



DEVELOPING NEW TECHNIQUES FOR MODELLING CROWD MOVEMENT

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VOLUME 1

PhD Thesis - University of Edinburgh, 1994





ABSTRACT

This thesis describes the analysis and development of new systems for modelling the movement of individuals in crowded situations. A literature review of previous research in this field is presented, and is accompanied by an analysis and appraisal of the methods and findings of these studies. Specific areas for potential research are identified and discussed, and the subsequent investigations by the author are described in detail.

Although some investigation into the potential use of hydraulic modelling is described, the majority of the research work is concerned with the computer simulation of the escape movement of individuals from a building. The computer program assigns a variety of attributes to each individual in the building population. These attributes include gender, age and body size. Specific algorithms that facilitate the simulation of escape movement include distance mapping, wayfinding, overtaking, route deviation, and adjustments to individual speeds due to the proximity of crowd members. These algorithms contribute to a computer package that displays the building plan and the position and progress of individual building occupants as they walk to the exits. Walking speeds, flow rates and movement parameters are compared to real-life data, and the success of applying the package to real-life problems is discussed. The thesis also describes the collection of new crowd data by the use of image analysis techniques.

ACKNOWLEDGEMENTS

The author wishes to thank the following people for their assistance during this project. The work described in this thesis was influenced by a wide spectrum of contributions.

EDINBURGH UNIVERSITY

- Dr. Eric W. Marchant - supervised the author for the entire duration of the project. Eric provided invaluable ideas and advice, which greatly influenced the functions and form of the modelling techniques that were developed. The author is also grateful for the resources that Eric was able to provide in the form of equipment, conference visits, constructive criticism, advice on the presentation of work, and plenty of enthusiastic support.
- Les Russell - provided the majority of technical advice on the construction of all experimental apparatus. Les was responsible for the practical construction of the fluid modelling equipment, and his ingenious ideas solved many of the problems that arose during the development of this type of apparatus.
- Prof. David N. Lee - whose background in the field of Psychology was particularly relevant to this project. David provided 'impartial' advice at a number of stages of the development of the computer model.
- Dr. Robin Wardlaw - assisted with much of the mathematical analysis of the fluid modelling, and advised on the formulation and future development of this type of modelling.

Ron O'Donnell - provided invaluable advice and technical support for the production of the many colour slides which allowed the author to present some of the material enclosed in this thesis at a number of international conferences.

Marie Cope - provided friendly advice and technical support when the author used the facilities at the Graphics Workshop to produce a large number of colour prints for presentation material.

Gordon Ricketts - was responsible for much of the data analysis for the movement of individual people in crowded situations, as part of his 4th year Honours project. Gordon was the other half of the 'film crew' described in Chapter 10, and the author is grateful for his patience and diligence throughout the period of data collection.

BATH UNIVERSITY

Dr. Steven Ledbetter - first had the idea of fluid modelling for the author's 4th year Honours project in 1989-90. Steve provided advice, support, and supervision for the initial one year project at Bath that inspired the commencement of this thesis.

Dave Skinner - provided technical support and general enthusiasm for all aspects of the practical work during the project at Bath, and whose ideas were used, later, at Edinburgh.

LUND UNIVERSITY

Robert Jonsson & Hakan Frantzich - became involved in the later stages of the project, with ideas for psychological parameters for the computer model, and the development of the model for movement on staircases. The author is grateful for the involvement of Robert and Hakan which has brought about collaboration and funding for the future development of the computer model, beyond the work described in this thesis.

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NOTATION

Each equation is presented with the relevant notation.

All units are SI (metric) unless otherwise stated.

ABBREVIATIONS

Due to the frequency with which it is referenced, the document "The Building Regulations 1991 - Approved Document B", (Section B1 - Means of Escape, 1992 ed.), HMSO Publications, is herein referred to as 'ADB1'.

CHAPTER 1

INTRODUCTION

Certain high-profile disasters have highlighted some of the shortfalls in modern building design, with respect to life safety. The need for new techniques to assess the capacity of a building for safe evacuation will be discussed. This chapter will outline the potential advantages and framework of development for different modelling methods, and will mention the collection of new data for crowd movement.

1.0 WHY DO DISASTERS OCCUR ?

Dixon(1994) stated that "..... most major (and minor) catastrophes result from a *combination* of human and environmental factors. The fires which destroyed Rome in AD64 and Chicago in 1871 have been attributed, respectively, to a 'psychopathic emperor' and the carelessness of an American farmer's wife who allowed her cow to kick over a kerosene lamp. But, and this is the point, neither Nero's act of arson nor Mrs O'Leary's cow would have resulted in cities being destroyed had it not been for a prolonged drought and winds blowing in the wrong direction. It is in this context of combinations between natural and man-made factors that we find some of the most disastrous decisions - those instances where human interference or lack of action managed to turn a natural hazard into a major tragedy". Disasters occur when human beings make a series of (subsequently fatal) decisions whilst interacting with the physical and physiological environment around them.

This thesis is concerned with the prevention of human disasters in the built environment. Such disasters are usually caused by a large number of individuals being trapped in a specific area of a building structure where loss of life is caused by asphyxiation due to crowd pressure, exposure to the toxic products of combustion, exposure to extreme heat, or the structural degradation of the building. Fruin (1985) suggested that four factors increase the probability of crowd accidents and needed to be addressed through design and crowd management strategies: time, space, information and energy. *Time* relates to the sequence in which the concentrations of occupants change in critical areas of a building. Fruin points out that crowd disasters "...typically occur in short periods of time, after the critical capacity limits of some pedestrian facility has been temporarily exceeded, but where intensive pressure to use the facility continues". Such situations result in a 'bottleneck' where the limitation of *space*, and the *information* perceived by a group of escaping people combine with dangerous *energy* from crowd pressure forces to produce a hazard to human life.

In 1989, ninety five people died in the Hillsborough football stadium crowd crush (Taylor - 1990) due to the combination of poor communications and management, and weaknesses in exit design. One hundred and sixty four people died at The Beverly Hills Supper Club in 1977 (Johnson - 1988) primarily because people were overcome by the products of combustion. However, the occupants would not have been harmed if the management strategy and exit facilities had been sufficient

for evacuation to occur before the onset of hazardous conditions. Fifty people died at the Summerland fire in 1973 (Sime - 1983) where poor communications and exit routing were, once more, to blame. A long list of other disasters including the Heysel Stadium crowd crush (1985), the Bradford City football stadium fire (1985), the Cincinnati Riverfront Coliseum concert (1979), and the deaths at Ibrox Park (1971) all underline the need for a better understanding of the underlying mechanisms involved in crowd movement.

1.1 THE CALCULATION AND MODELLING OF CROWD MOVEMENT

In 1911, the evacuation of the Empire Theatre in Edinburgh resulted in the death of 10 of the 3000 occupants. The escape process took two and a half minutes and was later viewed as a 'successful' evacuation. In the absence of any other data, this figure of 2.5 minutes was subsequently adopted by many regulatory authorities including those in Britain and the USA as a maximum 'safe' evacuation time, to be striven for in building design. This limited 'safe' evacuation time is used in conjunction with the maximum flow capacity of the exits from a building, which is calculated by a simple numerical process. The calculation is executed by multiplying the exit width by a standard maximum flow rate, expressed in persons per second per unit width, to obtain the flow capacity in terms of number of persons per second. The combination of 2.5 minutes evacuation time and the flow capacity calculations are the most commonly used basis for predicting the performance of a proposed building scheme when considering the potential escape of the occupants. This form of approximate 'optimal' prediction has been used by designers for over fifty years.

The demands of modern building design have brought about the development of building spaces with increasingly larger and more geometrically complex areas. These types of building include department stores, concert venues, and shopping malls where one of the optimal design objectives is to maximise the size and shape of a building plan with respect to the size of population that can be accommodated. In such buildings, the overall geometric form may exceed the normal design constraints specified by the statutory regulations. In these cases, ADB1 states that "A fire safety engineering approach that takes into account the total fire safety package can provide an alternative approach to fire safety. It may be the only viable way to achieve a satisfactory standard of fire safety in some large and complex buildings". When such an approach is required, a specialist fire safety consultant becomes involved in the

design stages. The consultant might use heat release predictions, smoke movement and extraction calculations and may attempt to predict the time at which a significant hazard to life would occur. One of the many available computer models for the prediction of the onset of hazardous conditions may also be used. It is commonly accepted that the evacuation of the building should be completed before human life is endangered, but the predictive tools that are available for evacuation time are still based on large assumptions and fairly simple principles.

The evacuation calculations available to the fire safety consultant still use the basic form of multiplying exit widths by maximum flow rates to calculate the time at which all occupants might leave the building. This calculation takes no account of the real form of exit usage by the occupants of a building during the evacuation process. Pauls (1980) is highly critical of this type of prediction because it is based on the sustained use of all building exits at a maximum flow capacity, which is rarely observed in real-life situations.

Most of the available computer programs for modelling crowd motion and the evacuation process make sweeping assumptions about the movement of groups of people through building spaces, as 'en masse' unified flows. The most common approach is to use a technique known as 'network-node' modelling, which segments a building space into a discrete number of rectangular areas, that are linked by movement 'arcs'. The population is treated as a moving 'mass' of people, and the mathematical formulae are based on real-life observations of crowd movement, in terms of total flow rates and average speeds of large numbers of people.

Some recent packages have attempted to model the movement of individual persons, but these have not led to any significantly new developments or a better understanding of the mechanisms by which individuals interact with each other to produce the process known as 'crowd movement'. In a few instances, fluid modelling has been used in an attempt to physically model the movement of crowds, but such attempts have met with little, or no success.

1.2 SCIENTIFIC DATA

Nearly all of the crowd movement data that has been collected in the past eighty years has been concerned with the speed and flow rates of groups of people, in relation to the population density over a defined 'test' area. Such data is only intended to be used to assess the capacity of specific areas of a building, such as corridors and doorways, to accommodate a uniform flow of escaping occupants. The use of such data, for design purposes will yield an approximate value for the evacuation time, assuming that the occupants use the exits in the intended, 'optimal' manner.

The collection of data concerning the movement of crowds has traditionally taken two forms. The first form, employed by researchers such as Hankin & Wright (1958) and Predtechenskii & Millinskii (1969) consisted of one scientist walking within a crowd of moving people, and timing his transition from one 'test' point to the next in order to estimate the average speed of the group that he was walking with. Another scientist would count the number of people passing through a previously located 'test line' or exit, over a specific period of time, in order to calculate crowd flow rates. The more recent form of data collection, used over the last twenty years, is the analysis of crowd movement by replaying filmed footage, or analysing a series of time lapse photographs in order to ascertain the parameters of crowd speed, density and flow rate. It has been many years since any new forms of crowd data have been developed, and hence very little detail is known about the movement of the individual in crowded situations.

1.3 THE AIMS AND PROGRESSION OF THIS PROJECT

Prior to commencement of the work for this PhD thesis, the author had used simple fluid modelling techniques to recreate certain aspects of crowd motion, as part of an undergraduate project at Bath University. It was the combination of the limited success of these early experiments, and the author's knowledge of computer programming that inspired the work described in this document.

At the commencement of the work for this thesis, the author devoted an approximately equal time to the development of fluid modelling techniques and computer simulation methods. As the two techniques developed, it was decided that the computer simulation method possessed much greater potential, both for research

and as a design tool. It was much more flexible, required no physical construction, and allowed individual characteristics to be assigned to each individual 'model' person. The fluid modelling system required a large apparatus which could not realistically be used to model complex geometric spaces. As a result, the main body of text is solely concerned with the computer simulation methods. The fluid experiments are described in some detail by the paper "Hydraulic modelling of crowd flow" in Appendix 1.2.

The computer simulation techniques were developed over a period of three years. The main feature of the computer package that was developed, was the use of algorithms that continuously reassessed the movement, position and decisions of every individual building occupant during the process of evacuation. The author adopted this approach because he felt that the previous computer models that had been developed did not accurately recreate the spatial complexities and human interactions that were necessary for the realistic simulation of crowd movement. The techniques that were developed for the analysis of travel distances, fluctuations in individual walking speeds, overtaking, and mutual interaction are all new. The derivation and use of these techniques illustrated the way in which the separate movements of a large number of individual people produce the overall effect of crowd motion.

The development of these new modelling methods required the derivation and collection of new types of data concerning the movement of a number of individuals through a building space. The highly specific nature of the required data brought about the development of a fairly complex form of data collection. Groups of people were filmed at various locations, and the footage analysed as a sequence of still frames, in order that the required information could be obtained.

The essence of this thesis is the development of new modelling techniques in order to deepen the understanding of the mechanisms involved in crowd movement.

CHAPTER 2

EVACUATION: A general overview of previous studies.

This chapter contains a brief description of the primary developments that have occurred in the field of crowd movement, focusing on the activity of escape after discovery of a fire. A chronological list of developments will be presented, as well as a discussion of certain characteristics of crowd motion. A more specialised, and in-depth analysis of specific studies will be presented in chapters 3 and 4.

2.0 EVACUATION: A general overview of previous studies.

The research into the escape movement of people has taken many forms during the course of this century. Data has been collected with stopwatches, cine film, video film and by simple observation. Technological developments in recent years have made some of the data collection a little easier. This type of observational research forms the basis of most of the statutory building regulations around the world, with regard to evacuation planning. In the early studies, the primary characteristics of crowd movement were regarded as the maximum flows achievable through specific widths of openings, corridors and staircases. Building codes usually specify a time within which the evacuation of a proposed building must be complete, based on the simple crowd flow capacities of the building routes.

During the last 20 years, the comprehensive advancements in calculating power and increased availability of computers to the scientific world has encouraged the development of many crowd movement simulation models. Initially, these tools made assumptions about the escape movement through a building that were similar to those made in the statutory regulations, such as ADB1. The simulation models have increased in complexity as the available computing power has increased, but psychological modelling still remains fairly simple due to the lack of accurate data.

2.1 THE PROGRESSION OF RESEARCH AND REGULATIONS

The information and data that support the statutory regulations, such as ADB1, are based on many different research studies. The evacuation guidelines come from work done by various scientists and engineers, but rarely psychologists. For this reason, a chronological summary of general research projects has been compiled, and the influence of some of the results on the content of regulations and standards is noted. In addition, a summary of research into the psychological behaviour of crowds is presented in Section 2.2.

The following table is a brief summary of what may be viewed as the primary developments in the field, with regard to the analysis and quantification of crowd motion, and which have a particular relevance to this project. Each of the following documents, except the Empire Theatre evacuation (no reference available), is referenced in author-alphabetical order in the list of references.

Year (Country) - Development

- 1911 (UNITED KINGDOM) - A fire, in which 10 people died, at the Empire Theatre in Edinburgh led to the evacuation of 3000 people. The band had started to play the national anthem at the same time as the alarm was raised. Nearly all of the occupants had escaped by the time the anthem had concluded. The duration of the evacuation was therefore known to be 2.5 minutes.
- 1917 (UNITED STATES) - The Engineering News Record produced an article detailing considerations of exit designs as detailed by the NFPA Committee on Safety to Life. The article mentioned the maximum emptying time for a building with no specific figure given.
- 1934 (UNITED KINGDOM) - The Manual of Safety Requirements in Theatres (HMSO) adopted the figure of 2.5 minutes for a total evacuation, based on the Empire Theatre evacuation. This time became a standard for nearly all U.K. building codes, written in later years.
- 1935 (UNITED STATES) - The National Bureau of Standards produced "The Design and Construction of Building Exits". It contained the term "unit exit width" (based on the width of a moving person), and specified flow figures such as 45 persons per minute per unit exit width down stairs.
- 1952 (UNITED KINGDOM) - The government produced "Post War Building Studies, No. 29", which was, to an extent, similar to the 1935(U.S.) report. It also expanded guide-lines for the field, in that it specified the recommended time for evacuation to a place of safety in buildings as 2.5 minutes (as used nowadays). This was based on the Empire Theatre evacuation in 1911. It contained flow rates for population capacity calculations based on 40 persons per minute per 21 inches of exit width.

- 1955 (JAPAN) - Kikuji Togawa produced the "Study Of Fire Escapes Basing On The Observation Of Multitude Currents". His many observations and analyses culminated in his single equation for "time required for escape" from a building. It took into account the flow time for an egress element, plus the time needed to traverse some distance in the egress system.
- 1958 (UNITED KINGDOM) - B.D. Hankin & R.A. Wright presented a document for the Operational Research Society, concerning passenger flows in subways. It detailed flow tests, both on schoolboys moving within a fenced circuit, and tests carried out observing passenger flows in the London Underground.
- 1971 (UNITED STATES) - John J. Fruin produced his book "Pedestrian Planning And Design". This dealt with many aspects of pedestrian traffic flow parameters, and graphs of flow behaviour. It was an important document, approaching many aspects of pedestrian traffic flow design, including the "body ellipse" description of the human body, and related movement variables.
- 1971 (HOLLAND) - I. Peschl produced findings of his experiments into the flow of students around a door / corridor circuit. At high person densities, he observed the types of exit-blocking known as "dynamic arching" and "static arching", where people bunch at a constriction in the flow path. He attempted to simulate these arching patterns using steel ball-bearings, stacked above a constricted opening.
- 1972 (UNITED KINGDOM) - A little-known paper was produced by J.G. Weston & J. Marshall, entitled "The Capacity Of Passageways For Uni-Directional And For Crossing-Flows Of Pedestrians", for the Department of Operational Research. They carried out a photographic survey of passenger movements, when two perpendicular flows of people met at Victoria Station on the London Underground. From their results, they produced an interaction curve for two (major and minor) crossing flows.

- 1972 (UNITED KINGDOM) - Poyner et al completed the SCICON report - "to develop a method of assessment for establishing the design characteristics for safe movement, accommodation and control within a football stadium and its immediate environment." Guidance and flow capacity calculations were based on filmed tests and observation.
- 1973 (UNITED KINGDOM) - The first issue of "The Guide to Safety at Sports Grounds" was produced. It was intended for use in the U.K. and contained guidance primarily for designers. The flow capacities quoted for doorways, stairs and corridors were based on those given in the SCICON report.
- 1975 (RUSSIA) - The English translation (from Russian) of Roytman's book "Principles Of Fire Safety Standards For Building Construction" (1969) was published. It contained calculation methods, based on many Russian experiments and observations, and detailed a complex graphical method of finding an evacuation time for a building.
- 1978 (RUSSIA) - The English translation (from Russian) of V.M. Predtechenskii & A.I. Milinskii's book "Planning For Foot Traffic Flow In Buildings" (1969) was published. This detailed more findings from Russian experiments into the field, and produced flow calculation formulae, recommendations, and graphical analyses of flow characteristics. The Russian work was also concerned with the flow patterns at junctions and merging points in contrast to the American and British aims of equating only the total evacuation time using simple passageway capacity calculations. Each person was seen as possessing an elliptical horizontal projected area on the building plan.
- 1978-1980 (UNITED STATES) - Pauls observed 58 separate evacuations of different buildings, using stop-watches and / or video cameras to record events. Developing the idea from Fruin (1971), he described an 'effective width' model for movement in spaces of finite width. This model reduced the finite, geometrical width of corridors or staircases by eliminating the observable gap between the moving people and the wall or handrail, for the purpose of calculating flow rates.

- 1979- (UNITED STATES) - Fred Stahl, Rita Fahy and others wrote and
1983 documented the Building Fire Simulation Model, named BFIRES. This was one of the first computer models for the simulation of escape from buildings. It was based on the network-node analysis form which segmented buildings into discrete areas, with passageway links which possessed parameters such as flow capacities, traverse times, and potential queues.
- 1982- (UNITED STATES) - Kisko et al wrote and documented the computer
1985 program EVACNET+. It was one of the important, early computer models for evacuation based on the network-node type of analysis, and incorporated aspects of queuing theory. During the 1980s many network-node models including those by Alvord (1983-85), Fahy (1985), and Berlin (1982) were produced in the U.S.A.
- 1983 (AUSTRIA) - Kendik developed the evacuation calculation methods described by Predtechenskii and Millinskii (1978) and compared the results of their application to real-life evacuations with some degree of success.
- 1983 (ISRAEL) - Polus et al filmed and quantified the movement of pedestrians on sidewalks in Haifa. They identified a relationship between crowd density and overall speed, but they also calculated statistical parameters of movement such as standard deviations and the coefficient of variation for crowd speeds.
- 1984- (UNITED STATES) - Levin et al produced the computer model EXITT.
1987 The movements of individual persons were modelled via the network-node type of analysis, and the program only accommodated a few individuals. The important aspect of this model was the complex behavioural attributes that each person possessed, although many of the behavioural properties were formulated by the programmer, and not based on scientific data
- 1988 (JAPAN) - Ando et al carried out many observations of commuters, and quantified speeds and flow rates. Some of the results were presented as graphs relating gender and age to normal, unimpeded walking speed.

