It remained like this for the majority of the remaining evacuation.

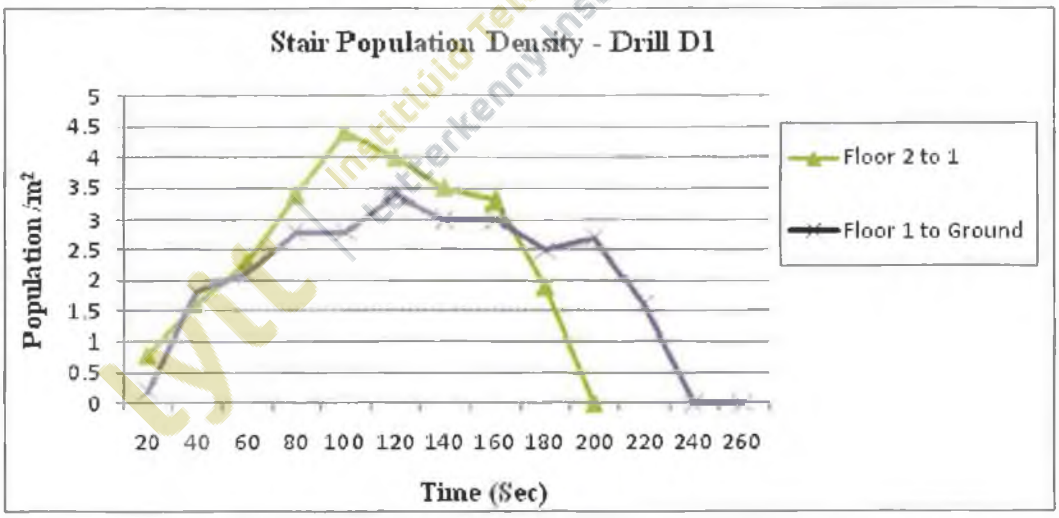


Figure 6.4: Stair Population Density Drill D1.

When the stair population density increased, it was observed that the speed of movement on the stairs decreased. Figure 6.4 shows that the highest recorded density occurred between the second and first floor at approximately one hundred seconds from the commencement of the alarm.

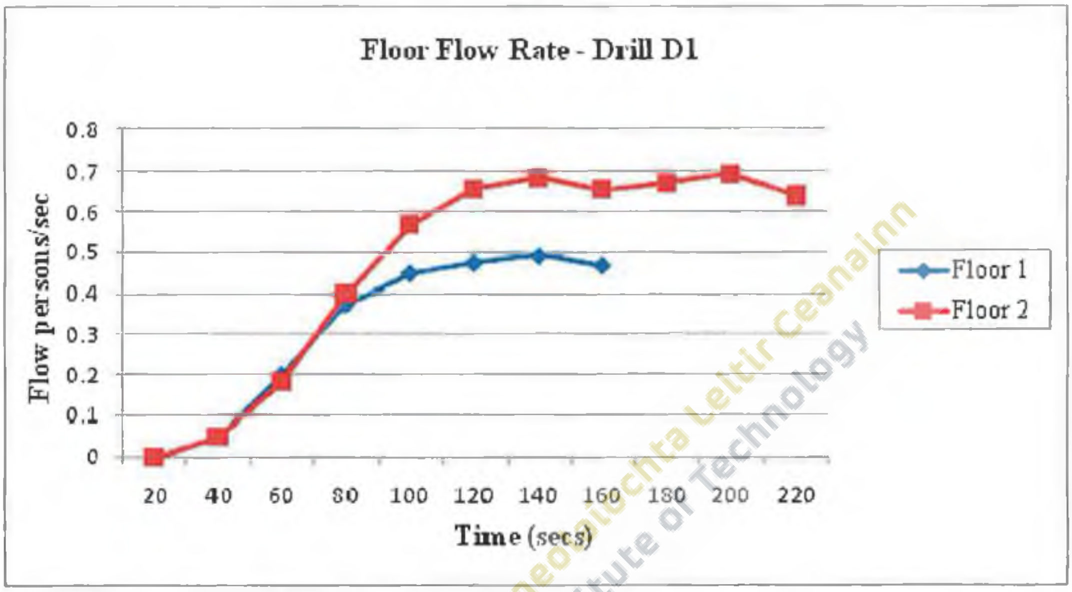


Figure 6.5: Floor Flow Rate during Drill D1.

During Drill D1 the relationship between the Floor Flow rate and the stair population density was not as evident as it was in Drills C2 and C3. Figure 6.5 shows the Floor Flow rate for floor one and two during Drill D1. The increase in the stair population density did not have the same impact as with the other drills observed in other buildings. A reason for this was the size of the stair and landing in each building. The position of the entrance onto the landing also had an impact on the floor flow rate

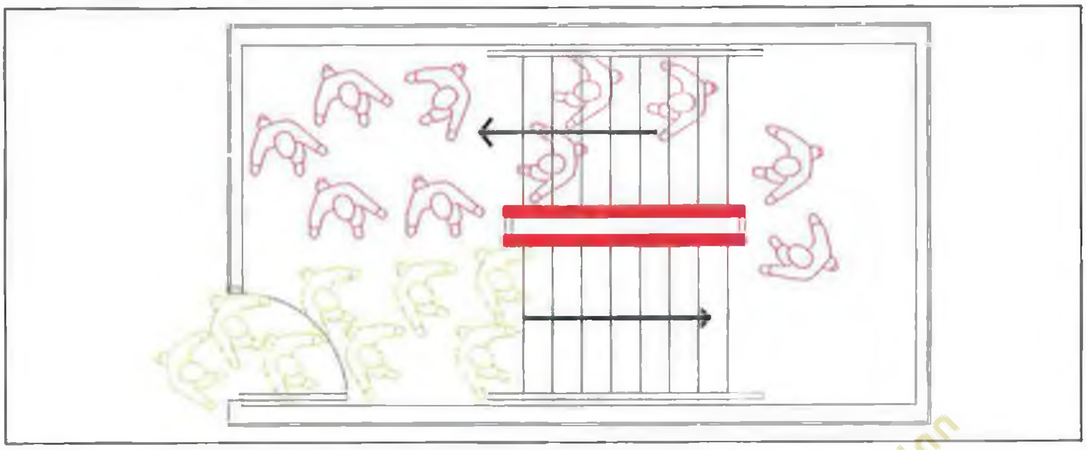


Figure 6.6: Two Flows from Floor Flow, Drill D1.

The door was positioned directly facing the outgoing stair therefore it was easy for the Floor Flow to move straight onto the outgoing stair. The Floor Flow onto the landing was able to form two flows as shown in Figure 6.6.

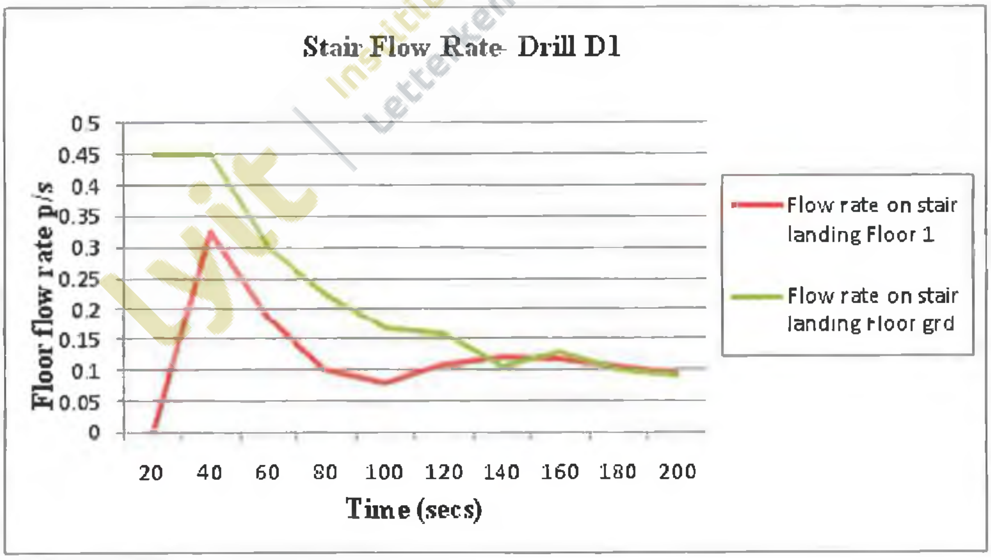


Figure 6.7: Stair Flow Rate during Drill D1.

As shown in Figure 6.7, the flow rate recorded on the stairs at the landing on the ground floor was high as no occupants entered from the ground floor. There were no delays occurring on the ground floor due to a lack of merging and deference behaviour. The Stair Flow rate was lower on the first floor landing as a result of the lengthy merging activity. The Floor Flow took priority, which resulted in the Stair Flow occupants having to wait until a space became free to enter the outgoing stairs. This in turn created a lower stair flow rate between the second and first floor. The occupants of the Stair Flow and on the floors above are put at a greater risk because of the resultant delay time.