- 1989- (UNITED STATES) - R. Fahy continued to be involved in the production
1994 of the computer model EXIT89, again based on a network-node analysis for simulation, at the National Fire Protection Association. This model is important because it can handle large populations, and tracks the progress of individuals through the building 'network'. It is incorporated in the HAZARD I package, and accepts data from other fire models, such as smoke movement and toxicity and assesses the effect of these parameters on the occupants.
- 1991- (UNITED KINGDOM) - Ketchell et al (1993) have been involved in the
1994 development of the computer program EGRESS. The model segments a building or transport vehicle plan into linked hexagonal cells, each of which are the size of one 'person'. In conjunction with EGRESS, a fairly advanced artificial intelligence model was produced to simulate the behaviour of crews on offshore platforms. A similar model called EXODUS also calculates fire growth and atmospheric toxicity and is being produced at the University of Greenwich by Galea (1993).
- 1991- (UNITED KINGDOM) - K. Still wrote the evacuation model VEGAS
1994 within a virtual reality environment. It represents each individual accurately in terms of body size and position and incorporates simple representations of smoke movement and atmospheric toxicity.

The list above does not include the Japanese computer simulations, such as that described by Aoki et al (1988). This is because the majority of these models are very similar to those described from the U.K. and U.S.A., especially when considering network-node analyses. A more complete appraisal of computer simulation techniques is presented in Chapter 4. It must be emphasised that this list is, by no means, a complete list of developments in the field of evacuation study and design. However, these developments can be considered as those of primary significance with regard to the analysis and simulation of crowd movement.

2.2 PSYCHOLOGICAL ASPECTS OF ESCAPE

Traditionally, the psychological aspects of escape from buildings are rarely, if ever, discussed in guidance which supports the building regulations such as ADB1. It is only recently that the regulatory authorities have begun to recognise the significance of aspects such as people's awareness and their different response to alarms. Au et al (1993) have produced a study to generate guidance for the management of crowd safety in public venues. Much of this work includes identifying risk areas. Some of the guidelines require the identification of the type of crowds, their anticipated behaviour, and the familiarity of the crowds with the event and the venue. Many different aspects of crowd safety are discussed, including the possible consequences of equipment failures. Crowd control strategies are required, and good, clear communication with the people in the building enclosure is regarded as extremely important.

It is important to understand some of the fundamental criteria applicable to the problem of people escaping through defined routes in an emergency situation. In certain circumstances, the psychological behaviour of the crowd, and individuals within that crowd, can become far more important than the physical constraints for escape created by the building geometry. Many of the findings of papers written on collective behaviour in simulated events are particularly relevant.

LaPiere (1938) stated that 'group action' is inevitable in a group of shocked individuals: "No aggregate of reacting individuals can, for however long, refrain from interaction from one another, if for no other reason than they are likely to come into physical contact with one another. Inevitably, therefore, the period during which members of a group react as individuals is brief and is followed by some form of collective behaviour. Unless regimented leadership operates, the collective behaviour will be panic in type."

Another interesting observation was made by Mintz (1958): "Co-operative behaviour is required for the common good, but has very different consequences for the individual, depending on the behaviour of others. Thus, at a theatre fire, if everyone leaves in an orderly manner, everybody is safe, and an individual waiting for his turn is not sacrificing his interests. But, if the co-operative pattern of behaviour is disturbed, the usual advice "Keep your head down, don't push, wait your turn, and you will be safe." ceases to be valid. If the exits are blocked, the person

following this advice is likely to be burned to death. If everybody co-operates (and obeys the pre-arranged flow patterns) there is no conflict between the needs of the individual and the needs of the group. However, the situation changes completely as soon as a minority of people cease to co-operate. A conflict between the needs of the group, and the selfish needs of the individual then arises.

Kelley et Al (1965) found that:-

- [1] As the threatened penalty for failure to escape increases, the percentage of persons who succeed in escaping declines.
- [2] As the size of the collection increases, the percentage escaping declines. This may be stated as an increase in the time required per escape with increasing size.
- [3] When people act together as a group, the escape rate increases if the group as a whole feels confident that escape is possible. If there is doubt that the escape routes are freely moving and/or blocked in some way then the escape rate decreases as lack of confidence is instilled, and the possibility of panic arises.
- [4] The availability of a distinctive response for the public expression of confidence greatly increases the percentage of people who succeed in escaping. To clarify this point; if a crowd of individuals communicate well, they are likely to be more organised, and hence stand more chance of escaping.

Both Freud (1922) and Schultz (1965) minimise the role of crisis or danger as being of paramount importance in creating group panic. What is important is the breakdown of mutual consideration between individual group members, and the resulting "en-masse" crowd behaviour. As the organised properties of crowd flow break down in the event of danger, so the rate of escape decreases. This happens at high person densities within a given area (usually exits) and is potentially lethal.

Another important aspect of fire escape psychology is that, on hearing the fire alarm, people do not necessarily head for the exits straight away, unless the danger is obvious or imminent. This can lead to a staggered flow from a building. Different corridor flows may have different feelings of anxiety, urgency, or even panic, resulting in differential flow rates. Smoke is an important consideration. Its presence can create a feeling of panic throughout a group. Any degradation of the internal building environment surrounding the crowd flow may create fear and hence, have a detrimental effect on the rate of people escaping. Bottle-necks may occur at exits and corridor junctions. A too-simple flow model may be upset by the staggered flow and urgency factors mentioned above.

2.3 PRIMARY ASPECTS OF HOW PEOPLE ESCAPE

Marchant (1992) identified three primary aspects of evacuation, in terms of people, as being psychological, physiological and physical. Proulx (1994) also suggested that there are three primary phases for the evacuation process;

PERCEPTION - INTERPRETATION - ACTION

She therefore named this the PIA process. Proulx wrote that "Occupants are alerted by a variety of auditory, visual, olfactory, and tactual cues. They then become involved in the process of information search, interpretation and appraisal, and decision making from which evacuation may emerge as the coping strategy ...".

In "Fires and Human Behaviour" (1980) many aspects of crowd movement are discussed. From this, and other similar publications it is clear that certain aspects of the building design and management are crucial to the escape behaviour of the occupants. The primary factors that affect the PIA process are;

- (1) ALARM TYPE (audible, visual, tactual). Certain types of alarm are more effective than others. People appear to be more willing to leave if a person with designated responsibility (a fireman or member of staff) is urging them to escape.
- (2) ALARM POSITION AND INTENSITY (volume, brightness, urgency). Usually, the more informative and intrusive alarms are the most effective. However if an alarm is too loud, it may hinder communication between individuals.
- (3) FREQUENCY OF FALSE ALARM. If false alarms occur often in a building, it can 'desensitise' the normal occupants to the alarm, to the extent that they may choose to ignore it altogether.
- (4) OCCUPANT ACTIVITY. If occupants are queuing for tickets, in bed, or even eating, they may be reluctant to leave the building.

- (5) **GROUP COMMUNICATION.** The speed of communication within the members of a crowd may be very important. A group of people who are familiar with each other may communicate information more readily than strangers. This does not necessarily mean that they will leave more quickly because it is possible that people who have known each other for a long period of time can become complacent, or less eager to escape when an alarm is raised.
- (6) **GROUP FAMILIARITY WITH THE BUILDING.** How familiar people are with a building can dramatically affect their chosen escape route. People may ignore unfamiliar exits.
- (7) **OCCUPANT CHARACTERISTICS.** Age, infirmity, disability.
- (8) **CLARITY OF SIGNAGE.** Unclear signage can create confusion. Emergency exits that are not clearly signposted will probably not be used. Signs in different languages may also create confusion.
- (9) **LIGHTING LEVEL.** In a dark environment, the escape process changes dramatically. If the ambient lighting fails after an alarm has been raised, people appear to become much more aware of the presence of danger, but wayfinding and passage through escape routes may be seriously impeded. This effect may be especially important during the period when the visual acuity of the occupants adjusts from one intensity of ambient lighting to another.
- (10) **PHYSICAL IMPEDIMENT BY ESCAPE ROUTE.** Inadequate capacity for escape within a building can cause severe injury and sometimes death. Problems include insufficient passageway widths, passageways constricted by objects, locked emergency exit doors (unfortunately, still commonplace), unexpected steps or changes in floor level, and fatigue from excessive travel up or down staircases. The transport of smoke, heat and noxious products of combustion will also cause a problem

- (11) **PHYSICAL IMPEDIMENT BY INDIVIDUALS.** Too many people attempting to escape through a narrow doorway can prevent successful evacuation, and cause a blockage in the system. Also, in a crowd of moving people (for example, at a density of 3 persons per square metre), people slow down even though there may be no bodily contact. This phenomenon, the 'invasion of personal space', will be discussed in detail in Chapter 3.

The above list only provides a summary of the main areas of the PIA process. Other events may affect the escape process, but they have not been quantified. The aim of this project is to model important aspects of the escape process, and this can only be realistically done in areas where data is available, or can be collected reasonably accurately. Two quantifiable areas that have been identified as being important in the PIA process are the time for response to alarm, and the choice of exit routes in a building.

2.3.1 TIME FOR RESPONSE TO ALARM

Many evacuations have been observed by researchers in different buildings around the world, but rarely do they note the time delay between an alarm being raised, and people actually beginning to move towards an exit. Some examples of where this time delay has been quantified are Sime (1992), Rubadiri (1993), and Proulx and Sime (1991). These studies have illustrated the wide range of time delays due to the response to alarm.

Sime(1992) suggested that "... the nature of the warning system and communications at the beginning of the evacuation are likely to be crucial in predicting evacuation times from an assembly setting". Test evacuations of students from a lecture theatre produced an average response time to an alarm of 30 seconds, but Sime recommended that a minimum of 2.5 minutes delay be expected, for design purposes, when attempting to predict the evacuation of a building. This time delay should be added to the 2.5 minutes normally allowed for the escape movement of the occupants. Research and Inquiries on disaster, such as the Summerland Fire, Beverly Hills Supper Club Fire, Woolworth's Fire, Kings Cross Fire indicate that the time to start evacuation could be far longer.

One of the more interesting studies in this field was carried out by Proulx and Sime (1991). A series of evacuations were carried out, without the prior knowledge of the evacuees in Monument Station on the Tyne and Wear Metro system. Different types of alarm were tested, to compare their relative effectiveness on the evacuation of the people in the station.

(1)	Alarm bell only. No assisting staff. or P.A. announcements.
(2)	Alarm bell + local P.A. announcements by two members of staff.
(3)	Alarm bell + repeated P.A. message "Please evacuate the station immediately."
(4)	Alarm bell + assisting staff + P.A. issuing directive messages to particular people in the station to move (CCTVs used).
(5)	Alarm bell + P.A. issuing directive messages to individuals and also giving information about the fire location. No staff assistance

TABLE 2.1 - Types of alarm for 5 evacuations, Proulx & Sime (1991).

Evacuation	Time to start to move		Time to clear the station	Appropriateness of behaviour
	Concourse	Bottom Escalator		
1. Bell Only	8:15	9:00	14:47 (not all people leave)	Delayed or no evacuation
2. Staff	2:15	3:00	8:00	Users directed to concourse
3. P.A.	1:15	7:40	10:30	Users stood at bottom escalator
4. Staff + P.A.+	1:15	1:30	6:45	Users evacuated
5. P.A.++	1:30	1:00	5:45	Users evacuated by trains and exits

TABLE 2.2 - Results of 5 evacuations, Proulx & Sime (1991).

The five different evacuations were conducted on five week days at around mid-day. The different types of alarm are listed in Table 2.1, and the results of the evacuations are listed in Table 2.2. The results of these evacuations were very significant. Certain types of alarm appeared to be significantly more effective than others.

It is evident from this study that an ordinary, continuous alarm bell can be ignored completely. When staff direct people out of the station, they tend to move more quickly, but the directive P.A. system is most effective. Informing people of the fire location also appears to aid the evacuation process. In short, people evacuated earlier when they were supplied with more information.

Rubadiri (1993) observed and quantified a series of evacuations at different buildings. In the cases where response time to alarm was quantified, members of staff were present. This probably speeded up the response time to alarm of the other occupants. In the conference residences and hotel, the response time ranged from 6 - 22 seconds. In two disabled residences, the response times ranged from 4 - 20 seconds, and 13 - 24 seconds.

Horiuchi et al (1986) presented the findings from a post-fire survey of occupant decisions and actions resulting from a fire on the fourth floor of a multi-storey office building in Osaka, 1984. In this incident, the public address system was used to announce that a fire had started, but less than 20% of the occupants decided to leave immediately after the announcement. Many people required further confirmation that there was a real emergency, by seeing smoke in the corridors or by verbal confirmation from others.

2.3.2 CHOICE OF EXIT ROUTE

Most, if not all, network-node computer models of evacuation assume that occupants head towards the nearest exit. The same is assumed in the building regulations (ADB1). However, in the light of research over the past 10 years, it has become generally accepted, amongst the fire safety community, that this is not always the case. Many post-disaster investigations have highlighted this problem, and research studies support the view. It is well known that if an emergency exit is not well signposted, then it is unlikely to be used in an evacuation. Another

important factor is the familiarity of the occupants with the building layout. People who are faced with emergency conditions may choose to leave by the route that they entered the building, or certainly with a familiar route. This may be counteracted by good staff training in the event of an emergency, but it is rare for people to be informed of all available escape routes when entering a new building environment. People sometimes prefer to leave by the most familiar entry and egress route because they are acquainted with the geography of the route, but they may have no idea of the geography of the escape pathway entered via an unfamiliar emergency exit.

In a test evacuation of staff at a Marks & Spencer store by Rubadiri (1993) it was found that 57% of people used the nearest exit, but the rest of the population took those exits that were either better signposted or more familiar. This is surprising, because in this department store staff should be fully aware of the emergency exits.

Sime (1992) carried out studies of the evacuation of two lecture theatres, 'F' and 'R'. Each lecture theatre was evacuated twice with different people each time, using a standard fire alarm. In both lecture theatres, the entrance doorways were at the rear. The fire exit in 'F' was also at the rear, but in 'R' the exit was in clear view, at the side of the lecture theatre and close to the lecturer. The room dimensions and seating layouts in both lecture theatres were the same. A summary of the results is presented below.

Lecture Theatre	% using route		Instructions from lecturer
	Entrance	Fire Exit	
F	55	45	To leave the room (exit unspecified)
R	0	100	To leave the room via the fire exit only
F	62	38	To leave the room (exit unspecified)
R	30	70	To leave the room (exit unspecified)

TABLE 2.3 Exit choice - from Sime (1992).

Note that in lecture theatre 'R', the fire exit was regularly used as an exit at the end of lectures, but the fire exit in 'F' was rarely use in this way.

This study produces some interesting insights into the exit choice of building occupants. In the tests presented, the most favoured exit was both familiar and in full view of the subjects. When told to leave via a specific exit, all the subjects did so. The entrance and exit doorways were both at the rear of the lecture theatre 'F', had similar dimensions, and were on either side of room, but there was, on average, a 3:2 preference for the doorway that was normally used. To summarise, people had a slight preference to exit by the normal route, but direct instructions would dominate the escape process.

Horiuchi et al (1986) found that the choice of an evacuation route depended mostly on the amount of smoke, but gender, job and familiarity with the building were important factors. In the conclusion of the report, Horiuchi stated that "The choice of an evacuation route will often be a regularly used route if the evacuee is familiar with the building. For those not familiar, following or relying on others is the norm. If familiar with the building, occupants have little difficulty finding exits even in heavy smoke. If the location of the stairs is not known, finding an exit can be of great difficulty. In all phases of the evacuation process, familiarity with the building was found to be the primary determinant of speed and ease of evacuation".

2.3.3 THE USE OF PSYCHOLOGICAL DATA IN EVACUATION MODELS

Very few evacuation models have attempted any form of complex psychological modelling. Those that have include EXITT (Levin et al - 1989) and VEGAS (Still - 1992). EXITT uses behavioural rules that were mostly formulated by the programmer, such as decisions such as helping other occupants, investigating the fire or leaving the building. VEGAS attempts to simulate leadership behaviour and group 'flocking' as well as fire investigation. Neither program has used significant quantities of 'real-life' data on which to base their algorithms on. This is probably due to the general lack of such data, and these attempts at modelling behaviour are of particular interest.

Only a few of the psychological aspects listed above, have been modelled in the systems described in this thesis. This is primarily due to the lack of available data, the incredible complexity that such modelling generates and the time constraints imposed on the project. Concepts such as 'the invasion of personal space',

reaction to alarm, population characteristics, wayfinding and familiarity of routes are discussed again in later chapters.

2.4 SUMMARY COMMENTS

The majority of research studies for crowd movement and the evacuation process have, in the past, been primarily concerned with collating data that evaluates crowd motion as the transition of a motive, homogenous mass through a defined exit plane, such as a doorway. As a result, tables of data concerning the overall parameters of crowd movement, in terms of flow rates, average speeds and average densities are widely available. However, there have been no detailed studies of the movement of individual persons in crowded situations. Little is known about the process by which each individual interacts with another, in close proximity, and the way in which these mutual interactions combine to produce the effect of crowd movement. The computer models that have been written are limited by the data that is available, and therefore the majority of such models make large assumptions about crowd motion and do not adequately simulate the complexities of such movement.

The psychological studies of various behavioural aspects of the evacuation process have highlighted certain areas that significantly affect the total time taken for the occupants of a building to evacuate. The 'pre-action' time (when occupants perceive an alarm, interpret the stimulus, and respond to the information received) can often be more important than the 'action' time when the occupants actually walk out of the building space. The familiarity of the occupants with the building environment around them can also be an important factor in determining the total evacuation time because it may influence the usage of different escape routes throughout the building structure. The behavioural and physical processes which combine to produce 'evacuation', require more detailed scientific investigation if we are to evaluate the safety of building environments in a more detailed and comprehensive manner.

CHAPTER 3

A REVIEW OF THE ANALYSIS OF CROWD MOVEMENT

This chapter reviews research into crowd movement parameters, some relevant design recommendations, and the importance of certain aspects of the data presented is discussed. All graphs (except Figure 3.11) are presented with their original units, because the original units used often affected the range of data collected in each study. The graphs are re-drawn using metric units in Chapter 8.

3.0 PREVIOUS RESEARCH INTO CROWD MOVEMENT

Some of the work that is most directly applicable to the type of modelling attempted in this project was described in books by Fruin, Predtechenskii & Milinskii, and papers by Hankin & Wright, Weston & Marshall, and Peschl. It is also important to recognise the figures for crowd motion specified in the statutory regulations. Different researchers used different units for equations, and it was important to compare their different relative attributes and methods of analysis. One of the most important equations, relating to the parameters of movement and capacities of exit routes takes the form described in Equation 3.1.

$$\text{Crowd flow rate} = (\text{crowd speed}) \times (\text{crowd density}) \quad \dots\dots\dots (3.1)$$

The equation above was used by many researchers to calculate crowd flow rates, using a speed / density relationship that had been derived by observational analysis. Others quantified crowd flow rates directly by counting the number of people passing through a single plane over a measured time.

The shape of the human body is elliptical on plan, and this is an important property to simulate in the modelling of pedestrian movement. Much of the work described below uses this body ellipse when specifying the space occupied by human bodies. The important dimensions are shoulder breadth and body depth.

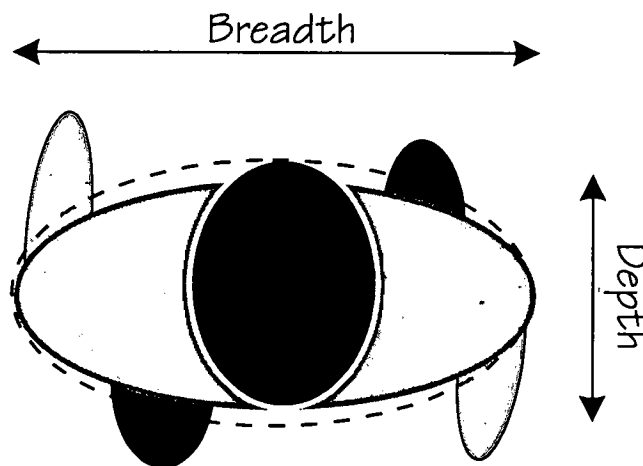


Figure 3.1. The Body Ellipse

3.1 FRUIN (1971)

Fruin's book "Pedestrian Planning and Design" is recognised as one of the most important works in the field of crowd movement analysis. The work was extensive, but more discursive in its nature than the numerical methods presented at a similar time by the Russians (Roytman - 1969, and Predtechenskii and Milinskii - 1969). It did, however, tackle the essential basis of pedestrian flow in great detail. It dealt with the body ellipse, pedestrian queuing, flow per unit width of passageway, density and speed of pedestrian flow, and level-of-service standards. Most of the work is based on the analysis of commuters and shoppers on city walkways.