6.5 Speed of Movement

The average observed travel time is shown in Figure 6.8. The results show that the second floor occupants recorded the slowest time. This was mainly due to the congestion on the stairs and landing and the delays from merging and deference behaviour occurring on the lower floors. The delays created a higher density on the stairs.

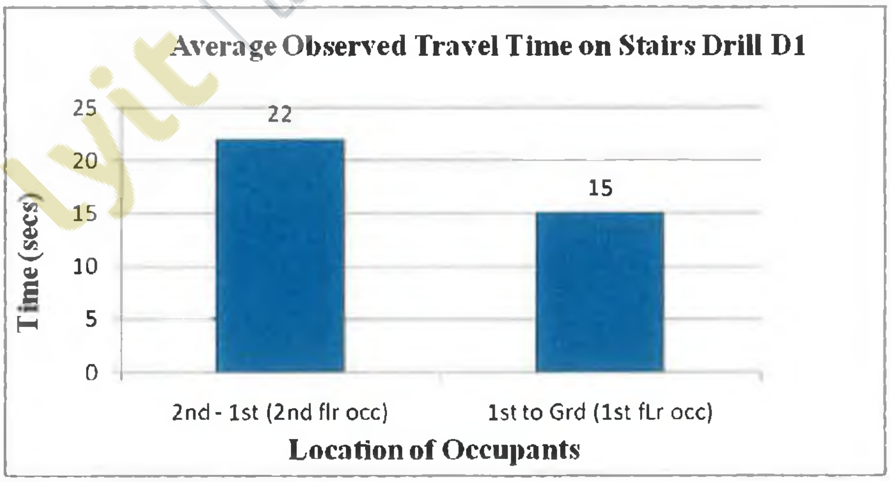


Figure 6.8: Average Observed Travel Time on Stairs between Floors Drill D1.

Figure 6.9 shows the average speed of movement on the stairs between each floor during Drill D1 as observed on the video recordings. The fastest speed of movement occurred between the first and ground floor at 0.533m/s. The first to ground floor had a faster speed on the stairs as there were no occupants entering the stairs from the ground floor and hence no merging and deference behaviour.

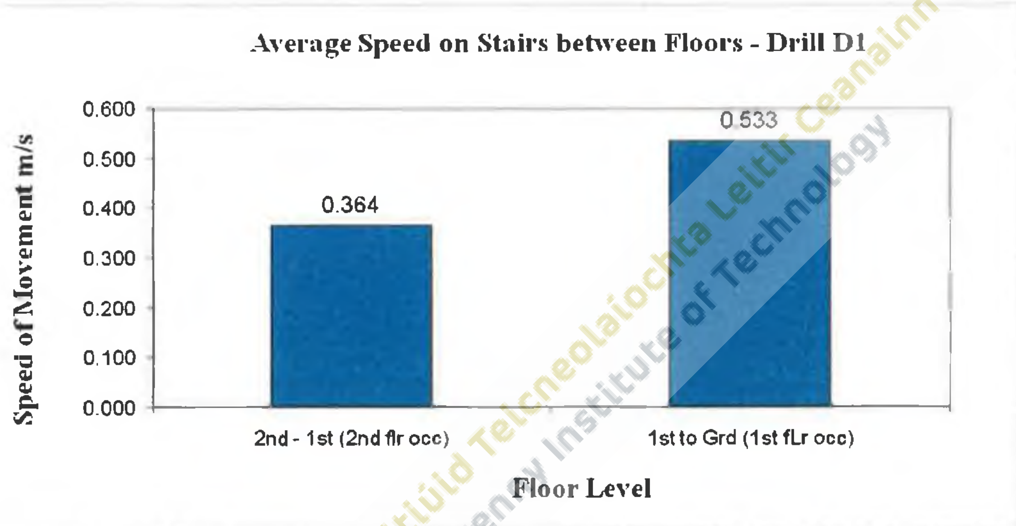


Figure 6.9: Average Speed of Movement on Stairs Drill D1.

Table 6.2 shows the observed speed and predicted speeds for Drill D1. The variation for the predicated speeds depended on the population density for that floor. The density on the stairs between floor two to one in Drill D1 had a lower density therefore it had a higher predicted speed. The predicted speeds recorded between the second to first, and first to ground was much slower due to the high population density.

Stairwell	Floor	Density p/m2	Observed mean speed m/s	Calculated speed m/s s= 1.08 -0.266.1.08Dpop)
Drill D1	2-1	1.214	0.364	0.731
	1-Grd	1.298	0.533	0.707

Table 6.2: Observed Speed and Predicted speeds for Drill D1.

Figure 6.10 shows a comparison between the observed average speed and the predicted speed.

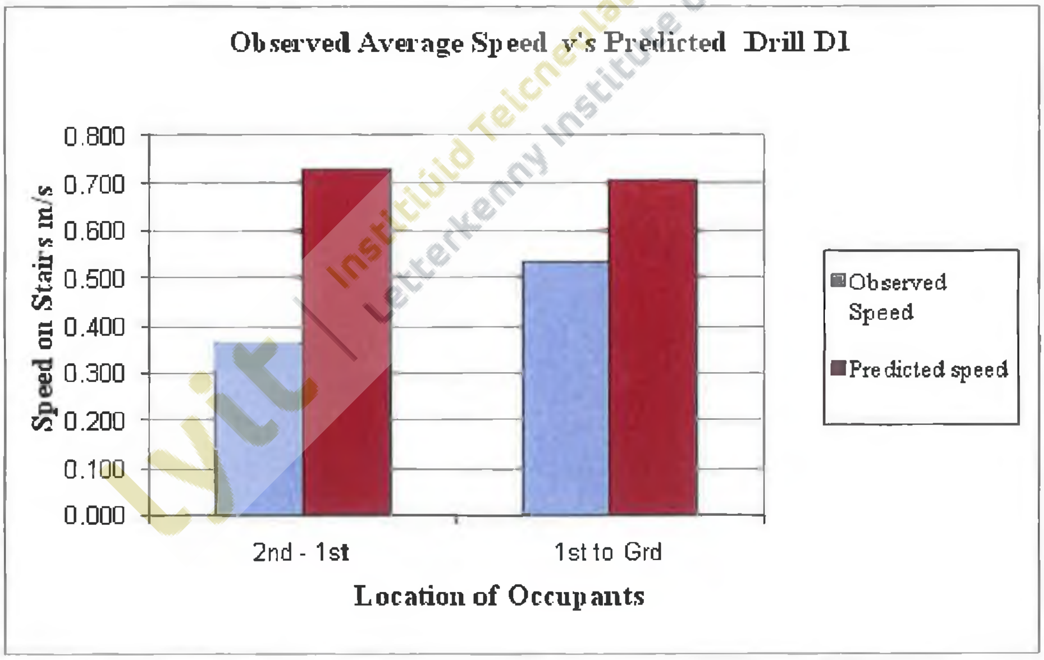


Figure 6.10: Observed Average Speed vs. Predicted Speed Drill D1.

The results reveal that there was a significant difference between the observed speed and the predicted speed found for all of the floors in Drill D1. The discrepancy between the predicted and observed speeds found in Drill D1 concurred with the results found for Drill L1.

6.6 Stoppage and Delay Time

Figure 6.11 shows the average delay time experienced by the evacuees on each floor. It clearly shows that the second floor occupants experienced the greatest delay time where the first floor occupants experienced a very short delay of six seconds. The main factors that caused the delay during Drill D1 were the congestion on the stairs and landing, and the position of the entrance onto the landing. The position of the entrance onto the landing allowed the Floor Flow to have a steady flow rate onto the landing throughout the drill. The Floor Flow dominated the landing space throughout the evacuation and this forced the stair flow to stop and wait until a space was free to enter the landing. Because of the Floor Flow, dominating the landing space the congestion on the stairs increased causing complete stoppage. The maximum delay time recorded for Drill D1 was 59 seconds, which was experienced by the second floor occupants.

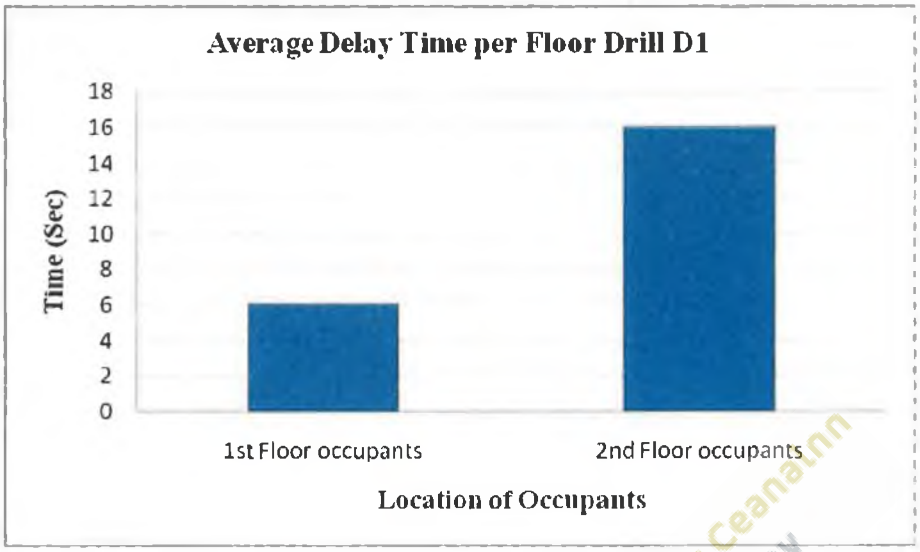


Figure 6.11: Average Delay Time per Floor Drill D1.

During Drill D1, deference behaviour was not as evident as it was in the other drills C2 and C3. A reason for this was the high congestion that occurred on the stairs and landing because of factors previously mentioned. There was one occurrence of deference behaviour where a male staff member from the floor flow deferred to a female staff member from the stair flow. It is possible that the male staff member was familiar with the female staff member.

6.7 Summary of Findings

During Drill D1, three escape stairs were blocked making only one stair available for the occupants. This created a large number of occupants using the stairs during the evacuation. This in turn caused a high population density on the stairs during the evacuation. The width of the stair and the size of the landing were larger than Drills L1, C1, C2 and C3. This allowed for the large number of occupants to use the stairs during the evacuation. The position of the entrance onto the landing allowed the occupants of the Floor Flow to evacuate without having to stop and defer to the Stair Flow. The swing of the door i.e. the direction of the door opening meant that the door had to be held open when the Floor Flow entered the landing.

The Floor Flow developed two flows onto the landing. The Stair Flow also developed two flows onto the landing but found it difficult to enter into the outgoing stair. It was found that when one or two occupants leading the Stair Slow were not able to enter the stair the occupants behind them moved by the wall of the stairwell to attempt to enter into the Floor Flow. Stoppage occurred on floor one because of the merging between the Stair and Floor Flows. Congestion was high on the landing and congestion became high on the stairs as a result, which in turn caused a stoppage on the stairs above.

6.8 Conclusions

The position of the entrance onto the landing seemed to have a huge impact on the outcome of the evacuation Drill D1. The door opened directly onto the landing facing the outgoing stair and adjacent to the incoming Stair Flow from floors above. This layout allowed the Floor Flow to move directly onto the landing and the outgoing stair without stopping and deferring to the occupants from the Stair Flow. It also allowed the Floor Flow occupants to enter the landing and outgoing stairs in two lines. When the Stair Flow reached the landing, it proved difficult for them to move onto the outgoing stair. They had to wait on the landing until a space became free. Some occupants tried moving to the wall to enter the Floor Flow and proceed with their evacuation through the Floor Flow. This also proved to be difficult because of the high floor flow rate. There was only one occurrence of deference behaviour from the Floor Flow, which allowed a number of the Floor Flow occupants onto the outgoing stairs however; this was for a short period. It was interesting to find how one incident of deference behaviour was capable of changing the priority of flow between the Stair and Floor Flow.

It should also be noted that the swing of the door i.e. the direction of the door entrance might have slowed the Floor Flow rate slightly. The door had to be held open by the Floor Flow occupants throughout the evacuation of Drill D1. This was also found in the other drills but was more obvious in Drill D1.

Chapter 7: Conclusions

7.1 Introduction

Evacuation studies in the past have focused mainly on evacuation timing and occupant movement. The most common factors considered by researchers during evacuation studies on stairs are density, flow rate and the occupant speed of travel. This research has identified the need to examine more closely factors, which can affect stair evacuation and occupant movement. Human behaviour is a large field of research. Numerous studies have been carried out on human behaviour, however research on the type of human behaviour that occurs during a stair evacuation continues to be limited.

The primary purpose of this research was to investigate the area of merging and deference behaviour and how this behaviour can affect a building evacuation. This research has investigated the merging process and deference behaviour on the stair -floor landings by observing five evacuation drills in three different building types. The merging process and the type of deference behaviour in the evacuation studies observed had a profound effect on the outcome of the evacuation.

7.2 Key Findings

From the findings of five evacuation drills, it was obvious that merging occurred on a stair floor landing between the Stair Flow and Floor Flow during a building evacuation. The research indicated that the priority between flows varied for different stair and landing geometries and occupancy types. The results of the priority of flow between the Stair and Floor Flow varied for the five different evacuation drills. When the priority belonged to the Floor Flow, it affected the evacuation of the Stair Flow and the occupants on the floors above. When the priority of flow belonged to the Stair Flow, which was the case in just one of the evacuation drills, it slowed down the floor flow rate at the entrance onto the landing. The stair geometry may have influenced the variance of priority between floors. The case where the stair flow had priority the stair was much wider; however, the congestion on the stairs was not as high as in the other evacuation drills. This particular drill also employed a phased evacuation procedure. The priority can vary depending on the type of evacuation procedure.

The priority of flow also depended on the occurrence of deference behaviour. Deference behaviour occurred in four of the evacuation drills. The two-door layout onto the landing in Building C resulted in two floor flows, which resulted in one flow having priority over the other. This appeared to be a result of the location of the entrances onto the landing.

During the analysis of the merging activity, it was highlighted that deference behaviour had the ability to change the priority of flow. The Floor Flow rate changed also due to the merging activity. When the Stair Flow deferred to the Floor Flow, it resulted in the Floor Flow having a steady floor flow rate. Because of the steady floor, flow rate the deference behaviour continued to occur by the Stair Flow. The combination of both the deference behaviour by the Stair Flow and the steady floor flow rate onto the landing by the Floor Flow resulted in stoppage and delays occurring in the Stair Flow and the floors above.

The Floor Flow dominated the merging space on the landing four of the evacuation drills. During the evacuation of Drill D1, the Floor Flow had priority; however, it was difficult to determine whether deference behaviour caused this. The deference behaviour recorded was mostly influenced by the high congestion on the landing. The stoppage time caused unnecessary delay to the occupants of the floor above.

The results showed that merging is easier when the density is lower e.g. the occupants from both flows move freely onto the landing and the merging is more evenly shared. It can be concluded that when the crowd density varied crowd movement varied. The merging activity that occurred lead to the occurrence of deference behaviour. Deference behaviour is more likely to occur when the stair population density increases. Two types of evacuation procedures were studied. The phased evacuation employed by Building L decreased the population density on the stairs. The simultaneous evacuation procedure in Buildings C and D created a higher population density due to all floors evacuating simultaneously. Whereas the phased evacuation allowed occupants to move freely onto the stair with limited merging between the stair and floor flow. It was difficult to determine whether gender played a role in the deference behaviour observed in all drills. Drill C2 and C3 showed a strong possibility of gender or role-playing. A very similar case of deference behaviour that occurred in Drill C2 involving the same occupant characteristics also occurred in Drill C3 with the same results which highlights the possibility of role playing having a contributing factor to the occurrence of deference behaviour.

Three of the evacuation drills had more than one merge point. Three estimated merge points were used to study the merge ratios between the Stair and Floor Flow and the flow rates at each of the merge points. The results showed that there was a relationship between the flow rate and the stair and floor ratio. It was found that when the merging was evenly shared between the flows merge the flow rate was high. When one flow had priority over the other, the flow rate was found to be lower. It can be suggested that more there can be more than one merge point on a stair-floor landing.

The geometry of the stairs and landing played an important factor in the findings of the evacuation drills of three different building types. The most apparent was the location of the entrance onto the landing. The results found that when the door was located opposite the incoming Stair Flow the floor flow rate decreased. When the door was positioned adjacent the incoming stair flow an increase in the floor flow rate resulted due the Stair Flow deferring to the Floor Flow of that entrance. It can be suggested that there are advantages and disadvantages with both entrance layouts. The advantage of the door opposite the stair flow decreased the floor flow rate and allowed a higher stair floor onto the landing. This in turn decreased the likelihood of stoppage and delayed times to the stair flow and the occupants on the floors above. The disadvantage of the door adjacent the Stair Flow increased the likelihood of stoppage and delay to the occupants of the stair flow and the occupants of the floors above. Because the Floor Flow dominated the landing space during Drill D1, the Stair Flow had to stop when they reached the landing and wait until a space became free to enter into the landing space. The density on the stairs was high because of blocking other stairs in the area. The results of Drill D1 showed that the Floor Flow took priority throughout the drill and it showed how difficult it was for the stair flow to evacuate when they began to merge with the floor flow.