This publication introduced the "level-of-service" concept for pedestrians, which relates person flow density to its effect on the speed of the people in the flow. The concept was first developed in the field of traffic engineering on roads. The basic idea is that as the number of persons per unit area (density) increases, then the ability of a person to select normal locomotion speed decreases, and the flow of people slows down. A more dense person flow provides a lower quality level-of-service, i.e. normal locomotion speed is restricted as is the ability to by-pass slow-moving pedestrians. Fruin related flow per unit width to density of people in a passageway.

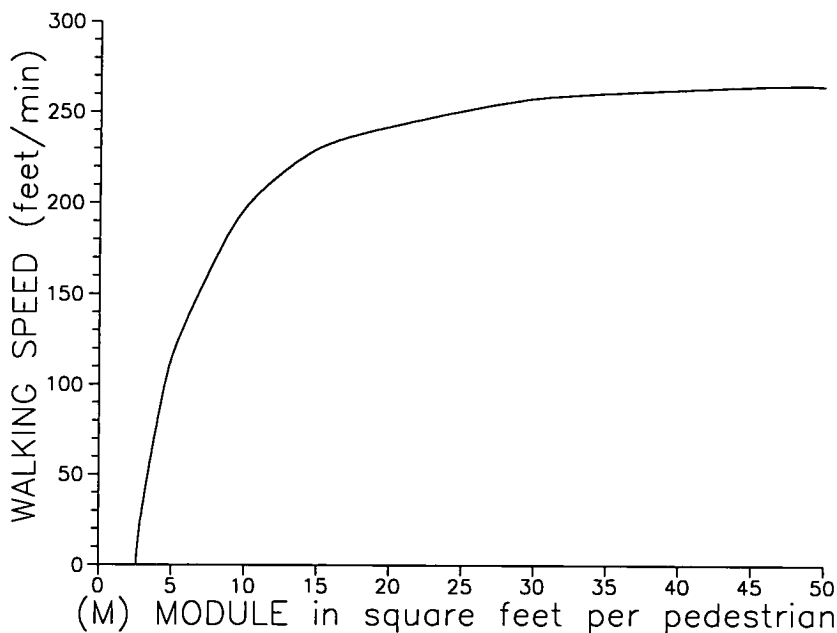


Figure 3.2. Graph relating walking speed and crowd concentration (re-drawn from Fruin - 1971).

Fruin used time-lapse photography to quantify certain movement parameters. The time-lapse studies were used to obtain the relationship between crowd density (Module-M) and average speed, illustrated in Figure 3.2. Fruin used Equation 3.1 to obtain the relationship between density and flow illustrated in Figure 3.3. It is important to note that the highest crowd density figure plotted for these graphs was 6 square feet per pedestrian, which is significantly less concentrated than the maximum possible packing density of people in crowded situations. The graphical curves drawn in the region 2.5 - 6 square feet per pedestrian, may therefore be viewed as an educated judgement, rather than being based on specific data points.

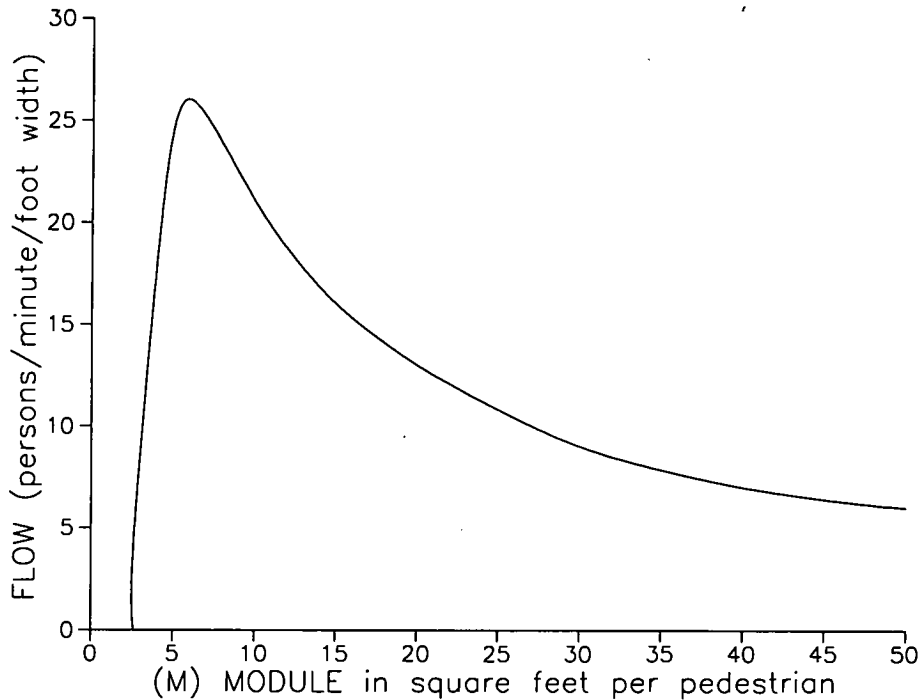


Figure 3.3. Graph relating flow rate and crowd concentration
(re-drawn from Fruin - 1971).

Fruin gathered qualitative data on body dimensions in the U.S. He found that:-

- 99% of people had a shoulder breadth of less than 20.7 inches (526mm)
- An extra 1.5 inches (38mm) should be added for heavy clothing
- 95% of fully clothed male labourers had a shoulder breadth of 22.8 inches (579mm) and a body depth of 13 inches (330mm).

- Body ellipse dimensions of 24 inches (610mm) by 18 inches (457mm) were used to determine the practical standing capacity of New York City Subway cars, and by the U.S. Army in its human factors design manual. This ellipse allows for baggage, body sway and the avoidance of bodily contact.

Fruin also described the concept of the "body buffer zone" (the quantity of space occupied by one person, including the amount of free space around the body). From observations of the packing behaviour of people he assumed a circular body buffer zone. In figure 3.4 he describes the "touch zone". It allows a buffer zone of 2 feet (610mm) diameter per person. Fruin states that any concentration increase beyond this "touch zone" incurs frequent, unavoidable contact between people, and movement is restricted to shuffling. This "touch zone" is observed in slightly crowded lifts, or the front ranks of a densely packed escalator or cross-walk queue.

12" RADIUS - Touch zone

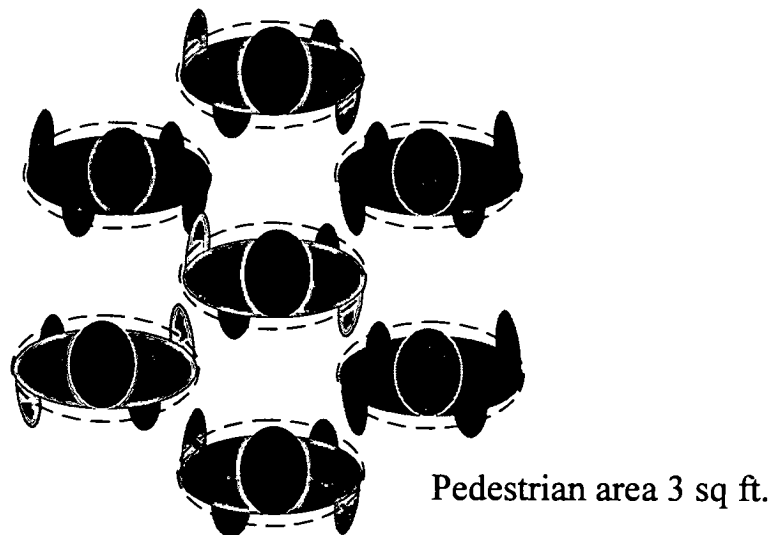


Figure 3.4. The "Touch zone". Any concentration beyond this geometry incurs frequent and unavoidable bodily contact (re-drawn from Fruin - 1971).

Figure 3.5 describes the boundary of the "no touch zone" using a 3 feet (914mm) diameter buffer zone. Contact with others can be avoided between the "touch zone" and the "no touch zone" boundaries as long as movement within the queuing areas is not necessary. However, movement as a group is possible and this

restricted spacing is actually within the range of pedestrian density that produces maximum flow capacity in passageways and stairs. Zones beyond the "no touch zone" boundary include the "personal comfort zone" and the "circulation zone" which were achieved in crowds that were much less densely packed.

18" RADIUS - No touch zone

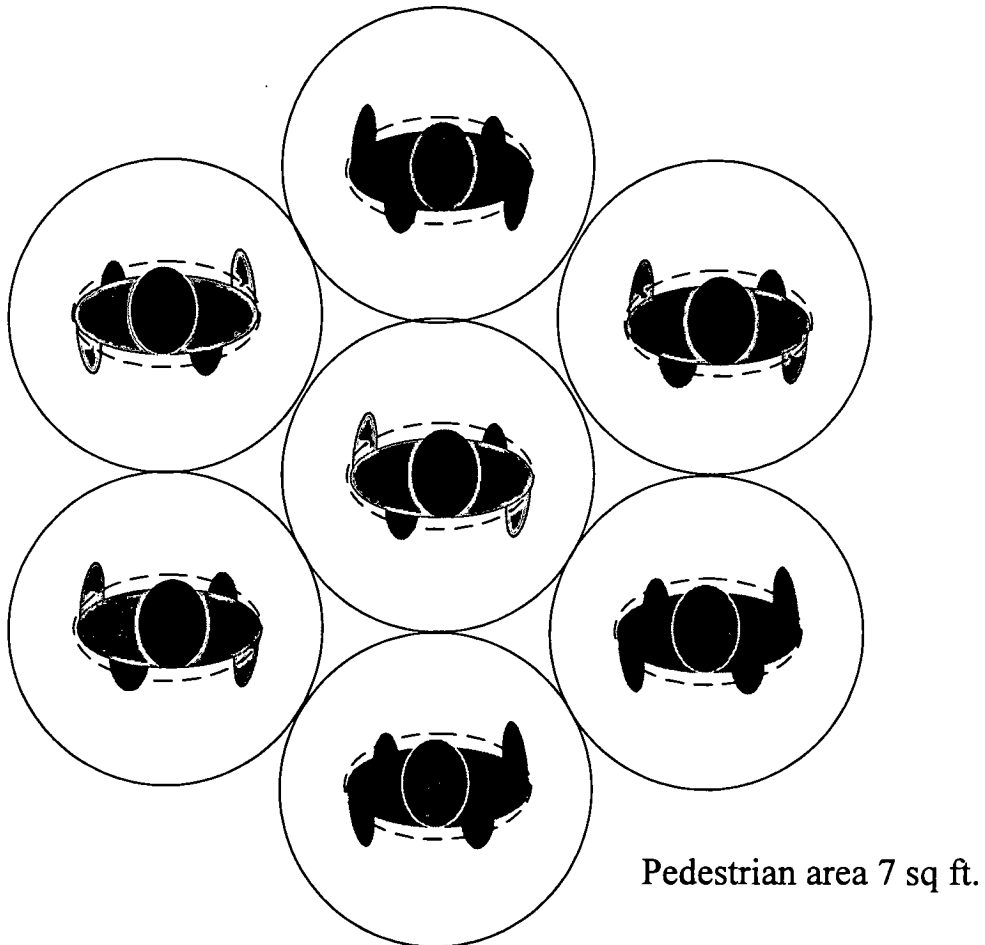


Figure 3.5. The "No touch zone". Maximum flow rates are achieved at concentrations in this region (re-drawn from Fruin - 1971).

Fruin also noted that in the situations that had been observed, there was a gap of free space between moving people and solid walls. He stated that this gap was usually between 1 and 1.5 feet. It should be noted once more, that this only applies to the observations in this particular study, which did not approach the maximum packing density of moving or static crowds. This consistent 'edge gap' is produced by

a combination of the comfortable area that a person desires to move in, and the swaying motion of the body of a walking individual.

This study was significant because it was one of the first in-depth analyses of crowd transit. Many of the figures produced are still used in building codes in the U.S.A. today. Some of the aspects that are particularly relevant to this project are the body sizes quoted, the graphs of speed and flow rate, and the forms of spherical packing described in Figures 3.4 and 3.5.

3.2 RUSSIAN ANALYSES (1965-1969)

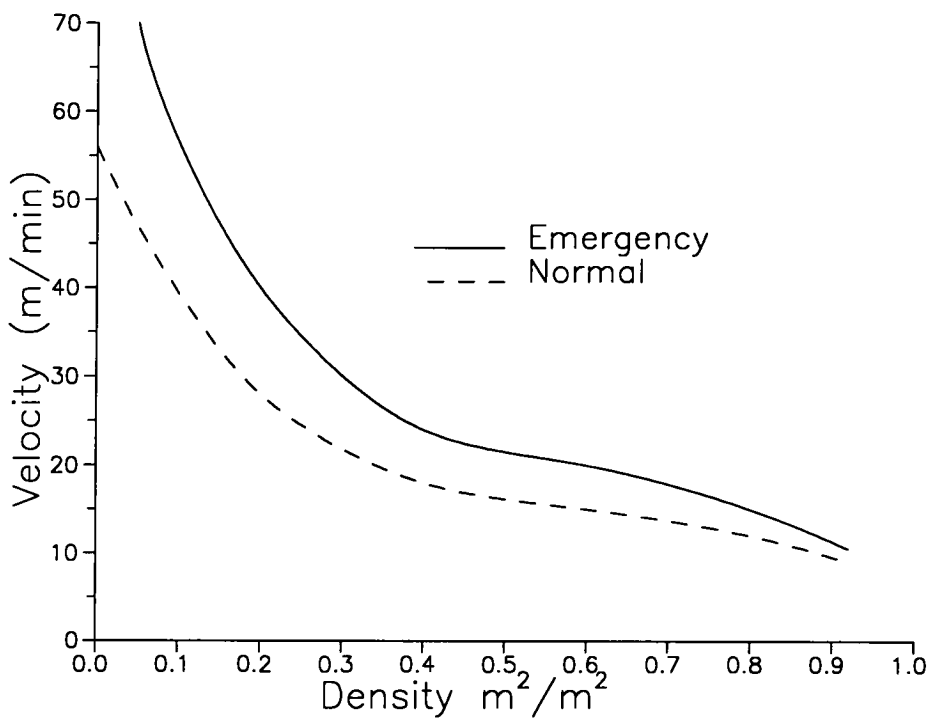


Figure 3.6. Graph of the relationship between crowd velocity and density (re-drawn from Predtechenskii and Milinskii - 1969).

The Russian studies were described in two books; Roytman (1969) and Predtechenskii and Milinskii (1969) which were translated into English in the 1970s. The work took a slightly different approach from Fruin. It was much more concerned with the merging and combination of flows than the American work in general, and was based on the combination of 7000 observational results from 3 institutes in the

Soviet Union. The first important difference from the work carried out in the United States, was the choice to use density units of "m² space occupied by human bodies per m² free space", as opposed to Fruin's Module(M) (square feet area per pedestrian). It should be noted that Roytman used the data to produce a graphical method of modelling the movement of crowds through building areas. The method was based on combining observed graphs of the flow/density relationship with the number of people in the building and passageway widths. Predtechenskii and Milinskii presented Roytman's data and also the data collected from other crowd motion studies in many different buildings throughout Russia. The readings were collated using stopwatches and / or cine-filming of the movement. The graphs that were derived from these studies are illustrated in Figures 3.6 and 3.7.

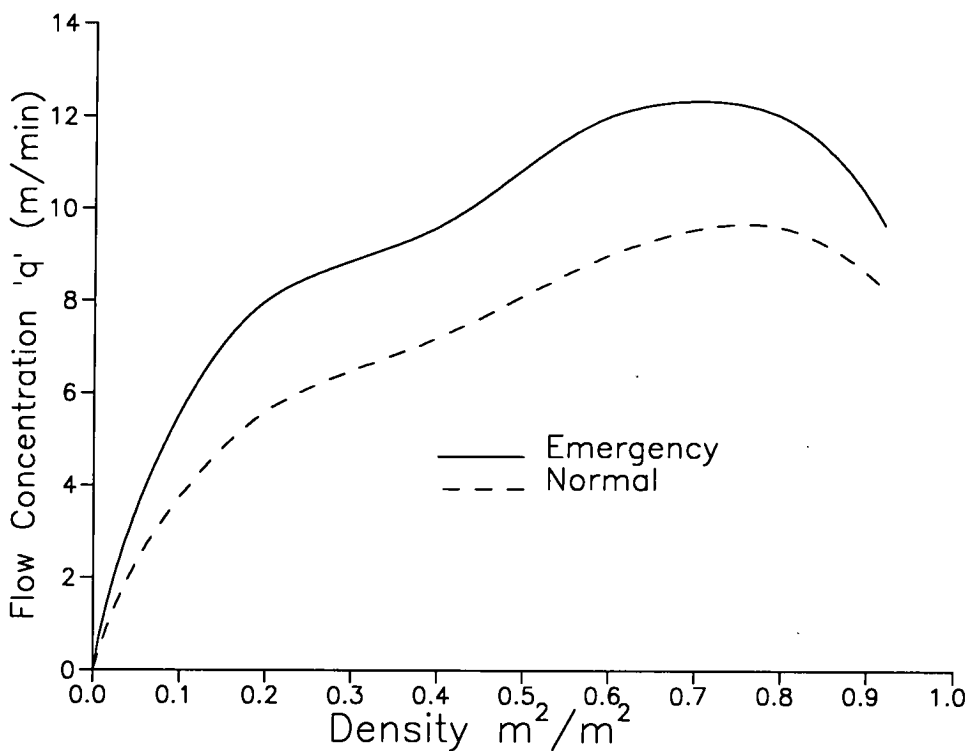


Figure 3.7. Graph of the relationship between crowd flow and density (re-drawn from Predtechenskii and Milinskii - 1969).

NOTE: The basic equations and units used for movement were;

$$D = \frac{\sum f}{\delta \times l} \quad \dots\dots\dots (3.2)$$

$$Q = D \times v \times \delta \quad \dots\dots\dots (3.3)$$

$$q = D \times v \quad \dots\dots\dots (3.4)$$

- δ = width of traffic stream, or passageway (m)
- l = length of flow of people (m)
- f = projected area of ellipse of each person (m²)
- v = average locomotion speed of people in flow (m/min)
- D = density (sum of projected areas per m²) (m²/m²)
- Q = traffic capacity of flow path (m²/min)
- q = intensity of movement (flow concentration) (m/min)

Predtechenskii and Milinskii tabulated their findings for average body dimensions, based on a more compact body ellipse than that used by Fruin. They called the area of this ellipse the 'area of horizontal projection', ' f '. This projected area represents the horizontal projection of the space occupied by that person on the building plan, and was calculated using Equation 3.5. The average body dimensions are presented in Table 3.1.

$$f = \frac{\pi}{4} \times a \times c \quad \dots\dots\dots (3.5)$$

- f = projected area of ellipse of each person (m²)
- a = body breadth
- c = body depth

The measurement of density as a ratio of occupied space to available space is significant. The result is that, for example, the density of a crowd with a specific number of people in a defined area will vary, depending on the season. According to the figures shown in Table 3.1, the density of a specific number of people in a given room will increase by 25% from summer to winter, due to the increase in body ellipse size caused by winter clothing. The maximum value of D , representing the maximum physical packing density of people was found to be 0.92 m²/m². The maximum value of q (q_{\max}) under normal conditions was found to be 10.13 m/min. The density at this value was 0.75m²/m². In other units this gives a value of q_{\max} (flow rate) equal to 1.14pers/sec/m width for mid-season dress. Also, q_{\max} is 1.40pers/sec/m where D is 0.72m²/m² under emergency conditions.

Age and dress of person	Shoulder Breadth 'a' (m)	Body Depth 'c' (m)	Horizontal projection 'f' (m ²)
ADULT:-			
In summer dress	0.46	0.28	0.1
In mid-season street dress	0.48	0.3	0.113
In winter dress	0.5	0.32	0.125
YOUTH	0.43-0.38	0.27-0.22	0.09-0.067
CHILD	0.34-0.30	0.21-0.17	0.056-0.04
ADULT:-			
With child in arms	0.75	0.48	0.285
With baggage in hand	0.9-1.1	0.75	0.35-0.825
With knapsack	0.5	0.8	0.315
With light package	0.75	0.4	0.235

Table 3.1. Average Body Dimensions

- reproduced from Predtechenskii and Milinskii (1969).