The location of the door increased the Floor Flow rate and allowed the Floor Flow to have two flows onto the landing. If the door was positioned opposite the Stair Flow rather than adjacent, it may have encouraged a more evenly shared merging between the two flows. The swing of the door i.e. the direction of the door opening, opened out onto the landing in all three buildings. This meant that the occupants from the Floor Flow had to hold the door open while making their evacuation. It was evident in Building L and Building D that the swing of the door opening onto the landing had an impact on the floor flow.

During evacuation Drill D1, the entrance door onto the landing was positioned directly opposite the outgoing stair and adjacent to the stair flow. The position of the door allowed the Floor Flow to move directly onto the landing into the outing stair. This allowed a steady floor flow rate with minimal merging between the two flows and limited deference behaviour.

Deference is a behaviour that cannot be ignored in computer evacuation modelling. It has been shown in this study and other studies that its occurrence can have a negative effect on an overall evacuation from a number of building types. It was difficult to identify the reasons behind the occurrence of deference behaviour. There is no clear evidence that either age and/or gender are definitive sole factors to the occurrence of deference behaviour however research on a significantly larger sample size and across a wider range of building type usage may highlight the significance or otherwise of either as a defining factor.

A designed evacuation strategy for any building should consider the occurrence of merging and deference behaviour and how it can dictate how the evacuation will unfold. Generally, in order to minimise evacuation time in relatively high-rise buildings, occupants from upper floors should have priority use of the exit stairs. If total evacuation had to be carried out then congestion would occur on each floor at the stair case entry points where the entire building population would have to evacuate simultaneously.

7.3 Future Work

Additional experimental data is required to further investigate this area of human behaviour in fire. Another area of future research is to investigate the capability of current computer evacuation models to accurately predict the area of merging and deference behaviour on stairs. In order to form a larger database of information for the validation of computer evacuation models, then additional experimental data on evacuation drills similar to this research is necessary. It has also been found that occupants may have been influenced by gender or roles of authority when merging. This would also prove interesting to investigate further.

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Appendix I

Published Conference Paper

4th International Symposium

Human Behaviour in Fire 2009

13th -15th July 2009

Robinson College Cambridge

WHO DEFERS TO WHOM? DEFERENCE BEHAVIOUR ON STAIRS

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ABSTRACT

This paper investigates behaviour during egress via stairways to increase understanding and further investigate the crucial factors which can impede the safe and rapid movement of occupants during an emergency evacuation. The main focus of this paper is the merging process of the occupants and the deference behaviour that occurs in stairs during a building evacuation. The paper presents the initial findings of three evacuation studies to investigate the merging process and deference behaviour. The findings indicate that a number of factors can affect merging and deference behaviour i.e. gender and the various stair population densities and how the location of the entrance onto the stair-landing influences evacuation behaviour on stairs. The stoppage time that can occur as a result of these factors can put some occupants in a high rise building, i.e. on higher floors at greater risk during an evacuation.

INTRODUCTION

While observing evacuations of high rise buildings, it is common for researchers to find the occurrence of deference behaviour on the stair-floor landing[1]. Deference behaviour occurs during the merging of the incoming stair flow from higher floors above merging with the floor flow entering into the staircase. It describes how the occupants of the stair flow who are already on the stair give way to the occupants entering the stairwell from their floor and vice versa. A lot of studies have been carried out on the evacuation from high rise buildings and human behaviour while evacuating [4,6], however little work has been carried out to date on the type of human behaviour that occurs on stairs during an evacuation. Merging plays an important factor during evacuation as it can dictate the speed of movement on the stairs and hence can control the speed at which a floor can empty into a stair. Deference behaviour can have a negative or positive impact on the overall evacuation of a building. Its occurrence can dictate how an evacuation will unfold. Mac Lennan[3] has observed from evacuation drills a significant amount of disturbance of the continuity of flow when one flow stopped and another started at a merging region. Merging is more efficient when an exit route is utilized to complete capacity. In evacuations, however, there is normally the sharing of access at merging regions resulting in breaks in the egress flow causing a significant impact on capacity. The merging process and subsequent deference behaviour of the occupants frequently occurs in evacuating high rise buildings. Building codes base stair and exit widths on the estimated occupancy loading for a floor regardless of the entire building population. These widths are also based on phased evacuation procedures. If simultaneous evacuation were employed then congestion would occur on each floor at the stair case entry points. Observational studies on evacuation drills have given researchers a realistic approach to help create a better understanding of the factors which can impede efficient evacuation from high rise buildings.

The main objectives of this study are to:

- Investigate how occupants entering the stairs merge with the occupants who are already on the stairs; who has priority and what factors influence this priority?
- Investigate the merging process and merging trends with various crowd densities, directions of merge i.e. the flows that form from the stair and floor [8].
- Investigate whether the location of the door onto the landing has an impact on the merging process[2].
- Investigate the occurrence of stoppage on lower floors and how that stoppage proceeds up the stair to higher floors.
- Investigate whether the floor flow rate onto the stair decreases as the stair population density increases.
- Examine the type of behaviour resulting from the merging process i.e. deference behaviour. How can such deference behaviour be altered or managed to make sure that the most endangered occupants are given priority in their evacuation[5]. Who defers to whom and what affects such deference behaviour?

The main issue with investigating this type of human behaviour is the lack of experimental data [7]. This
study has investigated the merging process and deference behaviour on landings on stairs by observing three evacuation drills in two different building types. The paper presents initial findings and a discussion of the results of the three observational studies undertaken.

BACKGROUND

To date some degree of work has been conducted in the area of merging and its subsequent occupant behaviour. Takeichi et al[8] conducted experiments to identify the impact of merging in a staircase during an evacuation and the effects of merging in relation to various crowd densities, direction of merge and whether the door joining a hallway to a staircase was opened or closed. The relationship between the ease of merging and the staircase population density demonstrated that merging is easier when the density is lower. When the density on the stairs increases, the floor flow rate onto the landing decreases. When the door entering the landing is located adjacent to the incoming stair the floor flow rate is greater than when the door is located opposite to the incoming stair flow. It was found that when merging occurs the flow opposing stair traffic is about 15-20% lower than the flow when merging occurs in the same direction as the stair flow. Another experiment revealed that the floor flow rate entering the landing is 30% lower than when the door is initially opened therefore, Takeichi et al[8] reports that it is easier to merge when the door is initially open. The experiments only involved twenty seven test subjects and gave only short periods of merging. However, the results of the experiments demonstrated that the geometrical layout of the stair –floor interface and the density of the stair flow are significant in understanding the merging process.

A modelled study by Galea et al[2] found that the speed at which a floor can be emptied onto a stair can be improved by connecting the floor to the landing adjacent to the incoming stair rather than opposite the stair. They reported that configuring the stairs in this way, while reducing the floor emptying time resulted in a corresponding decrease in the descent flow rate of those already on the stairs. They suggest that in high-rise buildings, floors should be connected to the landing on the opposite side to the incoming stair. They also noted that more experimental data is required to verify modelling predictions in this area. Pauls[5] outlined that he observed merging and deference behaviour in a number of early Canadian evacuation studies in the 1960s and 1970s where a 2:1 merging ratio was found. He noted that this type of behaviour could drastically affect the ability of evacuees from more endangered upper floors from getting away from a fire. He highlights that the occurrence of the merging process and deference behaviour warrants careful attention. Once more, Pauls[5] found the occurrence of deference behaviour where the occupants from the stair flow met with the floor flow occupants attempting to enter the exit stairs. He discovered stair flow deferred to the floor flow on many occasions. Not only did this behaviour lead to a shuffling speed but more importantly to complete stoppages increasing the evacuation time of the occupants in the higher floors above and for the occupants who are already in the stairs.

There is a limited amount of experimental data available to provide a better understanding of the area of merging and deference behaviour and how this behaviour has an impact on an overall evacuation from a high rise building. Pauls[5] has suggested for research to be undertaken in the area of deference behaviour in large multi-floor buildings in the exit stairs, and posed the following questions; what affects such deference behaviour? Can it be altered or managed? Who defers to whom?

METHODOLOGY

Unannounced evacuation drills were conducted in two buildings. An additional announced evacuation drill took place in one of the buildings. Building L located in London took place on 23rd February 2009 and Building C located in Cavan took place on 13th February 2009. Table 1 gives a breakdown of both building characteristics. Building L is an office building consisting of basement, ground and seventeen upper levels with a rooftop plant level. There are two escape stairs, one at the central core (south) and one at the rear (north) serving all floors. Building C is a change of use building from an apartment building to a third level institute consisting of a ground floor and four upper floors. It comprises of classrooms, workshops and relating offices. There are two stairs one located at the front (southeast) and one at the rear (northwest). Both students and staff occupy the building. The evacuation drills of both buildings were observed using digital video cameras and questionnaires were distributed to the evacuees.