Predtechenskii and Milinskii described complex methods of calculation for assessing crowd flow, based on Equations 3.2 - 3.5. Essentially, this consisted of calculating the number of people in a specific area, the resulting density and then deriving the speed and flow rate of the crowd from data points on the graphical curves in Figures 3.6 and 3.7. The calculation method also took into account merging traffic flows, and the resulting changes in density and flow rate. It may be seen as an early form of network - node analysis, where the building is segmented into a network of discrete areas, linked with doorway 'nodes' of specific widths. One important aspect of this method of calculation is that it does not restrict the designer to a maximum flow capacity for any particular doorway. If a crowd of density 0.75 m²/m² passes through a doorway, then a high flow rate will be achieved. The author believes that this may be hazardous because it has been proven that at such concentrated densities, crowds either stop completely or possess extremely irregular flow rates through constrictions.

The graphs illustrated in Figures 3.6 and 3.7 are potentially more useful than those presented by Fruin in Figures 3.2 and 3.2 because the Russian graphs are based on a much larger number of data points, with a good range spanning zero density to the maximum physical packing density of people.

Another significant aspect of this work is that Predtechenskii and Milinskii recognised, like Fruin, the existence of free space between the edge of a moving crowd and a solid wall. However, unlike Fruin, they discounted this gap for the purposes of calculation, because it was deemed to be insignificant, especially at higher densities. This disparity was probably due to the fact that Predtechenskii and Milinskii had observed the movement of crowds at much higher densities.

3.3 HANKIN & WRIGHT

During studies carried out for London Transport, these researchers carried out two series of observational tests.

[1] 200 schoolboys were circulated around a 4 foot, 3 inch wide chestnut paling circuit, held up by other boys. Speed measurements were taken at various concentrations for several passage widths, and the shapes of speed/density and flow/density curves were derived. The primary purpose of these tests was to develop a greater understanding of the relationship between crowd density and flow rate and crowd density and speed. The data collected was used to develop the graph shapes that would be applied to data from later observations.

[2] Measurements were taken on the London Underground, involving two observers with stop-watches logging data on crowd flow, by mixing with the crowds. One observer walked within the crowd, and timed his passage over a set distance, while the other noted the flow rate of the crowd through an end location of specific width. Again, speed/density and flow/density curves were derived. These curves are illustrated in Figures 3.8 and 3.9 and represent unidirectional motion.

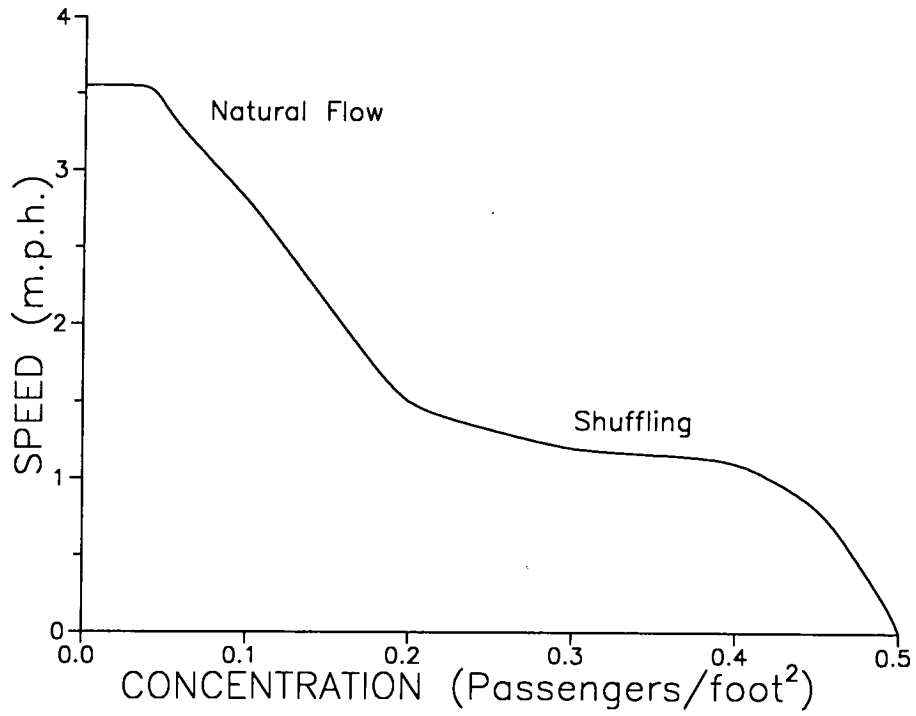


Figure 3.8. Graph of speed against concentration for commuters walking in the London Underground, re-drawn from Hankin & Wright (1958).

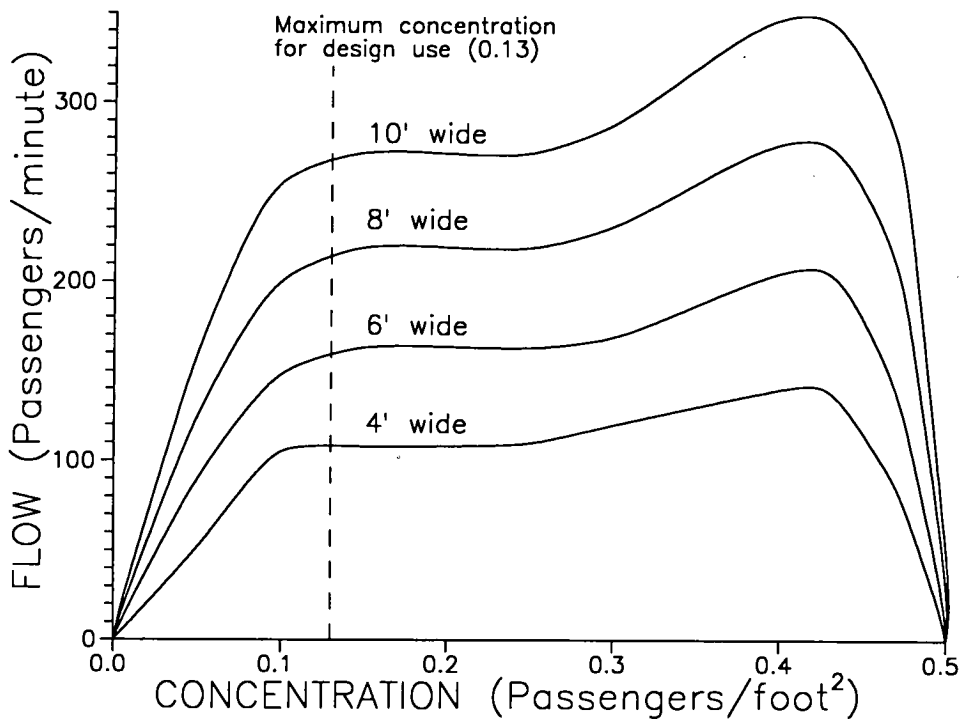


Figure 3.9. Graph of unidirectional flow rate against concentration for commuters on the London Underground, re-drawn from Hankin & Wright (1958).

These flow rates, combined with the figures recommended in "Post War Building Studies no. 29" (HMSO -1952) form the basis for the flow rates specified in the current British building regulations (for example, "Approved Document B", HMSO -1991). Figure 3.9 indicates that for passageways greater than 4 feet wide, passage width is proportional to maximum crowd flow, which was one of the conclusions of the study. The design flow recommended from this study was 27 persons per foot width per minute (1.48 persons/m/sec).

3.4 PAULS - EFFECTIVE WIDTH MODEL

Two references for Pauls (1980 and 1987) are major summaries of his work, and this number of references does not represent the large number of publications produced by him. The main reason for this is that Pauls was primarily concerned with the movement of crowds along stairs, and the primary interest of this project lies with movement on level passageways. However, some of the concepts introduced by Pauls are nonetheless of particular relevance.

Pauls has been very critical of the use of maximum possible flow rates and mean flow rates, and also highlighted the inability of some reports to distinguish between flow rates achieved under test conditions and those achieved during real evacuations. Test conditions can achieve unrealistically high flow rates because they can be based on trained individuals of similar body size and fitness passing through passageways in a regular, regimented fashion, with unrealistically small spacings between individuals. This criticism seems fair and it does appear strange that unlike almost all other aspects of building design, there are no factors of safety applied to calculated evacuation times.

The most important aspect of Pauls' work was the "effective width model". He noted that Fruin had recognised the existence of a gap between solid walls and the adjacent moving body of people, and called this the "edge effect". Pauls' basis for this "edge effect" was formed from the data obtained from 58 different building evacuations.

Pauls found that mean evacuation flow was proportional to measured stair width, and when this relationship was plotted on a graph, it crossed the stair width axis at 0.3m, when adjusted for stair & occupancy factors. Another reason for his adoption of this 0.3m 'edge effect' space is given in the following quote. "A 1958

report of crowd movement studies by the London Transport Board concluded that for level passageways flow is proportional to width. An examination of the report's graph, with flow data plotted, suggests, however that a regression line should intercept the width axis at about 300mm (12 in.) and not at zero as drawn". However, the author believes that Pauls' analysis has some flaws. A comparison of the graphs shown in Figure 3.10 will illustrate the point. The original data plotted by Hankin & Wright (for the London Transport Board) and Pauls intercepts the stair width axis at zero. It is only Pauls' adjusted data that crosses the width axis at 0.3m. It is not specified how the adjustments were made.

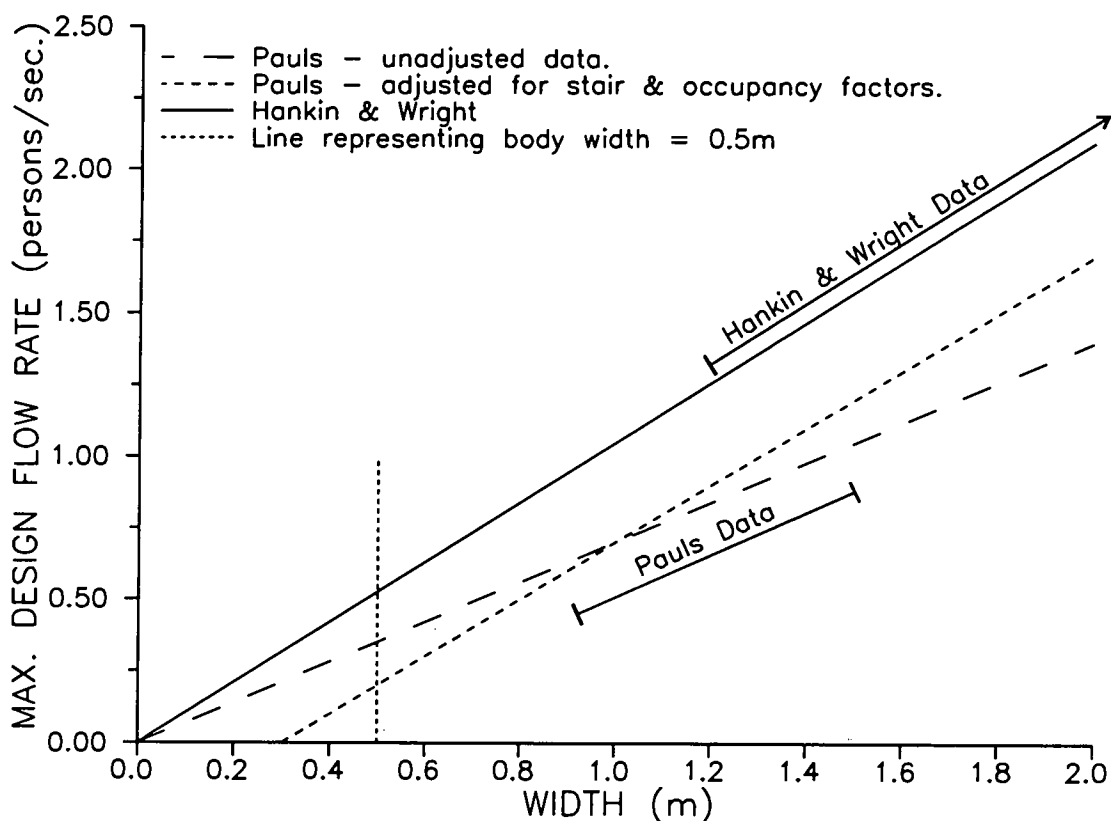


Figure 3.10. Graph of Maximum Design Flow Rate on Stairs against Stair Width.

Note: Lines are projected beyond the data that they are based upon.

Original data ranges for Pauls and Hankin & Wright are plotted.

This is not intended to undermine the 'effective width' model, but merely to clarify that the exact figure of 0.3m may not be accurate outside the ranges of density

that Pauls observed. However, this model did introduce some interesting concepts. Equations 3.2 and 3.3 were important parts of the calculations.

$$W_e = W_s - 0.3 \quad \dots\dots\dots (3.2)$$

$$F = 0.206 \times W_e \times \left(\frac{P}{W_e} \right)^{0.27} \quad \dots\dots\dots (3.3)$$

Note;

W_e is effective stair width in metres

W_s is actual stair width in metres

F is the evacuation flow in persons per second

P is the evacuation population (number of people)

Equation 3.3 implies that larger building populations achieve higher flow rates on staircases. Pauls stated that "Population has an effect that might be likened to pressure in a hydraulic model. In human terms it can be related to what some called the urgency factor...". He also wrote that the model was intended only for the design of buildings with populations of 800 or less.

For later use in this thesis, it is important to note that Pauls stated that the shoulder width of a 50th percentile U.S. adult with medium thickness outdoor clothing was found to be 0.5m.

Researcher(s)	Movement type	Density observed (persons/m ²)	'Edge Effect' distance (mm)
Fruin	Level & Stairs	0-1.8	457
Pauls	Stairs	2-3	150
Predtechenskii & Milinskii	Level & Stairs	0-7.4	negligible

Table 3.2. The 'Edge Effect'.

Note that the edge effect figures represent clear distance between one edge of a crowd and a wall.

It is important that the 'edge effect' of clear space between a wall and the edge of a moving crowd has been recognised by Fruin, Pauls and Predtechenskii & Milinskii. The observations are summarised in Table 3.2. It would appear that people tend to stay away from the walls in low density crowds, but are forced towards the walls as the crowd density increases.

3.5 WESTON & MARSHALL

These researchers carried out a cine-film analysis of two crossing, perpendicular flows of people, one larger (major), one smaller (minor) at a defined area in Victoria Station on the London Underground. After recording the flows, they played the footage back on an analysis projector, so that each frame could be stopped, and analysed. Speeds of individuals were calculated by measuring their progress over 10 frames (4-5 seconds). The film was replayed for the same period to count the number of people per unit area, and hence calculate the crowd concentration.

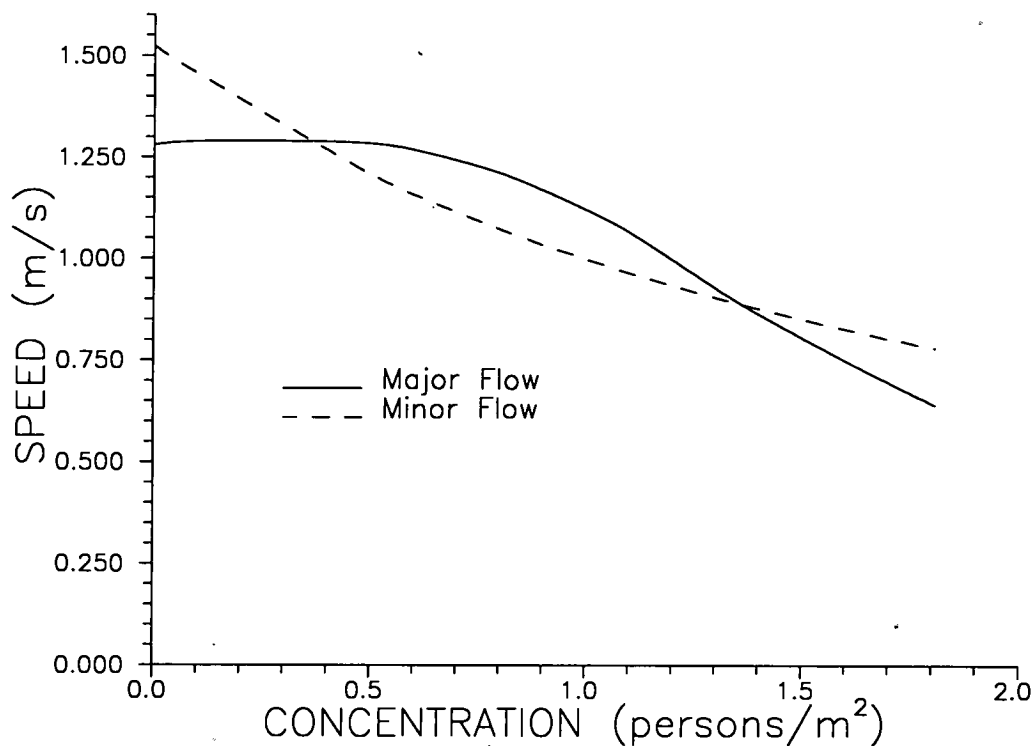


Figure 3.11. Speed / Concentration Graph of Crossing Flows , re-drawn from Weston & Marshall (1972) and converted from original units of sec/ft & persons/ft² to allow comparison of speeds with other work.

From their observations, they produced a graph of the interference effect on the speeds of individuals within both the major and minor flows. It was evident that the effect of the merging caused differential slowing of the major and minor flows. This graph is illustrated in Figure 3.11.

The study drew some interesting conclusions, although it should be noted that the densities in each flow were only one quarter of that which is physically possible, and that no data points were drawn on the graph presented.

For two perpendicular, crossing flows;

- the major flow behaves in a similar way to a unidirectional flow, whose density is increased, and hence, slowed.
- the minor flow is slowed by the crossing of the two streams, but in a slightly different way from just a simple density increase.
- the sum of the major and minor flow rates is equal to the total flow rate.
Therefore, Major Flow + Minor Flow = 23 persons/foot/min
(total maximum combined flow= 1.26 persons/m/sec)

3.6 PESCHL

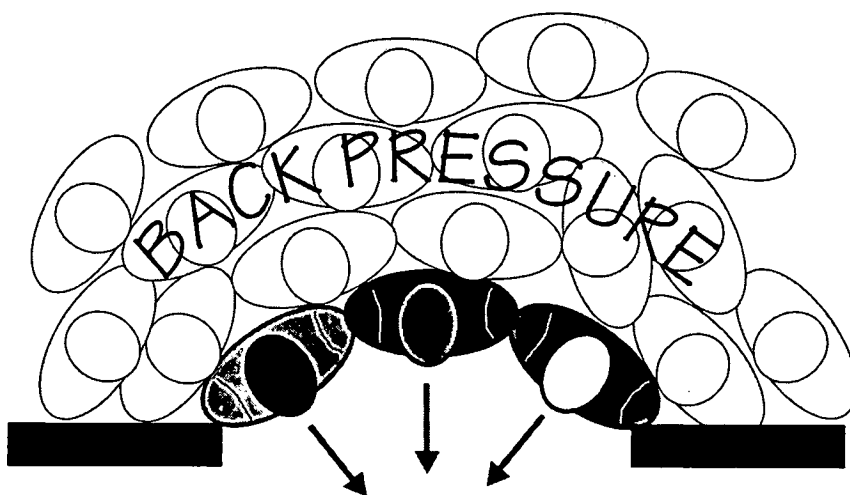


Figure 3.12. A 'Body Arch' - where high densities can lead to blockages.

Peschl carried out experiments involving students circulating around a corridor system of variable width, with different door openings. At high localised densities, he observed blockages within the system. Many students attempting to get through the door at the same time would set up an arched structure of bodies around the opening, preventing or hindering continued flow.