	Building L (London)	**Building C (Cavan)**
Occupancy Type	Office	3rd Level Institute (Educational)
No. of Floors	16 accommodated	5 accommodated
Stair Type/Arrangement	Dog Leg	Half turn and Dog leg
No. of Stairs	2	2
Location of Stairs	Central Core/ North	Front (southeast) Rear (northwest)
Evacuation Strategy Employed	Phased	Simultaneous

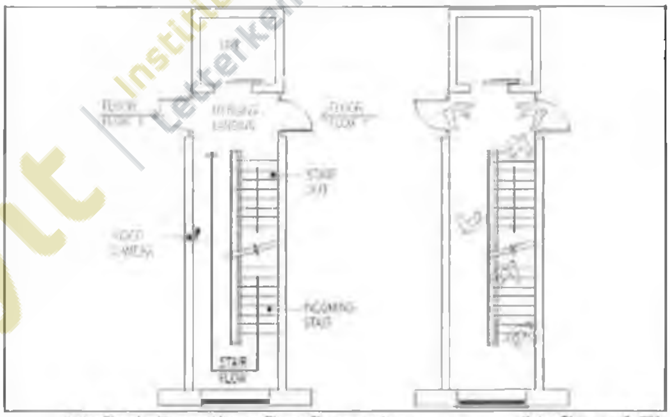
Table 1: Building Characteristics.

PREPARATION WORK

The equipment consisted of six Sony handy cams and four Panasonic digital cameras. The cameras were mounted and fixed to the walls in the stairwells and positioned to be capable of viewing occupants already on the stairs, the landing and the entrances onto the landing. Correct positioning of cameras was crucial in order to capture the behaviour and movement of the occupants. The positioning of the cameras varied for both buildings due to the physical layout of the stair and landing. Each camera and video tape was numbered before the drill and their precise locations are identified on the floor plans. The evacuation plans were reviewed in advance of evacuation drills which provided a determination of how the occupants were likely to respond to the alarm and behave during the evacuation. Building C employed a simultaneous evacuation procedure and Building L employed a phased evacuation procedure. Measurements of the stair and landing dimensions were recorded before each drill in order to calculate floor flow rates and stair population densities. Necessary measurements included the height of risers, length and width of the going and the floor landing dimensions. The number of steps between each landing was also recorded. Two evacuation drills were carried out in Building C in Cavan, Ireland, C1 unannounced and C2 announced and one unannounced evacuation Drill L1 in Building L London, England.

Building C

For both evacuation drills, five cameras were mounted onto the walls in the front (southeast) stair angled appropriately to capture the movement and behaviour of the occupants on the stairs and landing. Figure 1 depicts a plan of the stair and floor configuration and the direction of the three flows of occupants in the stairwell. Weather conditions on the day were mild but cold.



(a) Stair/Landing Configuration. (b) Crowd Flow.

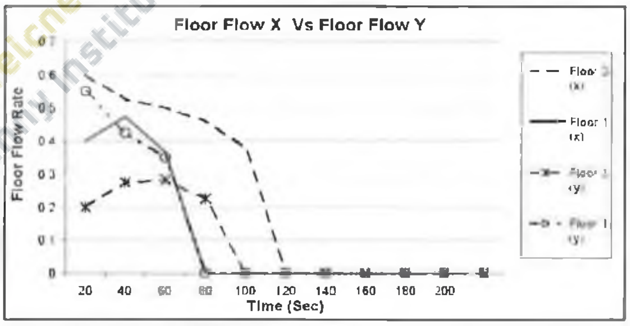
Figure 1: Stair Configuration Building C.

The digital video cameras were installed and were started ten minutes before the alarm was sounded and ran continuously until the drill was completed. Wide lenses were attached to the cameras to capture a wider view of the landings. Sound was also recorded through the camera, which allows for observation of the overall atmosphere of the evacuation. Both evacuation drills in Building C were conducted on Friday 13th February 2009. Throughout the drill, the wardens were available on each floor offering assistance to the occupants during the evacuation. The stair to the rear (northwest) was blocked in the second drill C2.The alarm sounded at 10.28 a.m. Upon hearing the sound of the fire alarm the occupants were directed to the front stair by the fire wardens on each floor.

Results from the Announced Evacuation Drill C2

As the building employed a simultaneous evacuation procedure all evacuees on all floors moved to the stairwell and began their descent to the final exit. A total of 160 occupants were observed on the recordings. From the video recordings the resulting deference behaviour was analysed. The configuration of the stairwell is shown in Figure 1 (a). There are two entrances onto the landing from each floor observed. As a result of the two entrances from each floor there were three flows merging on the landing, two floor flows, Floor Flow X and Y and one Stair Flow as indicated in Figure 1 (b). Significant crowding was observed on floors three, two and one as a result of the occurrence of merging and deference behaviour and high stair population densities. In most cases the Floor Flow X took precedence over the Floor Flow Y however, whichever floor entered the stair first began a faster flow rate. This occurred on floor one where Floor Flow Y entered the landing first and began a faster flow rate (see Figure 2(b)). However once Floor Flow X entered the landing this slowed down the flow rate for Floor Flow Y. Hence it can be said that the first flow to enter the landing can begin a faster floor flow rate.

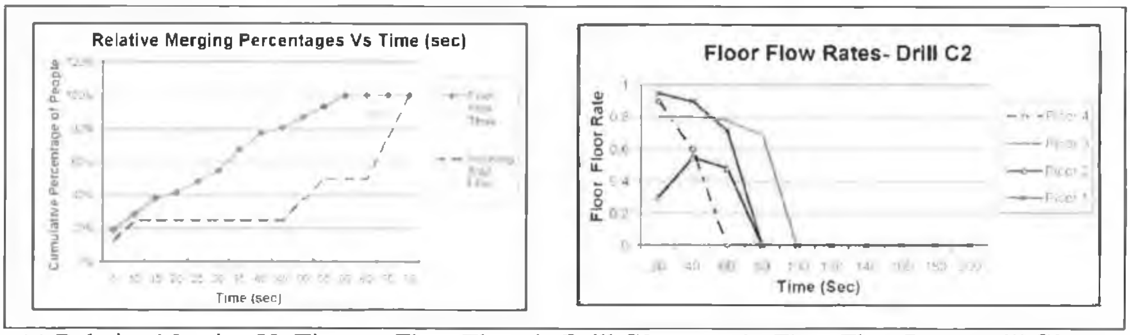
(a) Floor Flow Y Entering Landing First.



(b) Floor Flow X Vs Floor Flow Y.

Figure 2: Floor Flow Rate for X versus Floor Flow Rate for Y on Floor One.

The location of the doors entering onto the landing may also play a role in the floor flow rate. When Floor Flow X entered into the stair first it appeared to have an advantage over Floor Flow Y, which made it difficult for Floor Flow Y to enter into the stair when Floor Flow X had already developed a steady flow into the stair. Some deference behaviour from Floor Flow X allowed some occupants to enter into the stair. An example of this occurred on floor three, were the occupants from Floor Flow Y attempted to enter the stair but discovered that the Floor Flow X had developed a steady flow into the stair. Therefore the first person from Floor Flow Y deferred to allow eight people from Floor Flow X to continue into the stair as shown in Figure 2 (b). The ground floor experienced insignificant evacuee numbers to determine a floor flow rate.



(a) Relative Merging Vs Time on Floor Three in Drill C2. (b) Floor Flow Rates Drill C2.

Figure 3: Evacuation Drill C2

Also on floor three a male occupant from the stair flow wearing a security uniform stopped at the landing deferred to sixteen females entering the stair from the floor flow, before he began his descent (refer to Figure 3(a)) and snapshot Figure 7 (b). As a result of this deference behaviour a higher floor flow rate occurred on floor three as can be seen in Figure 3 (b) and eventually a complete stoppage occurred in the stair above. Two possible factors could have been a cause for this deference behaviour; a young male allowing young females to proceed onto the stair or the fact that he was in a security uniform, was it role play? Merging on the second floor was found to be 50:50 as the Floor Flow Y entered the stair first it seemed easier to develop a 50:50 merge with Floor Flow X. However, the crowd movement slowed down considerably then eventually it came to a halt due to deference behaviour which occurred on floor one. On floor one the stair flow deferred to the entire floor flows when three young girls leading the stair flow stopped at the first floor landing and waited until the entire floor emptied see Figure 6 (a). This behaviour resulted in a complete stoppage on the floors above. Figure 4 shows the relative merging percentages over time and the obvious result of deference behaviour of the stair flow which occurred on floor one. Figure 3 (b) shows a steady floor flow rate on floor one also a result of this deference behaviour.