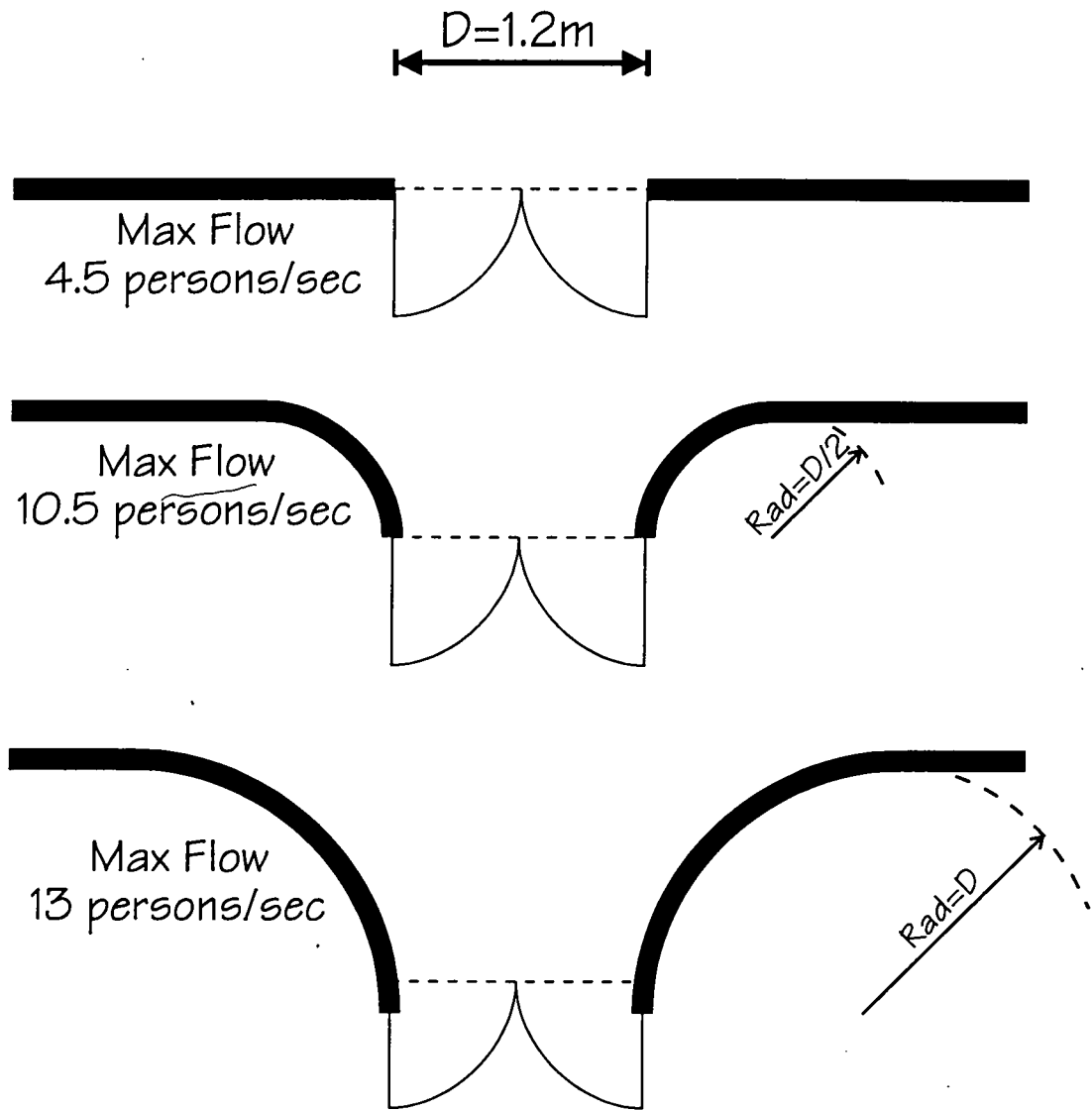


Figure 3.13. Flow Capacity of Door Openings for Simulated Panic Situations (re-drawn from Marchant (1978) and based on Peschl (1971)).

The flow through the experimental doors was observed to be of a pulsating nature, at high densities. This pulsating flow occurred due to the formation of body arches which managed to self-break and release flow until another arch formed. He called these self-breaking arches "dynamic arches". When an arch of people formed under such high density that it did not break, the experiment was stopped to prevent the crushing of people. Peschl noted that the arching effects were significantly reduced if the doorway had curved corridor walls funnelling people into the opening. Marchant (1978) produced diagrams to explain this mechanism for 1.2m wide doorways (Figure 3.13). With the extremely high densities involved, bodies were twisted, pushed and people were often injured, and the extremely high flow rates should certainly not be used for any form of safe design. The adoption of the curved forms of 'funnel' into a doorway may, however, be very useful if it is possible that a large number of people will attempt to escape through the doorway under hazardous conditions and with little regard for others. A good example of this might be a panicking crowd at a football stadium.

Peschl managed to simulate the arch pattern, to an extent, by stacking steel ball-bearings vertically over an opening, and allowing flow to occur by gravity. This arching at openings was also observed by Predtechenskii & Milinskii (1969) when the density approached $0.92\text{m}^2/\text{m}^2$.

These arching effects are very important. They are caused either by the wedging of people at the opening edges, or localised density increases as the corridor width is constricted. It is these arches that often create the crushing of bodies, in emergency situations, and potential loss of life due to asphyxiation.

3.7 ANDO et al

Ando et al generated a considerable amount of experimental data for crowds moving in a unidirectional flow. The work was carried out to improve the flow of passengers through railway stations at peak times. One important fact mentioned in this study is the observation of densities up to 15 persons per square metre, in very dangerous situations. The graphs illustrated in Figures 3.14 - 3.15 are for commuters at railway stations in Japan and bear some resemblance to the graphs produced by Hankin & Wright (1958) and Predtechenskii & Milinskii (1969). Figure 3.14 represents the formation of individuals in a crowd as approximating to the 'spherical packing' observed by Fruin (1971). It is also important to note that stagnation could be observed at 4 persons per square metre, but restricted movement was also possible above this density.

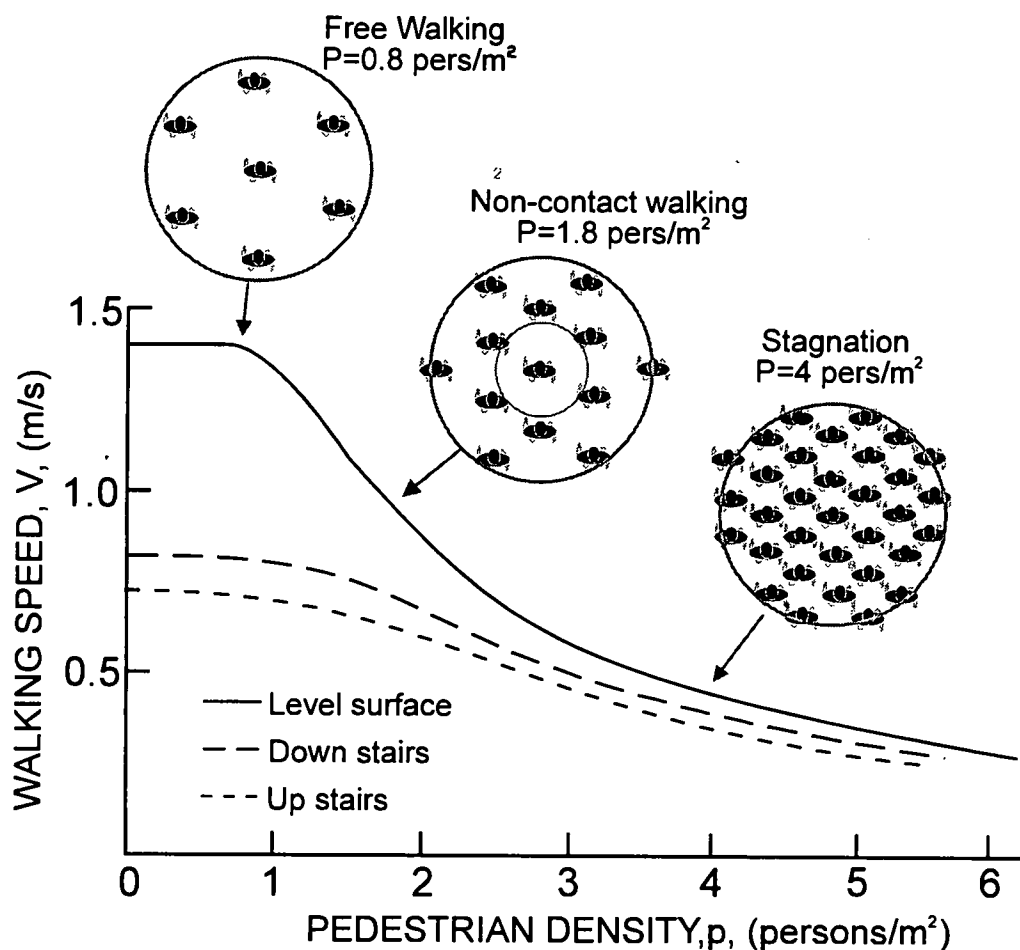


Figure 3.14. Walking Speed as a Function of Density.

- re-drawn from Ando et al (1988).

The graph in Figure 3.15 is derived by taking the data in Figure 3.14 and applying Equation 3.1 to obtain the flow rates illustrated. Peak flows of 1.7 - 1.8 persons/m/sec can be observed. It is significant that the flow rate is fairly consistent above densities of 1.5 persons/m². This peak flow rate is slightly greater than that observed by Hankin & Wright (1958).

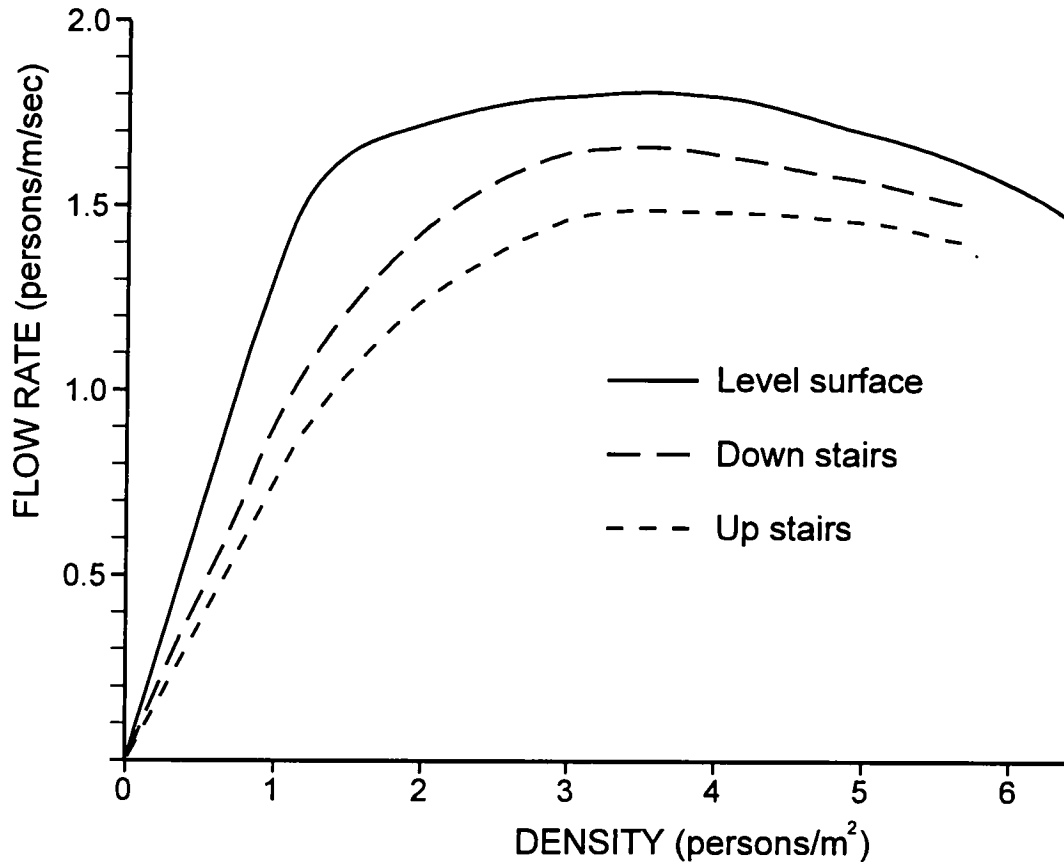


Figure 3.15. Flow Rates derived from Figure 3.14.

Ando et al also collected data on normal, unimpeded walking speeds for different genders and age groups. The graph of this data is presented in Figure 3.16. Some useful conclusions may be drawn from this graph. Male commuters have a consistently higher speeds than the females, and the elderly and very young walk at speeds that are 40 - 50% less than for young adults. Males are generally taller, and hence have longer strides, and it is also possible that the males are slightly more 'aggressive' in their journey to and from work.

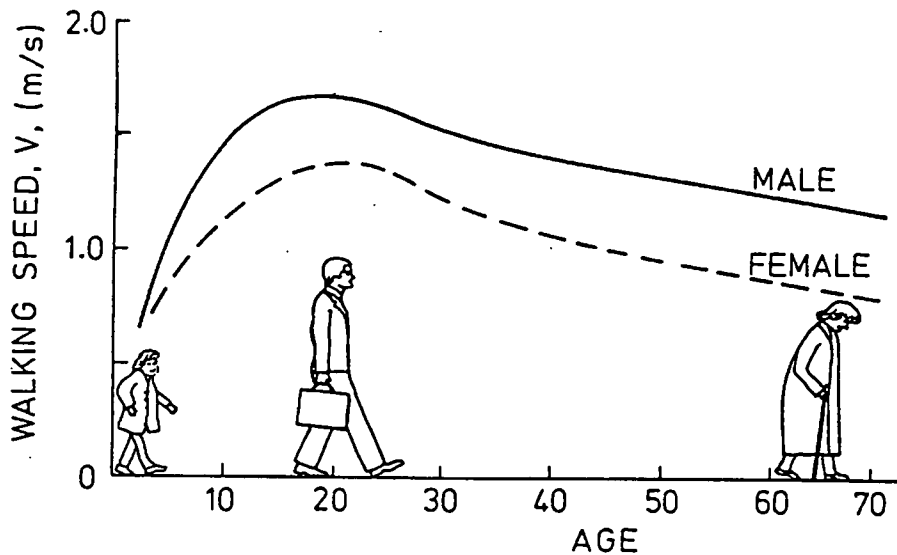


Figure 3.16. Walking Speed as a Function of Age, re-drawn from Ando et al (1988)

3.8 POLUS, SCHOFER AND USHPIZ

Polus et al (1983) carried out studies of walking speeds at different locations on Haifa sidewalks, using a video camera. A rectangle, 2-3 metres on each side was marked out at each location, and pedestrian movement recorded onto video tape. A timer was also recorded onto the tape, with an accuracy up to 1/100th of a second. Results were obtained by replaying the film, and measuring the progress of individuals through a group of people with measured density. The observed relationship between walking speed and density was very similar to the graph produced by Hankin and Wright (1958) illustrated in Figure 3.8, but comparisons are only possible for the first third of the graph, because Polus et al only measured the low densities in this range.

Polus et al carried out some statistical analysis on the data. It was found for a given density between 0 and 2.2 person/m² the walking speed had a standard deviation from 0.2 to 0.4, and the coefficient of variation was calculated to vary from 0.15 to 0.75. Crowd density and variations in speed were not related. In other words, although a crowd may be slowed down by a density increase, the speed does not fluctuate to a greater or lesser degree. This appears reasonable for the densities measured, but Ando et al (1988) indicates that crowds approaching 4 persons/m² have a tendency to 'shuffle' or stop altogether.

3.9 SHORT EXTRACTS FROM EXISTING GUIDANCE

The following section contains short extracts from various literature sources, that the author regards as relevant to this study.

"Post War Building Studies no. 29 ", HMSO (1952).

This document mentions the adoption of unit widths for escape, where one unit width represented the width of a single person in The Factories Act (1937). The unit width was specified as 22 inches (55.9 cm). This method of only incrementing flow in steps of unit widths across a passageway was also adopted in some of the early U.S. codes. The concluding guidance, however, produces flow rates very similar to the modern "Approved Document B", HMSO (1991), where flow rates are proportional to width for passageways above 1.1m wide, but are restricted for narrow corridors.

"The Building Regulations 1991 - Approved Document B", HMSO (1991)

The following table specifies allowable flow rates for passageways over a 2.5 minute evacuation period for the whole building. The figures yield a flow value of 1.33 persons/sec/m width for widths greater than 1.1 metres.

Corridor width (m)	0.8	0.9	1.1	1.2	1.3	1.4	1.5
Number of occupants	50	110	220	240	260	280	300

Table 3.3. Flow Rates for Different Widths of Passageway.

Note: Above 1.1m add 5mm width per person.

"Concepts in Building Firesafety"- M. David Egan (1978)

This book recommends unit exit widths for both still and moving people:

Standard unit width = 0.55m(still), 0.70m(moving)

Adult in wheelchair = 0.70m(still), 0.80m(moving)

Adult on crutches = 0.85m(still or moving)

3.10 MAXIMUM PEDESTRIAN FLOW RATES

Source	Maximum design flow (persons/m/sec)	Ultimate flow capacity (persons/m/sec)	Comments
Approved Document B1	1.33		Standard British code for buildings
SCICON report	1.37		Data from football crowds
Guide to Safety at Sports Grounds	1.82 (unit exit width method)		Based on Japanese data and derived from 1.0 pers/0.55m/s unit exit width calculation
Hankin & Wright	1.48	1.92	Commuters under normal conditions
Fruin	1.37	4.37	Max. flow is ultimate regimented, 'funnelled' flow under pressure
Daly	1.43		
Ando et al		1.7-1.8	Commuters under normal conditions
'Fire and Building' (The Aqua Group)	1.50		
Predtechenskii and Milinskii	1.70	2.06	Peak flows at high density for adults in summer dress.
NFPA 101 (U.S.A)	1.64 (unit exit width method)		Extrapolated from 60 persons/24in./minute
Polus et al	1.25-1.58 pers/m/s	1.56 pers/m/s	

Table 3.4 Summary of Maximum Pedestrian Flow Rates for Level Passageways.

A summary of maximum flow rates on level passageways, from different sources is presented in Table 3.4. The table does not include flow rates through doorways, which is generally 10 to 40% greater than in open passageways. Flow rates on stairs tend to be 10 to 30% lower.

The extraordinarily high figure of 4.37 persons/m/s. quoted by Fruin (originally as 80 persons/foot/minute) was taken from a series of tests in Germany where "... pedestrians flowed through a funnel-like corridor, under pressure from the rear to create dense crowding and fast walking speeds. The extraordinary peak performance was obtained after the pedestrians became acclimated to the dense conditions, and adopted a practice of placing their hands on the shoulders of the pedestrian in front. This practice established a uniform space between pedestrians, and allowed the following pedestrian to sense the correct speed and pace from his tactile contact with the pedestrian in front, rather than relying on the normal but slower vision-and-foot reaction process." Hence, by creating a smooth, regimented flow of people that overcame the effects of the 'invasion of personal space', unrealistically high flow rates can be achieved.

3.11 PRIMARY COMPONENTS OF CROWD FLOW

The research described in this chapter has identified specific aspects of crowd movement. Different researchers have produced data that varies to some degree, but results such as the maximum flow rate are fairly similar in the majority of cases. It is possible to categorise the primary components involved in the process of crowd flow, based upon the research discussed in this chapter.

(1) PSYCHOLOGICAL STATE OF THE CROWD

The psychological state of individual people will affect the direction of crowd movement, walking speed, how regular the motion is, and the density at which movement ceases completely. There is a vast difference between a normal, non-panicking crowd and one that is confused or panicking. All of the flow rates quoted in Table 3.4 are for non-panicking crowds. No reliable figures exist for panicking crowds because of the danger involved, as proven by Peschl when his students were severely injured during his tests!

(2) PHYSICAL DIMENSIONS OF INDIVIDUALS

The body sizes of individual people in a crowd is extremely important when considering the physical nature of crowd movement. If we use the data presented by Predtechenskii and Milinskii, the maximum flow of a crowd under 'normal' conditions is 1.70 persons/m/s for people with light summer dress, but is 1.36 persons/m/s for people wearing thick winter clothing. The formulae in Equations 3.2 - 3.4 predict that flow rate (in persons per metre per second) is inversely proportional to the horizontal projected area (body size) of crowd members. Flow rates observed by Hankin and Wright for boys (in test conditions) were significantly larger than those achieved by adult passengers on the London Underground.

(3) NORMAL WALKING SPEED OF INDIVIDUALS

The natural walking speeds of crowd members is obviously important, especially in crowds that are not very densely packed. A crowd containing many elderly or disabled people will move more slowly than one consisting completely of fit adults, because of the naturally slower walking speeds. As a result, flow rates achieved by the 'infirm' crowd are lower, due to speeds that are significantly less than the 'fit' crowd for the same concentration of people.

(4) THE INVASION OF PERSONAL SPACE - SPEED EFFECTS

This is the most important factor when considering the mechanism of crowd movement. In simple terms, when people in a crowd get closer together they slow down, even if no bodily contact occurs. The spacing between crowd members is crucial to the flow rate achieved by that crowd. The square of the distance between individuals is proportional to the density which is related to the crowd speed, as shown in Figures 3.2, 3.6, 3.8, and 3.14. At very low densities, there is no 'invasion of personal space', and hence no reduction in walking speed. The density at which personal space becomes invaded, and walking speed is reduced, ranges between 0.4 pers/m² (Fruin) and 0.8 pers/m² (Ando et al).

(5) PHYSICAL CONTACT BETWEEN INDIVIDUALS

This is negligible in low density crowds, but becomes more frequent as crowd density increases. Fruin stated that physical contact was frequent and unavoidable at 5 sq.ft. per pedestrian (2.2 persons/m²). When frequent physical contact occurs, frictional effects influence the crowd motion and irregular shuffling is observed. At very high densities, the inevitable contact between bodies leads to highly erratic flow and eventually stagnation (observed by Peschl). Ando et al observed that the stagnation of crowd movement, under normal conditions, occurred in the range 4 - 6 persons/m².

(6) THE 'EDGE EFFECT'

Table 3.2 presents the different observations of Fruin, Pauls and Predtechenskii and Milinskii, concerning the amount of free space between the edge of a crowd and an adjacent wall. It is apparent from these observations that as crowd density increases, the 'edge gap' decreases and becomes negligible at very high densities. Bryan (1985) states that body sway reaches 38mm left to right, during normal free movement, but can increase up to 101mm in crowded corridors and on stairs. This 'edge effect' is important and should be considered when attempting to simulate crowd movement.

Crowd motion can become very complex, and is created by the interaction of the components listed above. All of these components should be considered, in some depth, for an accurate model of crowd movement to be achieved. No existing computer model has yet achieved the simulation of crowd motion by modelling the interaction of these complex influences.

CHAPTER 4

COMPUTER MODELLING: A review of previous models

The basis and format of computer models for evacuation are presented in this chapter. Different modelling techniques are discussed and individual programs are examined in some detail. The relative merits of the different approaches are scrutinised, and their application to real-life scenarios is discussed.



4.0 AN INTRODUCTION TO COMPUTER MODELLING

Until the late 1970s, the only methods for predicting the evacuation characteristics of a building were by calculating suitable door widths for design. Doorway widths were generally calculated using occupancy/flow rate tables such as the one presented in Table 3.2. Researchers such as Togawa (1955), Predtechenskii and Milinskii(1969) and Roytman (1969) developed methods which were more complex, but rarely used because the complexity of the methods led to very laborious, time consuming calculations. The methods involved the segmentation of building plans into discrete blocks of area, with door or passage links. Each area possessed the potential to contain a maximum number of people, who 'moved' from one area to the next through the passage links. Movement was dictated by the allowable flow rate for a passage link.

The rapid increase in availability and use of computers began in the 1970s and accelerated in the 1980s. This significant increase in computing power hugely reduced the amount of time taken to process complex calculations. As a result, the methods described by Togawa, Roytman and Predtechenskii & Milinskii, became a lot less time consuming. All of the evacuation models developed in the 1970s and 1980s were based on this type of analysis called 'Network - Node' modelling. In the 1990s, some of the shortfalls of this type of modelling have been highlighted, and the development of some new techniques has been embarked upon, primarily in Britain. These will be discussed later in this chapter.

The vast majority of computer models for evacuation are still of the network - node type. New, more complex network - node models are being developed currently in the U.S.A., Australia, Britain, Canada and Japan. The models are diverse. Some specialise in the physical flow capacities of the building routes and are able to model the evacuation of a large number of people. Other programs attempt to model the movement of a small number of people through a building 'network' and assessing the influence of certain psychological factors on the occupants, although there is little real-life data available for some of these factors.

Due to the proliferation of network node-modelling, it is important to understand the basic principles and the mechanism by which the movement of people through a building is simulated.

4.1 THE PRINCIPLES OF NETWORK-NODE MODELS

The papers by Watts (1987), Chalmet et al (1982), Stahl (1980) and Berlin (1978) all discuss different aspects of network-node modelling. They are comprehensive and detailed, and therefore some of the passages in this Section 4.1 are taken directly from these references.

A network model is a graphic representation of paths or routes by which objects may move from one point to another. Network models are useful for minimising the time or distance of travel from point to point and can be applied to solve complex geometrical problems. The connecting points in a network are referred to as *nodes*. Starting points are called *source nodes*, and ending points are called *sink nodes*. The connections themselves are referred to as *arcs* or *links*. These two elements, nodes and arcs, define a 'graph', thus allowing the application of many techniques derived from graph theory.

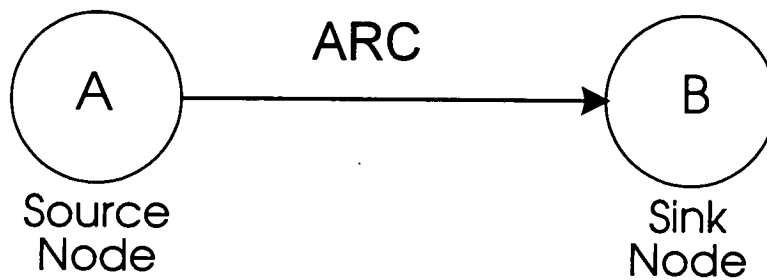


Figure 4.1. A Digraph (directed graph). Movement occurs by a 'person' moving from the source node to the sink node via the connecting arc. This is called a pathway.

A digraph (directed graph) is one in which the arcs have an associated direction, usually indicated by an arrowhead on the arc that indicates the direction of the one-way flow or movement. Evacuation modelling uses nodes to represent finite spaces within a building. Two rooms that are linked by a doorway can be represented as two spatial nodes that are linked by an arc. A spatial node (like a room) will possess the capacity to contain a certain number of people and an arc (like a doorway) will have a maximum flow capacity.

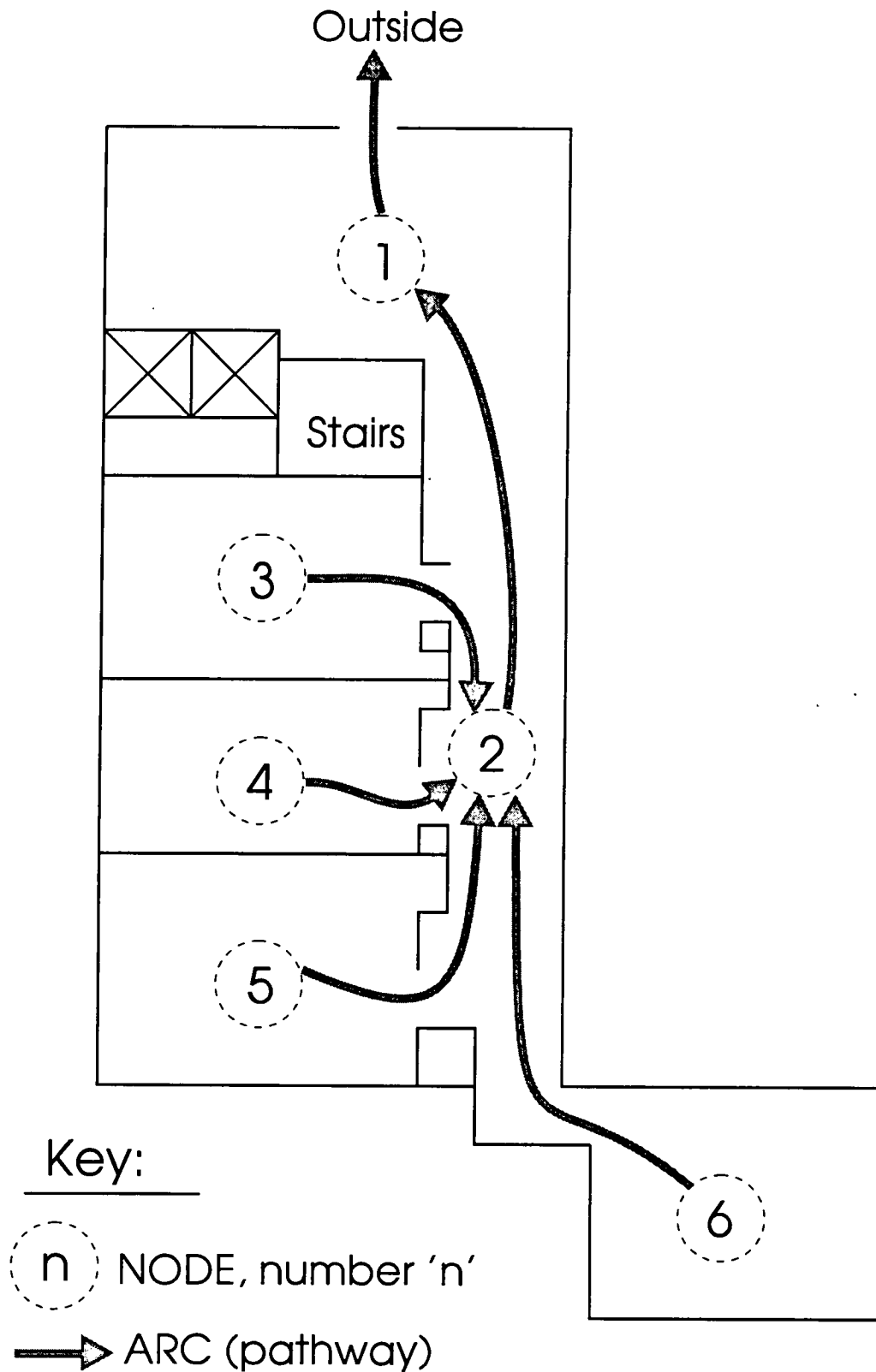


Figure 4.2. Representation of a Simple Network - Node Analysis for a Building Plan.

A building plan can be represented as a network of nodes that are connected by arcs. This form of representation greatly simplifies the building plan and transforms it into a mathematical system that can be solved for different geometrical attributes. Figure 4.2 demonstrates the use of nodes and arcs to represent a very simple building plan. The building consists of 4 rooms (nodes 3,4,5 and 6), a corridor (node 2), and a lobby (node 1) that are all linked by arcs. The arcs facilitate movement from one space to another, in the direction shown. When this system is used to represent a building space as a mathematical system in a computer, certain inputs are required. An example of the main menu from a typical network model is illustrated in Figure 4.3.

CODE	REQUESTED ACTION
-----	-----
EN	- ENTER NODE DEFINITIONS
EA	- ENTER ARC DEFINITIONS
LN	- LIST NODES
LA	- LIST ARCS
DN	- DELETE NODES
DA	- DELETE ARCS
SYS	- DEFINE OR REDEFINE SYSTEM ATTRIBUTES
SAVE	- SAVE CURRENT MODEL
RM	- RETRIEVE DEFINED MODEL
RUN	- RUN MODEL
EXAM	- EXAMINE RESULTS
QUIT	- TERMINATE EXECUTION OF EVACNET
HELP	- WHENEVER YOU HAVE QUESTIONS

Figure 4.3. Main Menu from EVACNET+. Reproduced from Watts (1987).

Firstly, all nodes and arcs are given a number as a label. When the nodes and arcs have been labelled, they are assigned attributes. The attributes of a node include the capacity of that node, and the initial contents, both of which are expressed as a number of people. The attributes of an arc include the time that it takes to traverse the arc, and the maximum flow rate of the arc. The flow rate is usually derived from the

flow capacity of the doorway or passage that the arc passes through. The flow capacity is calculated from the passage width using figures from building codes, or data obtained from research. These properties are depicted for the sample building in Figure 4.4 below.

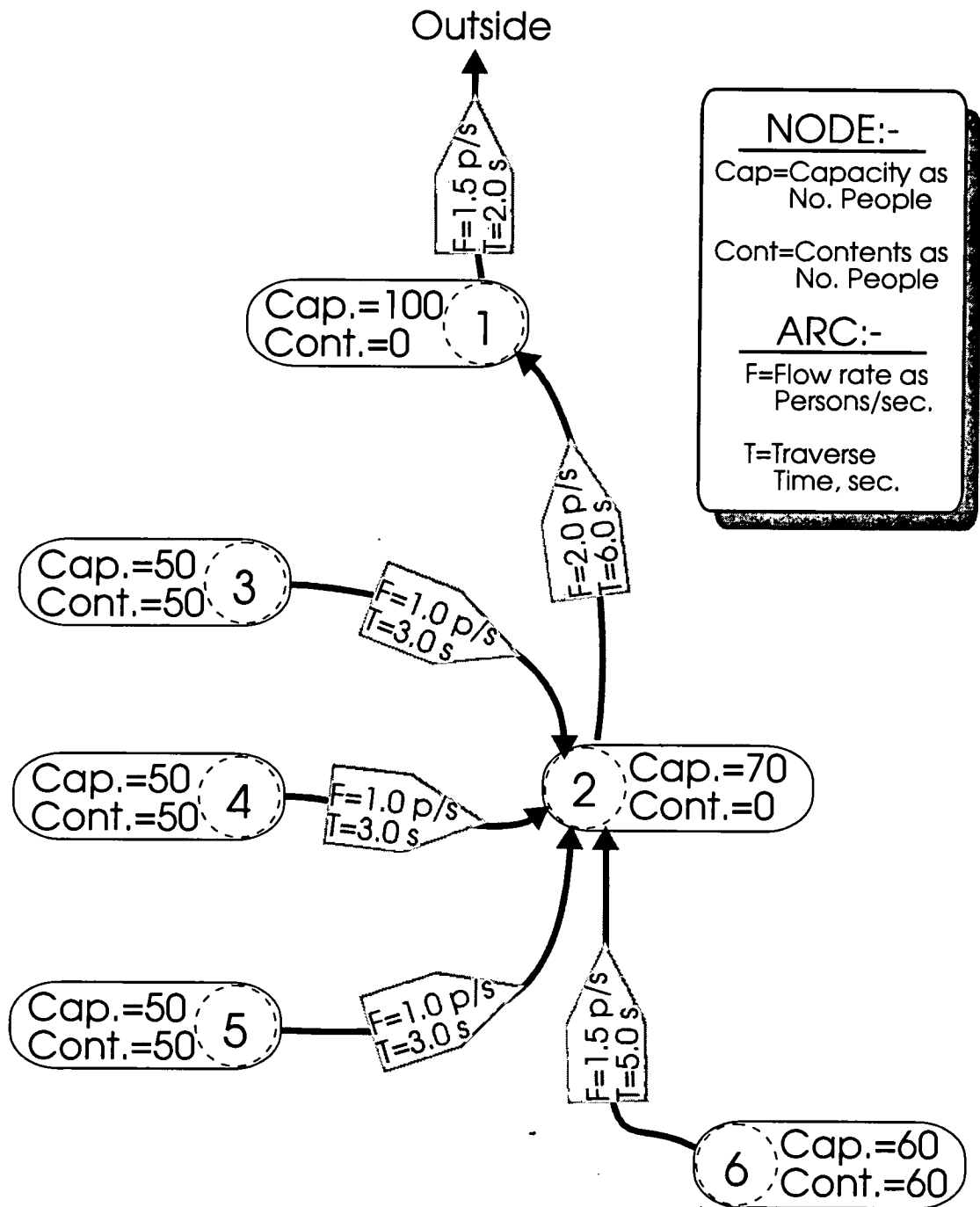


Figure 4.4. Data for a Network of Nodes and Arcs for the Sample Building

When the system attributes have been defined, the program is ready to be executed. In the sample building, the start of evacuation is simulated by the transfer of people from the rooms (Nodes 3,4,5 and 6) to the corridor (Node 2), via the four available pathways. The rate of transfer is dictated by the flow rates specified by each pathway arc, and the length of time that is taken to traverse that arc. If the corridor (Node 2) achieves the maximum containment of 70 people, flow from the rooms ceases until another person exits to the lobby (Node 1). At certain times, simultaneous movement will occur along all pathway arcs as people move from different spatial nodes into others or from the lobby node to the outside. The passage of time is modelled either by a program 'clock' that ticks over at regular time intervals (when the processing of simultaneous movement occurs) or by discrete event simulation, where people are moved one at a time through the arcs. Evacuation ceases when all the nodes are empty.

This is an example of the early type of network model, where whole rooms were represented by a single node, and the distance travelled through a doorway was represented by a single arc. In recent models, rooms have been divided into separate areas, where each area is represented by a node, and movement in a large room occurs by moving a person along several arcs and nodes to the 'doorway' arc at the edge of the room. Hence, slightly more complex geometries can occur. Complex trans-shipment algorithms can be used to optimise the building for a minimum evacuation time.

The nature of network models restricts the complexity of building geometries that can be modelled. The application of such models is therefore restricted to buildings with simple geometrical layouts. Structures which contain rectangular rooms, doorways and linear corridors are best suited to this type of modelling. It should also be noted that the models will only calculate the building's *capacity* for evacuation as an optimal, minimum time. Areas where maximum flow is achieved can be identified, but dangerous jamming at doorways such as that observed by Peschl (1971) and Predtechenskii and Milinskii (1969) cannot be simulated. The interaction of individual bodies is not simulated. The way in which a person in a wheelchair, moving slowly through a doorway, affects the surrounding crowd cannot be modelled accurately. In short, a network model can be a useful design tool for assessing the *potential* for evacuation of a building with a simple geometry, but will never simulate the complexities inherent in crowd motion. Complex geometries and

physical interaction between individuals in crowds is beyond the scope of this type of modelling system.

4.2 EARLY NETWORK - NODE MODELS

There have been many attempts to develop network models for evacuation. They all represent physical space in ways similar to those discussed in Section 4.1. Movement is achieved along arcs between room nodes, creating pathways. A few of the more significant developments are described below.

4.2.1 BERLIN (1978).

Berlin presented the first application of optimal route calculations to network systems. He described an algorithm for determining escape potential, by calculating the number of directed escape routes. For a specific node location, the algorithm identifies different potential routes to exit. For each route, the 'cost' (expressed as time or distance) of travelling from each individual node to the next is summed to yield the total 'cost' of that route. This analysis proceeds until all of the potential escape routes from that node have been assessed. Using the figures obtained, the total 'cost' of travelling through the system via any individual pathway can be equated, in terms of time or distance. After seeking out all of the potential routes, the route that requires the least amount of total distance or time to escape, and therefore has the least 'cost', is defined as the optimal route to exit.

It is more important to understand the concept of this optimal route calculation, rather than the abstract mathematical expression. It forms the basis for most of the route-finding methods employed by later networked evacuation systems. The method is effective, but inefficient because it entails far more calculation than is really required. The whole process is repeated, starting from a different node in the system each time, and calculating the entire potential pathway network, before deciding on the optimal pathway for that node. A much more efficient type of network analysis requires only one set of 'pathway' calculations by starting at the exits and working progressively through the rooms of a building, to create a linked route where the original exit is the 'goal'. This form of analysis was eventually used in EXIT89 by Fahy (1991) - see Section 4.2.6.

4.2.2 STAHL (1979) computer program BFIREs.

BFIREs attempted to simulate the perceptual and behavioural responses of building occupants involved in fire emergencies. The model attempted to simulate the response of individuals to a wide variety of emergency scenarios. By placing 'fires' in an occupied room, an adjacent room, or a remote location. Algorithms were written to emulate certain facets of human behaviour. These included a 'perception simulator', 'information interpreter and processor', and a 'response generator'. These discrete behaviour simulations were derived from a library of responses, but little hard data was available, so the libraries were formulated by the writer of the program in forms that were deemed suitable.

A standard plan for a single level domestic dwelling was entered into the network. Between 5 and 10 different scenarios were executed for four occupants in the dwelling. Different scenarios included occupants being asleep, fires in different rooms and occupants beginning in different locations. Each list of scenarios was tested for each of three different exit conditions; one in the kitchen, one adjacent to the kitchen, and two exits. Loss of life was perceived if a person stayed in a room for more than 4 minutes. A 'loss of life index' was calculated each time, which was equal to the [number of predicted fatalities] divided by [the number of bedrooms plus 1]. The calculations for the 'loss of life index' produced trends that were similar to the data collected from the statistics of real-life fire fatalities. The program predicted that loss of life for single exits was less likely when the exit was closer to the bedrooms, and was even less likely when there were two exits. The program was also applied to simulate life safety in office buildings, but was not developed beyond the early 1980s.

4.2.3 CHALMET ET AL (1982) - The Building 101 Dynamic Model.

The network model described by Chalmet et al is a fairly simple version of the type of model described previously, in Section 4.1. The paper does, however discuss some interesting details concerning the application of these early models. In the particular application described, calculations were reassessed for every ten seconds of simulated time. Chalmet noted that the model was highly sensitive to the arcs that traversed stairwells, which was not surprising because a large multi-level building was simulated. The model described used 5543 arcs, 2591 nodes and 58 ten

second time periods. As a result of the simulated evacuations, bottleneck arcs were identified. Output from the model included the number of persons using each stairwell, the time period over which the stairs were used, and flow rates at the most frequently used arcs.

Chalmet et al also wrote that "A major asset of modern network codes, being able to solve very large problems, can simultaneously be a liability, in the sense that such codes can overwhelm the user with input..". He also stated that "Queuing will occur in heavily 'loaded' buildings, and the dynamic model has the facility (via holdover arcs) to represent queuing and then only in a rudimentary, deterministic sense." The work was significant because it was one of the earliest attempts to apply complex networks to large, multi-level buildings.