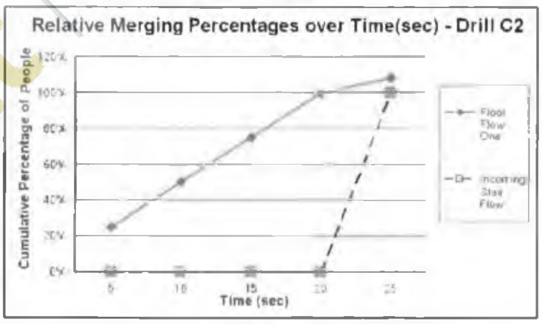
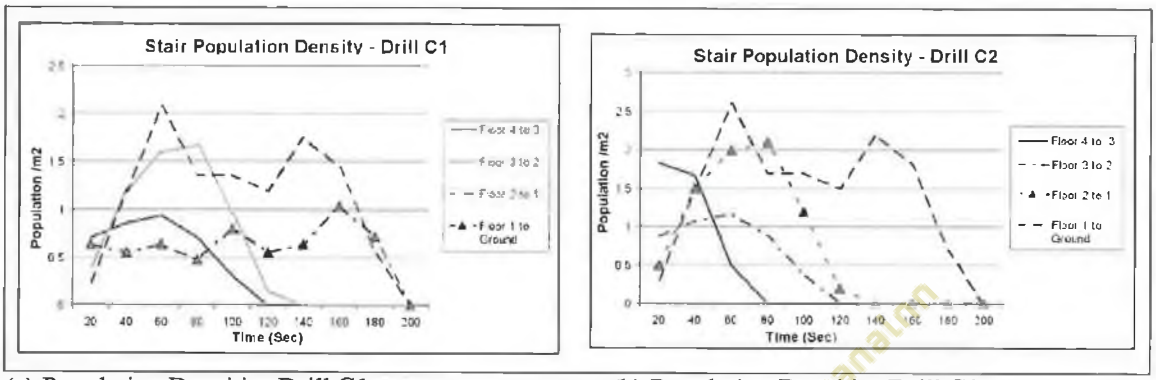


Figure 4: Stoppage due to Deference Behaviour in Drill C2.

The stair population density between the first and ground floor and the second to ground floor was high as a result of the deference behaviour observed on floor one (refer to Figure 5 (b)). This clearly shows that deference behaviour on landings of lower floors can cause the floors above a longer evacuation time. Figure 6 (b) taken from the video recording of the announced evacuation drill building C illustrates the congestion that occurred on floor two as a result of the deference behaviour on floor one.



(a) Population Densities Drill C1. (b) Population Densities Drill C2.

Figure 5: Stair Population Density for Both Drills in Building C.

Due to simultaneous evacuation and the discounting of one escape stair, the density on the stairs was considerably high. The occurrence of deference behaviour resulted in two cases of complete stoppage on the stairs above. Some of the occupants were able to descend shoulder to shoulder on the stair as they were conversing while evacuating. This may not be evident with other occupancy types where occupants may not be comfortable due to various factors e.g. their familiarity with other tenancies occupying the building on the various floors. As the stair population density increased it was obvious that the speed of movement on the stairs decreased and the floor flow rate onto the landing also decreased. There were two doors entering onto the landing (see Figure 1). The door adjacent to the stair flow served Floor Flow X which took priority over the Floor Flow Y therefore the door adjacent to the stair flow could have a positive impact on the overall emptying time of the floor.

(a) Deference Behaviour on Floor One. (b) Congestion on Floor Two.

Figure 6: Evacuation Drill C2.

The door opposite the stair flow although in close proximity to the exit stair which serves the Floor Flow Y experienced more confrontational congestion and in most cases could not begin movement past the door threshold until someone from Floor Flow X deferred to them. Floor Flow X on floor three had two single file flows from one entrance onto the landing see Figure 7 (a). This had a significant impact on the speed at which this floor was able to be evacuated from that side.

(a) Two Flows from Floor Flow X. (b) Deference Behaviour on Floor Three.

Figure 7: Evacuation Drill C2.

Unannounced Evacuation Drill C1

To provide a more realistic representation of evacuation drills they are usually unannounced, thus no information was provided to the occupants on the day and time of the drill to prevent any possible change to occupant response. For this evacuation drill both stairs were made available however, only the front stair (see Figure 1) was observed by the video cameras. Figure 1 (a) and (b) shows a plan view of the front stair and the direction of the crowd movement onto the landing and stairs during the evacuation drill.

Results from the Unannounced Evacuation Drill C1

The alarm bell sounded at 10:15 am and rang continuously until the drill was completed. As the building employed a simultaneous evacuation procedure all evacuees on all floors moved to the stairwell and began their descent to the final exit. Both stairs were used during this evacuation drill, however only the front stair was observed. Recordings from five cameras were used to capture the evacuation. A total of 62 occupants were observed on the recordings. The merging process and the resulting deference behaviour were analysed. Crowding was not as high as the announced drill C2 where only one stair was available. Merging was evident on the landings of floor one and two. The occupants in the third floor used the rear (northwest) stair to evacuate therefore no merging was observed on this floor. The Floor Flow X took precedence over the Floor Flow Y. On the Second floor, the Floor Flow X entered the landing first and Floor Flow Y deferred to Floor Flow X. The occupants of Floor Flow Y waited to allow Floor Flow X who had already developed a steady flow into the stair to empty completely before they began to move.

(a) One Floor Flow on Floor One. (b) Floor Flow Y Defers to Floor Flow X.

Figure 8: Evacuation Drill C1.

No occupants evacuated on floor one from Floor Flow Y as the classrooms were not accommodated in that area at the time of the drill. Therefore there were only two flows merging on the first floor landing which resulted in 50:50 merging between the Floor Flow X and the Stair Flow see Figure 8 (a). Merging seemed easier in this case where there were two flows rather than three. Due to both stairs being available for evacuation there was a lower population density than the announced evacuation drill C2 refer to Figure 5 (a). The lower density resulted in less merging times and no stoppage time. Merging only occurred on two landings. However, the merging was still quite evident between the floor flows where the Floor Flow Y waited to allow Floor Flow X to empty into the stair refer to Figure 8 (b). The door adjacent to the stair flow served Floor Flow X which took priority over the Floor Flow Y. Therefore the door adjacent to the stair flow could have a positive impact on the overall emptying time of the floor.

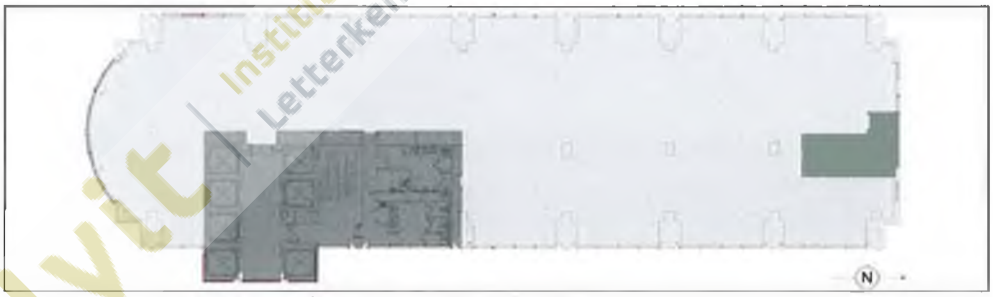
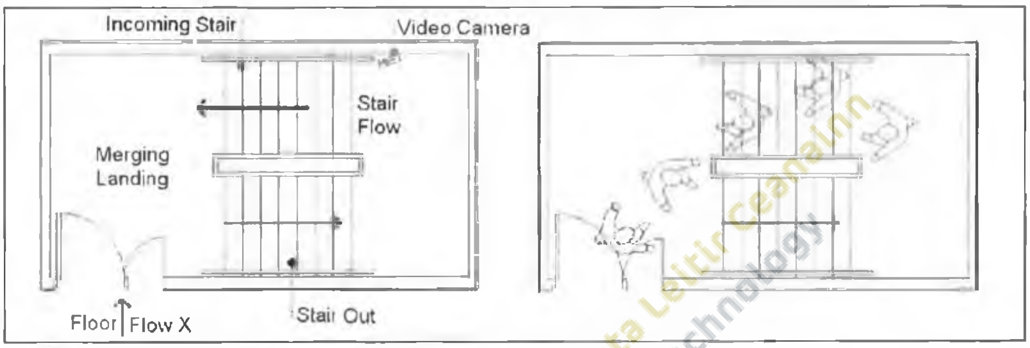


Figure 9: Building L Plan.

Building L

Building L had two stairs one in the central core (south) and one at the rear (north) serving all floors (refer to Figure 9). The participants of the study were the employees of the building. Eight cameras were mounted on the walls and angled to capture the movement of the occupants on the stair and entering the landing from the floor. Figure 10 (a) and (b) shows a plan view of the stair and floor configuration and the direction the two flows of crowd movement. Weather conditions on the morning of the drill were cold but dry. The cameras were installed in the north stairwell on floors, seven, nine, ten, eleven, twelve, thirteen, fourteen and floor fifteen. The planned evacuation procedure was as follows; the fire floor was floor nine therefore nine and ten evacuated immediately. After each ninety second period two floors at a time starting above the fire floor began to evacuate i.e. after ninety seconds floor eleven and twelve evacuated with floor fifteen and sixteen being the last floors above the fire floor to evacuate. Ninety seconds after floor sixteen evacuated the floors below the fire floor i.e. seven and eight were then notified to evacuate and every two floors below were notified at a ninety seconds periods with the first and ground floor being the final floors to evacuate. Again the drill was unannounced. However, only the north stairs (see Figure 5) were observed by the video cameras. Unfortunately during the course of the evacuation some occupants gained access to the second stairway.



(a) Configuration of stair and landing. (b) Direction of crowd movement.

Figure 10: Stair Configuration Building L.

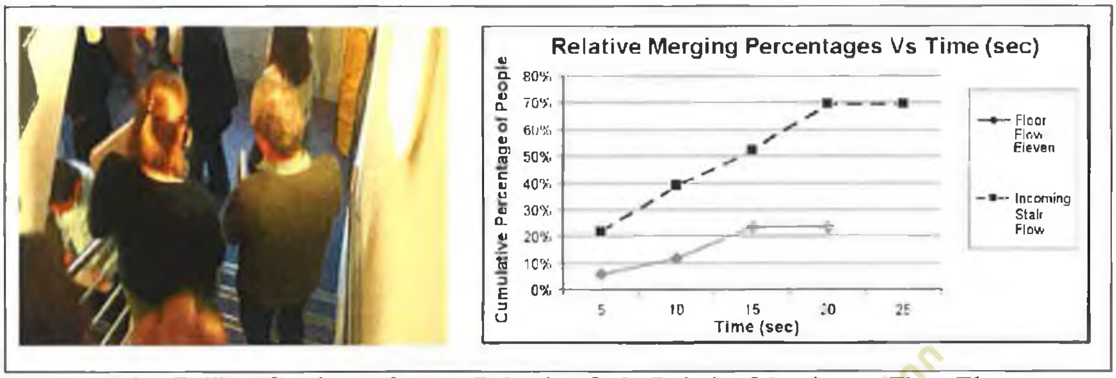
Results from the Unannounced Evacuation Drill L1.

The alarm bell sounded at 11:30 am and rang continuously for twenty minutes. Recordings from eight cameras were used to capture the evacuation and then analysed. A total of 174 occupants were observed on the recordings. Some crowding was observed on various floors however at no stage were there stoppages or long periods of merging. The crowd movement was fluid and consistent on the eight floors observed. Short periods of merging were observed on floors, nine, eleven, twelve and floor seven. No merging was observed on floors ten, thirteen, fourteen and fifteen due to a number of possible factors such as the phased evacuation procedure or the use of the south stair. The merging observed was mostly 50:50 due to a low density population on the stairs. Four periods of merging occurred and are illustrated in Table 2.

Evacuation drill	Merging region	No. of occupants merging	Merge period (seconds)	Merge ratio floor: stair
Unannounced L1	Floor 7	37	91	35:65
	Floor 9	11	14	18:82
	Floor 11	14	56	36:64
	Floor 12	37	28	44:64

Table 2: Quantifying the Merging Process for Building L.

On one landing, a male deferred to four females from the incoming stair flow to continue their descent. On another floor two females deferred to four people male and female from the incoming stair flow see Figure 11 (a).



(a) Evacuation Drill L. Gender Deference Behaviour? (b) Relative Merging on Floor Eleven, Drill L.

Figure 11: Merging on Floor Eleven, Drill L1.

From the short periods of observed merging behaviour the stair flow had priority as shown in Figure 11 (b). When the occupants from the floor entered into the landing they could see that the occupants from floors above were already on the stair and deferred to allow them to continue for small periods. Other behaviour observed in the stairs were occupants carrying mugs of coffee down sixteen floors see Figure 12 (a). From various floors four people carried their laptops with their screens open see Figure 12 (b) and others made phone calls and sent text messages. Overall the amount of merging that occurred on the landings throughout this evacuation drill resulted mostly in a 50:50 merge. It would be interesting to investigate how a high rise building like this could evacuate simultaneously. Also, it would have been interesting to have investigated the possibility of discounting one stair leaving only one stair available for evacuation. Would there be longer merging periods? How would the merging on lower floor landings affect the occupants already on the stairs above and the occupants trying to enter the stairs above from upper floors?

(a) Occupant Carrying Coffee Mug. (b) Occupant Carrying open Laptop.

Figure 12: Evacuation Drill L1. Observed Behaviour.

SUMMARY OF FINDINGS

The preliminary findings from the three observational studies suggest that despite differences in the nature of the evacuations they shared similar merging and deference behaviour.

Merging and deference behaviour was more evident in Drill C2 not only between the stair and floor flows but between the two floor flows. One floor flow had priority over the other. A reason for this may be due to the position of the entrances onto the landing. Even though one floor flow was closer to the stair the other floor flow further from the stair had priority. Also it is possible that the occupants of the floor flow closest to the stair allowed the floor flow further from the stair to continue evacuating and may have felt that the speed of movement of the further flow was too fast to begin a one for one merge. Merging between the stair flow and floor flow showed that the stair flow deferred which gave the floor flow which was positioned adjacent to the stair flow priority. This observation concurs with findings from Takeichi et al[8] and Galea et al[2] where the location of the door opposite the stair flow can cause a lower floor flow rate. There was only one entrance onto the landing positioned opposite the incoming stair flow in Building L (see Figure 10). Findings from the results of Drill L1 show that the stair flow took priority over the floor flow and cannot concur with studies by Pauls[5] where he found that evacuees in the stair flow generally deferred to those entering from the floor flow. However, the merging observed in Drill L1 were for short periods of time and may be considered as indicative.

Significant deference behaviour was observed in Drill C2. On floor one three young girls who lead the stair flow deferred to the entire second floor. On floor three a young male in uniform (trainee security guard) deferred to sixteen occupants mostly female (see Figure 7 (b)). Two possible factors could have been a cause for this deference behaviour, a young male deferring to allow young females to proceed onto the stair or the fact that he wore a security uniform was he playing a role of authority? The level of perceived risk was much lower than Drill C1 and L1 due to the fact that it was announced. The stair flow took priority over the Floor Flow in Drill L1 (refer to Figure 11 (b)).The occupants of the floor flow could see that the stair flow had taken priority. A possible reason for this may be that the occupants were not as familiar with the different tenancies in the building. The population density was considerably high on the stairs in Drill C2 due to simultaneous evacuation and only one stair available for escape. Figure 5 (a) and (b) shows the population density for both drills in Building C. The highest stair population density for drill C2 occurred between floor one and ground as a result of deference behaviour that took place on floor one. This corresponds to the floor flow rate graph see Figure 3 (b) where the floor flow rate is highest for floor one. The stair population density calculated in Drill L1 was lower than Drills C1 and C2 due to the larger stair width and a phased evacuation procedure .Stoppage occurred on the upper floors in Drill C2 as a result of the deference behaviour which occurred on the first floor landing. This is a hugely negative impact of merging and deference behaviour. It can put the occupants on the higher floors i.e. in the case of Drill C2 floors two, three and four at a greater risk during the evacuation.

CONCLUSION

The merging process and the type of deference behaviour in the evacuation studies observed had a profound effect on the outcome of the evacuation. From analysing the findings of the observational studies several conclusions can be drawn.

- Merging is easier when the density is lower. Deference behaviour is more likely to occur when the stair population density increases. When the stair population density increases the floor flow rate decreases. It can be concluded that when the crowd density varies the crowd movement varies.
- The location of the door has an impact on the merging process. The results found that when the door was positioned opposite the incoming stair flow the floor flow rate decreased. The door positioned adjacent to the incoming stair showed an increase in the

floor flow rate due to the stair flow deferring to the floor flow of that entrance.

- The two door layout onto the landing in Building C meant that there were two floor flows which resulted in one flow having priority over the other flow. This appeared to be a result of the location of the entrances onto the landing. The ease of movement between the stair and floor flow in Drill L1 was more fluid than Drills C1 and C2. Obvious factors for this was the larger stair width, position of the entrance onto the landing and the phased evacuation procedure which resulted in a bypassing of merging on some of the floors.
- The stair flow deferred to the floor flow in both drills in building C however in Drill L1 the stair flow had priority where the floor flow deferred. Therefore, the priority between flows varies for different stair and landing geometries and occupancy types.
- It is difficult to determine whether gender played a role in the deference behaviour observed in all drills. One case showed a strong possibility of gender or role playing.
- Stoppage occurred during Drill C2 as a result of the deference behaviour. It delayed the evacuation for some occupants especially the occupants of the higher floors.