4.2.4 WATTS (1987) - computer model EVACNET+.

This model formed the basis for the general description of network - node modelling outlined in Section 4.1. The flow rates for travel along connecting arcs are those specified by the U.S. codes. EVACNET+ takes the input data defining the building network and determines an optimal plan to evacuate the building in a minimum amount of time. This is done using an advanced capacitated network flow trans-shipment algorithm which achieves the optimal escape routing that is described in Section 4.2.1. The program also uses fairly complex forms of queuing theory to model the queuing process that occurs when the number of people entering a room node is greater than the out-flow facilitated by the exit doorway. A Gauss-Seidel iterative procedure for computing relative queue arrival rates from a stochastic transition matrix. As a result, the action of queues in the system can be analysed, and areas in the system where bottlenecks occur can be identified.

The output characteristics include the average time spent by people in a particular queue, the average flow rate achieved by network components, the average lengths of queues, the mean number of persons waiting to enter an egress component, and the percentage of total evacuation time that a particular egress component is in use. EVACNET+ was converted to run in BASIC on an IBM PC. The program was a significant development because of the detail about the evacuation process that it yielded. It was capable of handling large numbers of nodes and described the evacuation process through the network system in great detail.

4.2.5 KOSTREVA et al (1991) - computer model EXITT.

EXITT was the first evacuation model to be incorporated into the package HAZARD I which attempted to bring together the individual aspects of danger to life and property under fire conditions. EXITT was written to accept the output from other programs that simulated ignition, fire growth, sprinkler response, time to alarm, and smoke toxicity transport models. It attempted some fairly complex simulations for occupant response and behaviour, but was not capable of processing large numbers of people. Occupant characteristics included age, sex and whether they were awake or asleep. In the later versions, aspects such as individuals alerting and assisting other adults and children during the process of evacuation were considered. Direction to exit was chosen using an optimal route method. The output is a description of the decisions and movements over the course of the evacuation.

A program was also incorporated into HAZARD I to assess the effect of smoke toxicity on the occupants, and ultimately to calculate when toxins made a node impassable or brought about the death of an escaping occupant, within EXITT. In addition to time and distance, the network arcs were assigned the additional attributes of atmospheric toxicity, smoke temperature and optical density in the link. When a link becomes too dangerous for occupant travel, all optimal routes are recalculated so that the occupants avoid that link. This approach, where routes are recalculated during the course of the evacuation process is called 'dynamic programming'. Kostreva stated that "decision making in a dynamic environment which includes conflicting goals more faithfully reflects the situation faced by the occupants of a residential building which is involved in a fire".

EXITT was significant because of its attempts at modelling behavioural response during the course of an evacuation, and attempting to simulate the effects of fire and smoke on the evacuation process. It preceded the program EXIT89 which was later used in the HAZARD I package.

4.2.6 FAHY (1991) - computer model EXIT89.

EXIT89 was developed on the same basis as EXITT, but was also capable of handling large numbers of individuals. The maximum number of individuals was limited to 700, but this could be changed by the programmer. Each floor of a building was capable of containing up to 89 nodes. The number of behavioural characteristics that were simulated were less than those modelled in EXITT because it was felt that sensitive mutual interactions for a large number of occupants would make the calculations very complex, and excessively time-consuming.

This model was one of the first to solve optimal escape routes by identifying the exits and working backwards through the network to the nodes where the occupants exist. This method greatly reduces the calculation times involved when simulating evacuation. It also incorporates the dynamic programming approach, where if a route becomes untenable (from information received through HAZARD I), then routes are recalculated to allow for this, and occupants are routed around the impassable node.

Walking speeds were calculated using the data presented by Predtechenskii and Milinskii (1969). Therefore, this was the first model to evaluate different walking speeds for different population densities at different nodes. The author believes that this was an important progression for these types of modelling system, and was essential when considering large building populations. The program, however, does not calculate the speed for each individual person, but rather calculates the average speed of the crowd within each node, based on the crowd density. Because of this kind of approximation to crowd speed, EXIT89 cannot model any form of physical jamming or high-density shuffling of crowds. This may be seen as an area where the model could be improved.

The model has been used to simulate the real-life evacuation of a seven storey office building under non-fire conditions, which took 7 minutes. The building initially contained 700 occupants. The length of arcs between nodes were measured as the distance from the centre of each space to the centre of the openings between connected spaces. The model was first run using the 'emergency' velocities described by Predtechenskii and Milinskii which predicted a 5.6 minute evacuation time. When 'normal' velocities were used evacuation time increased to 10 minutes. These are encouraging results, but the model requires much more complete 'validation'.

4.3 RECENT BRITISH MODELS

Three important computer models for evacuation (excluding the model developed in this PhD project) have recently been developed in Britain. Two of these models, EXODUS and EGRESS, are based on network systems, but use a fine network of nodes where each node represents between 0.2 and 2 m². No significant developments have occurred in the U.S.A. since EXIT89, which is still being developed. There is also an increase in computer modelling in Japan but these are generally of a form similar to EXODUS and EGRESS, and less specific detail is available to the author than for the British systems. A good example of one of these new Japanese models is described by Aoki (1993).

4.3.1 GALEA (1993) - computer model EXODUS

This model is intended primarily for use in passenger transport vehicles, such as aircraft. It contains a comprehensive range of occupant characteristics. Large numbers of individuals can be accommodated, although the limit is not stated. The model controls the physical movement of the passengers from one position to the next within a pre-defined two-dimensional network / node grid that defines the properties of the environment space. Each node possesses a measure of its distance from the nearest exit, a measure of any obstacle that it may contain and has the capacity to receive air toxicity data from another program. Only one conscious person may occupy any one node at any instant, and the 'obstacle factor' of a node is increased if it contains an unconscious person. Arcs link the nodes with predefined distances and routes. Geometries of multi-levels can be accommodated by linking layers of these two-dimensional grids. Nodal values are set in a systematic manner in order to achieve a predetermined global evacuation method. It would appear that these routes are defined by the user.

Only four locomotion speeds are available: 'run', 'walk', 'leap' and 'crawl'. Movement is assessed at each even 'tick' of the simulation clock, while routing rules are used at each odd 'tick'. One 'tick' is equivalent to one twelfth of a second in the example given in the papers.

The behaviour model can be adjusted by the user. The 'desirability' of an exit can be adjusted by altering its 'potential', or catchment area. Exits can be blocked at

certain times, and routes recalculated. Each person is assigned twelve factors. These comprise sex, age, weight, mobility, agility, travel speed, response time to alarm, 'drive' (possibly a measure of aggressiveness), patience, condition, volume of air breathed and incapacitation dose. The first nine factors govern movement speed and are user-specified, and the last three are inputs from the toxicity values from another source. The model also includes atmospheric toxicity calculations, but this project is not concerned with the specific details of such predictions.

One validation exercise is described. The model has been used to attempt to simulate the Cranfield Trident Three experiments (Muir - 1989) aboard an aircraft. These experiments were performed in non-hazardous conditions, with a financial reward for the first thirty people emerging from the aircraft. A number of evacuations was executed with only one of either of the two escape doors open each time. The hazard and toxicity models were not used in the computer simulations and the alarm response time was set to zero. The model requires a considerable number of inputs relating to passenger and psychological attributes, so the computer operator incorporated values that appeared reasonable due to the lack of any such data. The simulation correctly predicted the observed trend of approximately linear evacuation flow, but predicted individual's evacuation times ranging from between 25% to 250% of those observed. Most of the predictions were within 50-60% of the observed values, which implies that EXODUS requires more development before the absolute numerical results can be used with any degree of confidence.

The network / node analysis adopted is a development of the principles for movement displayed in programs from the U.S. in the 1980's, such EVACNET+ (1985). Even though the principle has been developed to the level of each node being the size of one person, the method might not accurately predict the crowd flow patterns set up when large numbers of people interact, due to this method of spatial segmentation. Complex speed fluctuations are not modelled. Galea tells us that "...it is not necessary to regulate an individual's travel speed for motion in crowds as this is self-regulating. A fast individual trapped in the middle of a crowd or an exit queue will move automatically with the speed of the crowd or queue". The classic crowd speed / density curves of Predtechenskii & Millinskii (1969), Hankin & Wright (1958) etc. are not used. Overtaking is not mentioned and the model cannot accommodate more than one size of body.

The amount of flexibility in the twelve factors for each person could be very useful for describing a crowd of people where each person possesses specifically determined properties. Unfortunately, no detailed guidance is supplied with regard to these user-inputs, probably due to the lack of specific data for such factors. It is interesting that even in the aircraft simulation, where both the gender and motivation of individuals was known, the computer operator still had to personally assess these factors. The bulkhead evacuation was simulated three times with different personal factors applied for each. The simulated evacuation time was halved when each person was assigned the same walking speed, and other factors set to default values.

We might conclude from the validation exercise that the model is not accurate in quantitative terms, but does demonstrate some of the qualitative trends observed. Extensive efforts have been made to incorporate user-specified 'individuality' among the population, but suitable data is not available for these inputs and the model is very sensitive to such values.

4.3.2. KETCHELL et al (1993) - computer model EGRESS

In an attempt to bring some probabilistic modelling and artificial intelligence to the field, this program applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagon may be 'occupied' or 'empty'. An occupied hexagon represents the volume space of one person. Each person steps from one position to the next depending on certain rules, and speed is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real-life experiments will be carried out later in 1993.

The model has been applied to the problem of solving evacuations on oil rig platforms. In this form, the program incorporates artificial intelligence algorithms that attempt to simulate the effects of various stimuli on the behaviour of the occupants. Each occupant is also assigned a natural 'role' on the oil platform simulation. That is, patterns of movement typical of different people in different levels of authority are simulated according to rules laid out by the training drills.

This program has many properties in common with the EXODUS model. They both define the building / vehicle space as a number of finite nodes or blocks,

each of which represents the spatial volume of one person. Both programs also contain distinct movement and behaviour models, but there are definite differences in route-finding techniques, speed assessment and some of the behavioural aspects.

4.3.3 STILL (1993) - computer model VEGAS

The VEGAS system has arisen from the recent developments in virtual reality techniques, and is not a network-node type of system. It is a package that represents each person as a solid, thinking object within a virtual reality environment. The model is written in a derivative of the 'C' programming language on the commercially available V.R. environment called "Superscape". Individual people are defined very accurately in terms of physical space, including the dimensions of hands and feet.

After brief meetings with the psychologist Jonathan Sime (previously referenced in Section 1.3), Still included certain psychological aspects to the evacuation model. The psychological aspects modelled are: group behaviour, alarm awareness and the effects of smoke. The effects of group communication and leadership on a group of occupants is modelled, although none of these complex psychological characteristics are based on extensive real-life data.

The route-finding methods are also very different from the network-node systems. In a virtual reality environment, there are no predefined pathways, so a different system of wayfinding was adopted. Each person chooses a direction by assessing pre-set target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived.

The system illustrates fire growth, smoke spread, and occupant behaviour using real-time animation. The fire growth and smoke spread models are fairly simple, but the three dimensional visual presentation of the whole evacuation process yields a valuable insight into the escape process. Unlike EXIT89 this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic, the mutual obstruction of escaping people and forces acting on their bodies at crowded doorways. The system is restricted to simulating a few hundred people and is still under development.

4.4 CONCLUDING REMARK.

The different computer programs described in this chapter are only a few of the models that have been produced. Many other network - node models were produced in the 1980s in Canada, the U.S.A. and Japan, but a representative sample of the significant programs were chosen for discussion in this chapter.

None of the computer programs outlined above have yet undergone the extensive validation procedures required before they could be used a quantitative assessment tool, but their application (such as that done by Galea - 1993) does provide some interesting qualitative insights.

CHAPTER 5

COMPUTER MODELLING: initial ideas and approach.

This section presents a discussion of the shortfalls of current computer simulation techniques. Specific areas that require in-depth analysis and development will be identified. This discussion and analysis introduces the new ideas and concepts that form the basis of the computer programs described in this thesis. Some of the concepts that are introduced include route-finding, speed relationships and individual movement parameters.

5.0 THE NEED TO DEVELOP NEW SIMULATION TECHNIQUES

The full potential for computer modelling evacuation has not yet been realised. No computer program has yet taken full advantage of the capacity of modern computers for the accurate simulation of crowd movement, and the escape process as a whole. Although the VEGAS system (Still - 1993) can push a 486 almost to its limits, the vast majority of the calculation process is dedicated to the impressive three-dimensional graphics, rather than any particularly complex crowd movement algorithms. The network-node systems are generally quite fast but this is because, when compared to simulation systems in other fields, the calculations are relatively simple. Any of the early network-node systems described in Chapter 4, could easily be run on a modern PC in a short period of time. The more recent systems such as EGRESS (Ketchell - 1993), EXODUS (Galea - 1993) and that described by Toshiyuki (1993), require more calculating power, but still make large assumptions about the building space when segmenting it into nodal areas.

Only in the last five years have computer models been simulating crowd movement by attempting to simulate the movement of individuals within the building space. This is a reflection of the increase in available computing power, but the software is still lagging behind. No radically different algorithms were developed by the programmers of the recent models, when they attempted to simulate individual movement. The programs EXIT89 (Fahy - 1993) used the speed/density relationship formulated by Predtechenskii and Milinskii (1969) when assessing the speeds of individuals in a room, but all individuals were assigned the same speed. This is clearly not a true reflection of a real-life situation. Individual movement in EGRESS and EXODUS is achieved by stepping from one node to another when it becomes vacant, and VEGAS does not recognise that one person obstructs another until bodily collision occurs. The assessment of individual speed variations is just one example where modern programs are still using fairly crude algorithms.

Modern PCs are capable of executing millions of calculations per second, and commonly have large stores of 8Mb, or more, of memory. With this in mind, it was felt at the outset of this project that it should be possible to formulate more intricate methods to emulate the various mechanisms by which individuals escape from a building. It was also recognised that this process might require some new data which would form the basis of new movement algorithms. The VEGAS system made some attempt to model individual movement, but the author believes that the algorithms

contain certain flaws, such as the lack of proper speed fluctuations for individual movement caused by the invasion of personal space.

The early stages of the project were therefore concerned with identifying areas that previous models did not simulate properly. Although the recent models made some notable improvements over the early network-node systems there were significant shortfalls, especially when programs attempted to simulate individual speeds or complex escape routes. For example, the network-node system described by Toshiyuki (1993) restricts individual movement to steps of 4 directions, and that described by EGRESS is restricted to 6 directions of movement. The VEGAS system could accommodate any direction of movement, but this required the user to specify a very large number of directional target points for the escape route. It was therefore desirable that a more accurate system for travel direction be found. This lack of accurate, user-friendly algorithms was identified and certain specific areas were targeted for future development. The primary areas identified for development were;

(i) TRAVEL DISTANCE

None of the evacuation programs described can analyse the building space automatically and find the point that is most remote from an exit. The British regulations for England and Wales (ADB1) require the 'maximum travel distance' as a design parameter. The automatic assessment of this distance would be a useful inclusion in any computer model.

(ii) ACCURATE ROUTE TO EXIT

The only computer models that accommodate more than a few directions of travel require a large number of user-inputs to specify potential travel routes. There is therefore a need for a system that automatically assesses potential escape routes, to a high degree of accuracy, with little additional user-input. Factors that may affect an individual's route to exit include the proximity of an exit, signage and familiarity of that individual with the building access routes.

(iii) **INDIVIDUAL CHARACTERISTICS**

The characteristics of individuals are very important. Factors such as age, and gender may greatly affect an individual's walking speed and the effect that individual has on surrounding people.

(iv) **THE INVASION OF PERSONAL SPACE**

This was identified by Fruin (1971) as one of the most important influences on the geometry of crowd movement and the maximum flow rate achievable by a crowd of moving people. The author believes that it has not been modelled sufficiently well in programs such as EXIT89, EGRESS and VEGAS.

(v) **PSYCHOLOGICAL FACTORS**

Certain psychological factors will affect the entire evacuation process. Cultural differences, group response, reaction to an alarm are all factors that are very important and should not be ignored when assessing the potential outcome of a building evacuation

These areas were all regarded as important, but the program development was limited by the data available for individual aspects of evacuation. Aspects such as 'travel distance' and 'route to exit' were primarily geometric in nature, although very little data was available for the specific effects of signage and the familiarity of the occupants with exit routes. Some data was available for individual characteristics such as age and gender, but properties such as the rate at which bodies can twist and turn, under evacuation conditions, had not been researched. The invasion of personal space had been researched extensively in terms of the crowd as a whole, but some development was required if it was to be applied to each individual in a crowd. The most important areas that lacked comprehensive real-life data, were the psychological factors for escape movement. The existing psychological data was described in Chapter 2. Some other reports were also available, but they took the form of qualitative comments, rather than the quantitative data such as specific time delays and percentages of people choosing certain routes. Specific data must be used if accurate psychological modelling is to be attempted.

When work on the new computer modelling techniques began, the author decided that it was suitable to attempt to model all of the areas targeted for development, except the complex psychological aspects. The psychological effects that are experienced by different crowds vary considerably, and the lack of reliable data meant that such modelling would be complex and unreliable. Therefore the general approach of this project was to develop an evacuation program that simulated accurate route-finding techniques; physical aspects of evacuation; the characteristics of individual movement; and the invasion of personal space. Such a program would be useful as a stand-alone evacuation package which was therefore capable of incorporating complex psychological scenarios at a later stage when data was available, or could be collected. The program, would still be capable of assessing the evacuation characteristics of a building; the movement patterns of individuals; and the time for a crowd to evacuate, given certain assumptions about their psychological state and behaviour.

The two most important areas targeted for development were wayfinding, and individual movement. 'Wayfinding' includes the accurate assessment of travel distance and an evaluation of suitable routes to escape from a building. 'Individual movement' includes the invasion of personal space, physical characteristics of individuals, and new methods for assessing some of the parameters that had not been simulated before, such as 'body twist'. More complete explanations of the initial assessment of these topics are given below.

5.1 WAYFINDING

The regulations (Approved Document B1 -1991), require that the maximum travel distance in a building be calculated. It defines travel distance as "The actual distance to be travelled by a person from any point within the floor area to the nearest storey exit, having regard to the layout of walls, partitions and fittings". None of the available computer programs for evacuation were capable of accurately assessing this distance. It would therefore be very useful if any new route-finding technique was capable of assessing such a distance.

The route-assessment methods employed in the early network-node models were not accurate enough to be considered for development in this project. The decision had been taken, in the early stages, to model the movement of each

individual in an escaping crowd. The technique of representing a whole room as one dimensionless node, with a specified capacity for containing people was therefore not suitable. Two different methods for the assessment of individual escape routes within a building were used in the more recent computer models. These methods took the form of either nodal steps through a building space, or by the use of target points.

5.1.1 THE 'NODAL STEP METHOD'

The most accurate type of spatial representation in network-node systems segments a room or building space into a mesh of linked nodes, shown in Figure 5.1. Each node can contain a maximum number of people, and is assigned a distance to exit. Movement occurs where people move from one node to another, which is closer to an exit.

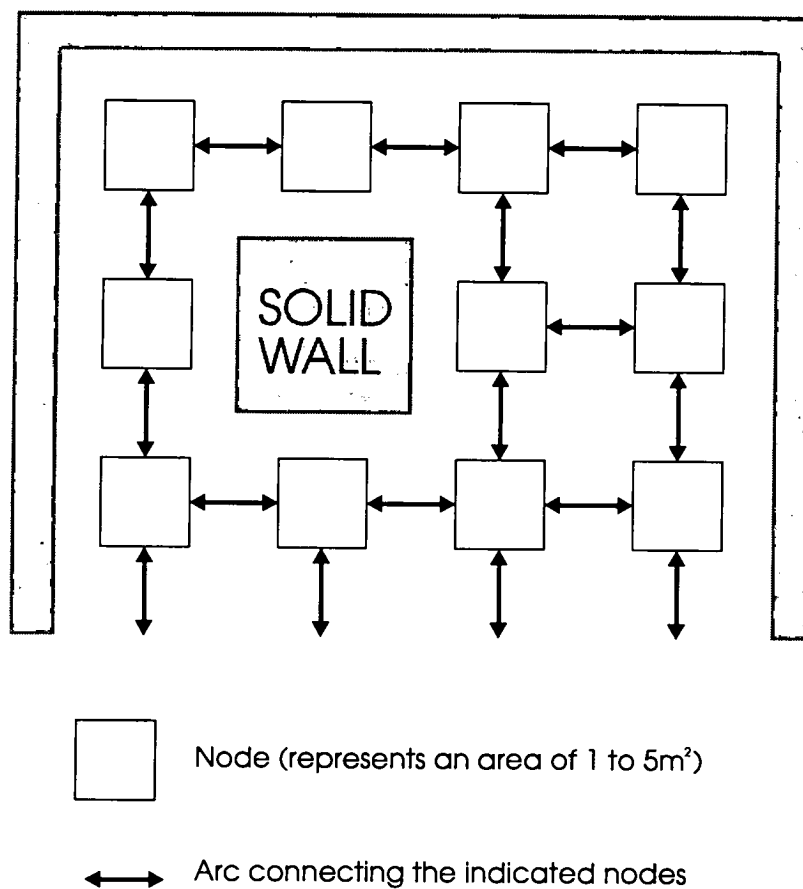


Figure 5.1. Representation of space and routes in a fine network-node system.