Deference is a behaviour that cannot be ignored as it has been shown in this study and other studies that its occurrence can have a negative effect on an overall evacuation from a number of building types. A designed evacuation strategy for any building should consider the occurrence of merging and deference behaviour and how it can dictate how the evacuation will unfold. Generally, in order to minimise evacuation time in relatively high rise buildings, occupants from upper floors should have priority use of the exit stairs. If total evacuation had to be carried out then congestion would occur on each floor at the stair case entry points where the entire building population would have to evacuate simultaneously.

FURTHER WORK

This paper is part of a larger study. A further two evacuation studies will be conducted. One in Building C for repeatability and negotiations for an evacuation of a different building are in progress. From a review of current computer evacuation modelling software programs one will be chosen to simulate the evacuation drills. Comparative testing will be undertaken to determine whether the results of the practical testing can be successfully predicted by the modelling software. It is envisaged that the information, studies and conclusions gathered will assist in the further advancement of knowledge and understanding of the factors that control occupant escape behaviour during the merging process on stairs.

ACKNOWLEDGEMENTS

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Appendix II

Internet Links

References 115 &119

Computer Models For Fire and Smoke

Model Name:	WAYOUT
Version:	3.6
Date:	2007
Classification:	Egress
Very Short Description:	Computes movement times of evacuation from multi-room and multi-storey buildings – part of FIREWIND collection
Modeler(s), Organization(s):	Victor O. Shestopal, Fire Modelling & Computing, Sydney, Australia
User's Guide:	Manual of FIREWIND
Technical References:	Manual of FIREWIND
Validation References:	Shestopal V.O. "Computer modelling of merging pedestrian traffic". Pedestrian and Evacuation Dynamics 2003. Proc. of the 2-nd Int. Conf., the University of Greenwich, 2003, pp. 395-403.
Availability:	Available from Fire Modelling & Computing (see http://www.optusnet.com.au/~firecomp)
Price:	$Aus400, or $US350 (the entire FIREWIND package)
Necessary Hardware:	Microsoft WINDOWS
Computer Language:	C
Size:	Approximately 600 kB (the entire package of 18 programs)
Contact Information:	FIRE MODELLING & COMPUTING, phone +61 2 9487 4858 fax +61 2 9487 4868, e-mail firecomp@optusnet.com.au, address 66 Westbrook Avenue, Wahroonga, NSW 2076 Australia

Detailed Description:

Evacuation model WAYOUT computes traffic flow in emergency situations from multi-room and multi-storey buildings. Only merging traffic flows are considered. In case of branching flows, a user is supposed to draw watersheds to divide the flows and compute them separately.

The model is based on a non-linear flow algorithm utilizing an experimentally obtained speed – density dependence by Predtechenskii & Mininskii. The model includes a trend of the pedestrian flow to jump into the maximum-density mode when the flow intensity reaches a critical value.

Verification of the model against available test data has been made and points to a slightly conservative character of the computed results.

Mott MacDonald

STEPS software

STEPS software predicts pedestrian movement under both normal and emergency conditions

Successful buildings require people to be able to move freely under normal conditions and evacuate rapidly in an emergency. Using simulation to optimise people flow can result in a more agreeable environment and more effective fire safety design in large and busy locations.

STEPS is a simulation tool we designed to predict pedestrian movement under both normal and emergency conditions. It originates from the Group's extensive experience in building design and in developing simulation tools for engineering design.

By producing real-time 3D simulations in an easily understandable graphical form, results can be interpreted by both non-specialists and experts alike – helping to identify natural bottlenecks and preferred exits, as well as testing evacuation routes and timings for different emergency scenarios.

Introducing STEPS 4.0

STEPS predicts people movement through three-dimensional space

STEPS is continuously being developed and the latest version was released in the Spring of 2010. STEPS 4.0, which contains additional features that improve upon the current capability, ease of use and visualisation of STEPS models.

A free demonstration is available to all clients. For more info please download the STEPS flyer [PDF 832KB] or email us at STEPS@mottmac.com.

Key features

Some key features of the STEPS software can be summarised as follows:

- modern agent-based microsimulation approach
- applicable to both normal and emergency operations

- extensive track record
- efficient handling of large and complex models
- direct import of 2D and 3D CAD models
- 3D interactive (virtual reality) graphical user interface
- route system as alternative to cumbersome origin-destination matrix
- moving vehicles eg trains and lifts
- variety of pedestrian movement metrics with graphical representation
- smoke data imports (CFX, FDS...)

Track record

STEPS has been applied worldwide both by Mott MacDonald and other major engineering consultancies to a variety of major projects and is one of the most widely used pedestrian modelling packages for metro and underground rail systems. Some typical example projects are listed below.

- New Yankee Stadium, New York, USA
- Delhi Airport, India
- Grand Central Station, New York, USA
- North/South Metro Line, Amsterdam, The Netherlands
- MTR Sha Tin to Central Link, Hong Kong
- Taipei Main Station, Taiwan
- City Line, Stockholm, Sweden
- New Wembley Stadium, London, UK
- Bahrain City Centre shopping mall, Kingdom of Bahrain
- Building Schools for the Future Programme, UK
- Adelaide Oval, Australia
- Maracaibo Metro, Venezuela

A study commissioned by the Railway Safety and Standards Board (RSSB) and completed during 2004 included an assessment of the suitability for station design of seven commercial products. STEPS was judged to be "fully compliant" in four out of the six categories considered – higher than any other product. The full report: Managing large events and perturbations at stations – passenger flow modelling technical review, can be obtained from the RSSB website: www.rssb.co.uk

General principles

STEPS employs a modern agent-based approach which predicts the movement of discrete individuals (virtual people) through three-dimensional space. This is in contrast to the older generation of pedestrian models which treat the problem as one of a continuum flow. The major advantages of agent-based models are that they give a more realistic representation of pedestrian movement and allow the elucidation of subtle but important details of pedestrian movement, thereby giving much greater insight to the designer.

The approach uses principles borrowed from the theory of cellular automata which are well-established in modelling pedestrian dynamics.

STEPS is one of the most

Pedestrian crowds, like many self-organising systems made up of individual entities, display complex emergent modes of behaviour which arise from simple deterministic and non-deterministic principles followed by the individuals making up the population.

widely used pedestrian modelling software

The STEPS model is able to recreate this type of emergent crowd behaviour which is fundamental to effective pedestrian simulation. The modelling approach has been verified and validated by comparison with analytical solutions, internationally-accepted design codes and full-scale testing.

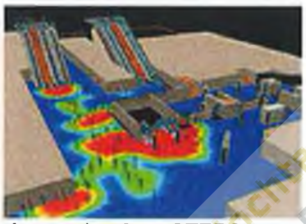
Normal and evacuation modes

The two key modes of operation for STEPS are:

- normal mode
- evacuation mode

with normal mode being the more general. In evacuation mode the STEPS entities are instructed to make their way to the nearest available exit of which they are aware, with their movement modified according to their own individual behaviour characteristics. In normal mode the entities will follow a variety of paths through the model in order to fulfil their different aims (for example: enter the station, buy a ticket and go to the assigned platform).

In evacuation mode, STEPS can be used to calculate evacuation times, exit usage and other criteria essential for fire-engineering design while in normal mode other parameters may be of interest such as level of service and space usage.



A snapshot from STEPS

Normal mode can be used to examine routine operating conditions, for example morning and evening peak flows, but also to assess operational incidents such as escalator failure or variations in train headway which may cause crowding and other problems.

Model output

There are several types of output available in STEPS (before, during and after a simulation) allowing maximum benefit to be gained from the model.

Interactive 3D visualisation ("virtual reality")

This is available when building the model and running the simulation. It is possible to navigate through the 3D model in an intuitive manner and observe the movement of people from different viewpoints which can be used to make fly-through animations of the model. Several rendering modes are available such as wireframe or solid and both texture mapping and lighting can be used. If desired, an existing 3D Studio Max model can be imported into STEPS to increase the realism of the visualisation.

Interactive 2D visualisation

This allows detailed information on particular planes, or parts of planes, to be plotted using colour contours. This information includes local densities and usage levels. These contours plots can be animated to show the development of the relevant quantity with time.

Animations and still images

It is possible to record animated sequences either from fixed or moving viewpoints in AVI format as well as still images in JPG, TIFF, PNG and BMP format.

Data export

A wide variety of numerical data can be exported, as selected by the user, such as number of people or density in a specific region and exit usage. The data are written to a CSV text file which can then be imported into a spreadsheet package for further analysis.

Pedestrian modelling and design consultancy

Mott MacDonald has an extensive track record of analysing the pedestrian dynamic of buildings and the built environment. We can advise and manage an entire project from conception to delivery, or we can provide a specific service to facilitate a project depending on your requirement. Further information about our pedestrian modelling and design service can be found here.