This technique was used by EXODUS (Galea 1993), and by Toshiyuki (1993). It is significantly more accurate than the early network-node systems, but the movement of individuals from one node to the next is typically limited to steps of ninety degrees. If this form of route definition is used, the travel distances incurred may be up to 41% greater than those encountered by direct travel to the exit at the correct angle. The most accurate form of this type of network was used by EGRESS (Ketchell - 1993). The unique, hexagonal type of spatial representation and route-finding used in this program is illustrated in Figure 5.2. As in Figure 5.1, movement occurs by a person stepping from one node to another with a smaller distance to exit. Because of the different way of segmenting the building space, the route to exit is significantly more accurate.

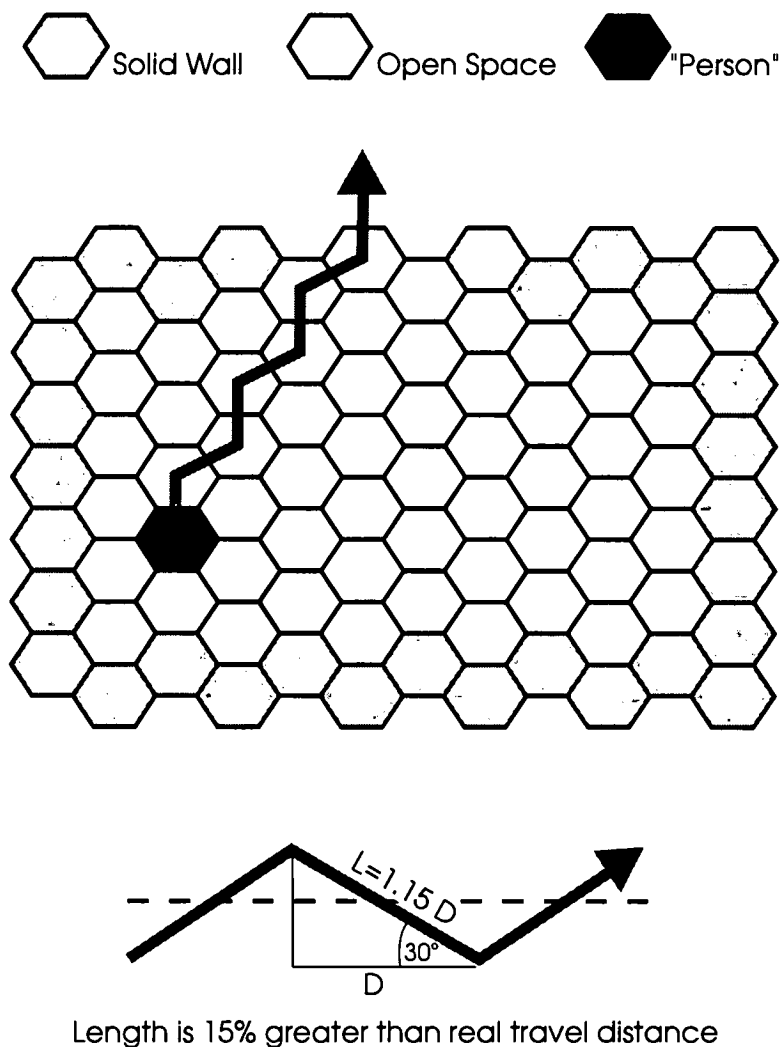


Figure 5.2. The method used for 'route to exit' in EGRESS (Ketchell - 1993)

These methods restrict individual movement to a few specific paths of direction. They do not accurately mirror the directional choices or the distance travelled by an escaping individual, and cannot model the kind of interactions observed in high density crowds. The 'stepping' from one spatial node to another can be very restrictive, when attempting to model movement in terms of space and distance.

5.1.2. THE 'TARGETED ROUTE' METHOD

VEGAS (Still - 1993) used a more accurate system of specifying potential individual routes. This system is illustrated in Figure 5.3, for one part of the escape route for one person. A very high degree of user-input was required, especially for large, complex buildings with many occupants. Every change of direction for each potential route was specified by the user, and any error in the positioning of target points could lead to 'people' becoming obstructed by walls that they would avoid in real-life.

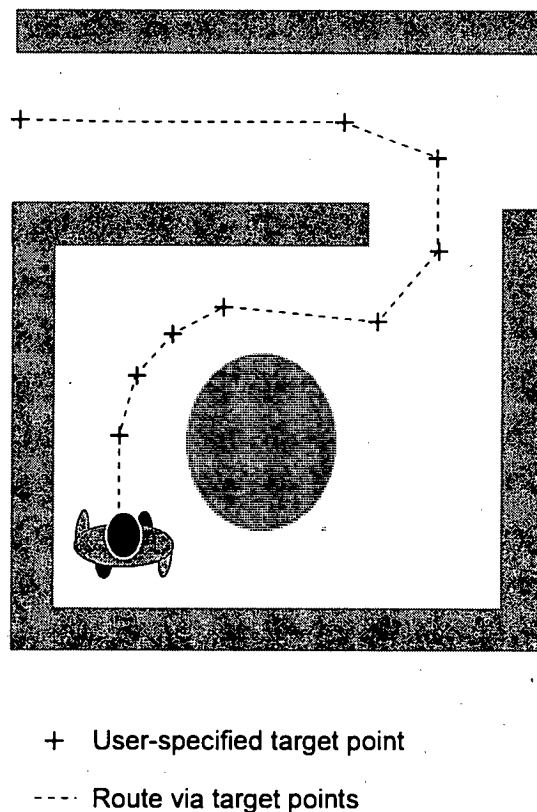


Figure 5.3. Wayfinding dictated by target points.

This system of defining target points was too onerous on the user. In a complex building, which could contain many people, hundreds of routes would need to be specified, requiring thousands of target points. One target point placed incorrectly can disrupt the whole evacuation, and produce a false result.

Another method of assessing routes for the movement of individual people was described by Okazaki and Matsushita (1993). This likened the route selection process to magnetic forces, where individuals were attracted to exits, and repelled by other individuals. The formulae presented were based on Coulombs Law for magnetic force. This was an interesting development, but there appeared to be no basis for the assumptions that were made, and there was no mention of any data to support this kind of 'magnetic' behaviour.

Many different types of route assessment were attempted, but none satisfied the criteria of 'user-friendliness' and geometrical accuracy. As a result, the development of a route assessment method that fulfilled both of these criteria was regarded one of the primary aims of this project.

5.2 INDIVIDUAL MOVEMENT

The movement of individual people must be modelled if crowd movement as a whole is to be simulated accurately. The initial position of each person, the mutual obstruction of bodies through narrow openings, and the range of normal walking speeds amongst individuals will have an important effect on the movement of a crowd of people. The simulation of the movement of each individual can only be achieved by using many complex, predictive algorithms, but is essential if we are to learn more about the evacuation process.

The early network-node models did not attempt to model the movement of large numbers of individuals, primarily because computers were much less powerful. Often, they took the form of a network of passageways whose flow rates were dictated by the figures from design codes, and therefore these early models shed little new light on the subject of evacuation. Some of the more recent models have attempted to simulate individual movement, but in a fairly crude geometric form. VEGAS represented body shapes very accurately, but did not correctly model the invasion of personal space, which led to some inconsistency of results when

analysing flow rates through a doorway. VEGAS predicted that for fairly narrow doorways, a 20mm increase in width could double the flow throughput of people. This result is in complete contradiction to the research carried out by Predtechenskii and Milinskii (1969), Roytman (1969), Hankin and Wright (1958), Fruin (1971), and all current design codes.

The 'edge effect' (Figure 5.4) has not been modelled by any computer program to date. Pauls (1980) modelled the 'edge effect' mathematically in his effective width model for staircases, although his calculations were based on fairly low density crowds. It would seem reasonable that the minimum 'edge effect' would be dictated by the body sway of individuals. Bryan (1984) stated that body sway for normal movement was 38mm side to side, and could be up to 101mm in dense crowds or on stairs.

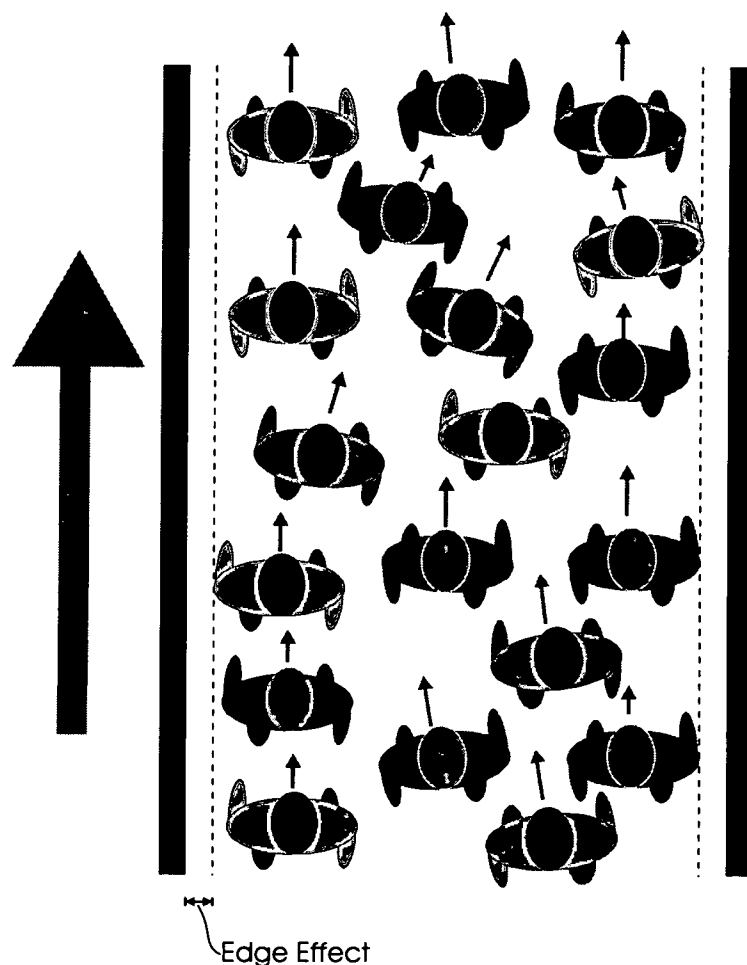


Figure 5.4. Individual movement and the 'edge effect' in a crowd 'flow'.

The invasion of individual personal space (Figure 5.5) is another aspect of crowd movement that has been neglected by all previous computer models. None of the early network-node models attempted such complex simulation. EGRESS and EXODUS simply allowed people to step into space when it became available. The only models to use speed / density curves to change crowd speeds as the density increased were EXIT89 and that described by Toshiyuki (1993). Individuals in a specific area were assigned a speed, depending on the number of people in that area. EXIT89 used areas representing whole rooms, while Toshiyuki used areas of $1.65 \times 1.65\text{m}$.

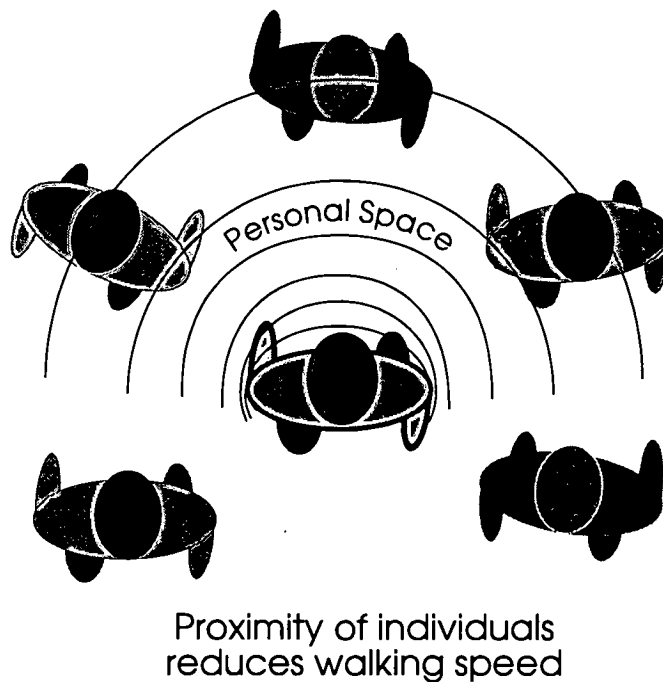


Figure 5.5. The invasion of individual, personal space.

The 'invasion of personal space' concept is very important, because it causes the kind of crowd packing characteristics observed by Fruin (1971), shown in Figure 3.5. A person whose space is 'invaded' will slow down or take evasive action, such as swerving or overtaking, if it is possible to do so. The spacing between individuals in a crowded situation results in an average crowd density. The relationship between crowd density and average speed was recognised by many researchers and was discussed, in depth, in chapter 3. The simulation of individual space, and the associated speed effects were therefore identified, in the early stages of this project,

as being crucial to the accuracy of any advanced evacuation model. Without accurate simulation in this area, a model which attempted to simulate individual movement would not be capable of reproducing realistic flow rates through corridors and doorways. No data was available for individual speed changes caused by the invasion of personal space. The development of a relationship between individual speed and the proximity of other persons was therefore regarded as necessary if the movements of individuals were to be accurately reproduced by a computer program.

Other parameters that had not been researched before included the possible rate of twisting or turning by an individual person. It was clear that this may be important when considering high density crowds trying to travel through narrow passages. Peschl (1971) observed twisting and turning frequently when studying high densities of students trying to get through narrow doorways. Therefore, for this project, some form of limiting individual turning rates would be required to prevent the simulated people twisting through large angles instantaneously. This turning rate was identified by image analysis techniques, applied to video recordings of the movement of real people, described later in Chapter 10.

5.3. A SUMMARY OF OBJECTIVES FOR THE COMPUTER MODEL.

The following areas were identified for research and development, so that they might form the basis for a new computer model for evacuation;

- (i) DISTANCE ANALYSIS - to analyse and 'map' out travel distances from all areas within a building space.
- (ii) ROUTE FINDING - to accurately assess individual routes and angles of movement within a few degrees.
- (iii) INDIVIDUAL PEOPLE - to create a building population with individual characteristics. Each individual should possess age, gender and a normal walking speed that reflected their characteristics

- (iv) DEVELOPMENT OF PERSONAL SPACE ALGORITHMS - to develop a relationship between the proximity of individuals and the resulting speed changes.
- (v) IDENTIFY OTHER MOVEMENT PARAMETERS - such as body twist and walking speeds suitable to for different people.
- (vi) PSYCHOLOGICAL FACTORS - the program should model the psychology of personal space, but not attempt to simulate other complex factors such as response to alarm, and the interaction of people with a fire hazard. The program should be structured in such a way that other complex psychological scenarios could be easily incorporated if the quantitative data becomes available.

The computer program that was embarked upon for this project was named SIMULEX (SIMULated EXit). Two other programs were required to supply data files to SIMULEX. The first, which was a simple drawing package to allow the user to input the building plan was named DRAWPLAN. The second, which was to create a map of distances throughout the building was called GRIDFORM.

CHAPTER 6

ANALYSING THE BUILDING SPACE

This chapter outlines how the building plan is input and processed by using the program DRAWPLAN and then transformed into a 'distance map' with GRIDFORM. New techniques to define a building space in terms of distance from exit, developed during the course of this project are discussed. The way that GRIDFORM segments the building space and then forms a fine mesh of points that define their own distance to exit is explained in detail.

6.0 INTRODUCTION TO THE ANALYSIS OF THE BUILDING SPACE

The first step required when developing the evacuation model was to develop a method of accurately defining the building space. This could have been done in two ways. The building could either have been drawn out on a commercial Computer Aided Design package, or a new program written specifically for this project. The CAD file formats are fairly complex, with curves and circles drawn, and co-ordinates can be expressed in three dimensions. This project was concerned with movement on a single plane, so a two dimensional plan of the building was sufficient. Therefore, a new program was written to allow the input of two-dimensional building plans, with a fast system of inputting a solid wall with just two clicks of the mouse. This is discussed in full in the following Section 6.1.

When the building plan has been input and stored as a file onto computer disk, it can be processed. The program GRIDFORM takes the building plan and segments the building space into a fine mesh of points. This mesh is processed so that the numerical value assigned to each point is a measure of the distance of that point to the nearest exit. The assessment of the travel distance to exit from any point in the building space is carried out rapidly, and never requires more than a few minutes processing time. The process is described in detail later in this chapter, in Sections 6.3 - 6.5.

6.1 TO INPUT THE BUILDING PLAN WITH 'DRAWPLAN'

The program DRAWPLAN was intended for use only for the development of the whole evacuation simulation system. If a commercial version of SIMULEX was to be produced, CAD files would need to be recognised and processed because many architects and engineers already design buildings on such systems and would have the files available to be processed. DRAWPLAN was intended for quick and simple input of a two dimensional building plan. Only a short appraisal of the system will be given because it is not part of the evacuation simulation and could be replaced at a later stage by output from a commercial CAD package.

DRAWPLAN allows the user to create a building plan by defining the building shape as a series of wall units. Each wall unit is a rectangle, which is defined by specifying two points with the computer 'mouse', as illustrated in Figure

6.1. The width of the wall unit is specified by the user pressing 'w', and typing the dimension in. The same width is maintained for successive wall units until the user specifies a new value. This method allows a complex building plan to be specified in a fairly short space of time.

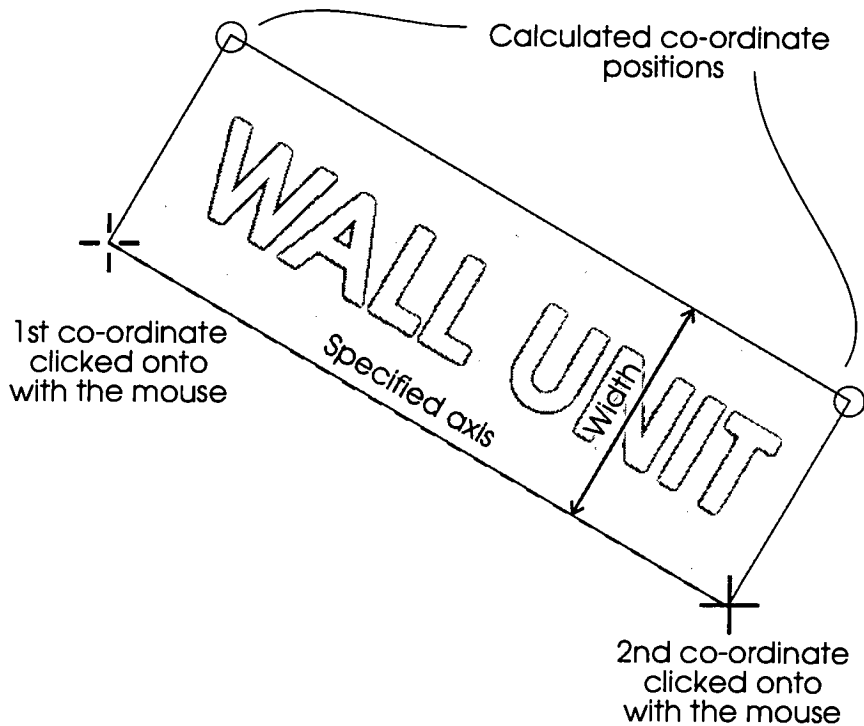


Figure 6.1. Drawing a 'wall unit'.

This program was intended to be fairly quick and simple, so there is no specific facility to draw curves. Curved shapes can be closely approximated by drawing many short wall units that are linked and are rotated at gradually changing angles. The method by which the graphics are displayed is derived from the equations of straight lines and the resolution of pixels* on the screen. However, the actual algorithms written for DRAWPLAN are not of prime importance in this project, so the development of these algorithms will not be discussed. The controls for the use of DRAWPLAN, and a screen display are illustrated in Figure 6.2.

**pixel*: a single dot on the screen of a monitor, and contained in computer memory. DRAWPLAN uses 640 (horizontal) × 480 (vertical) pixels to produce the screen image.

CONTROLS: Key functions

+ >> zoom / increase resolution (scale)

- >> move back / decrease resolution (scale)

w >> change width of wall unit (after pressing 'w', type in the width, in metres, then press enter).

Enter >> latch onto the nearest point of a wall unit so that it can be adjusted.

Delete >> delete currently selected wall unit.

Esc >>, followed byL >> load a project file.

.....S >> Save current file.

.....X >> Exit (press SHIFT simultaneously)

.....Esc >> return to main drawing screen.

Mouse buttons:

Left Button = start drawing a wall unit / finish drawing a wall unit.

Right Button = flick the current wall unit around on its axis.

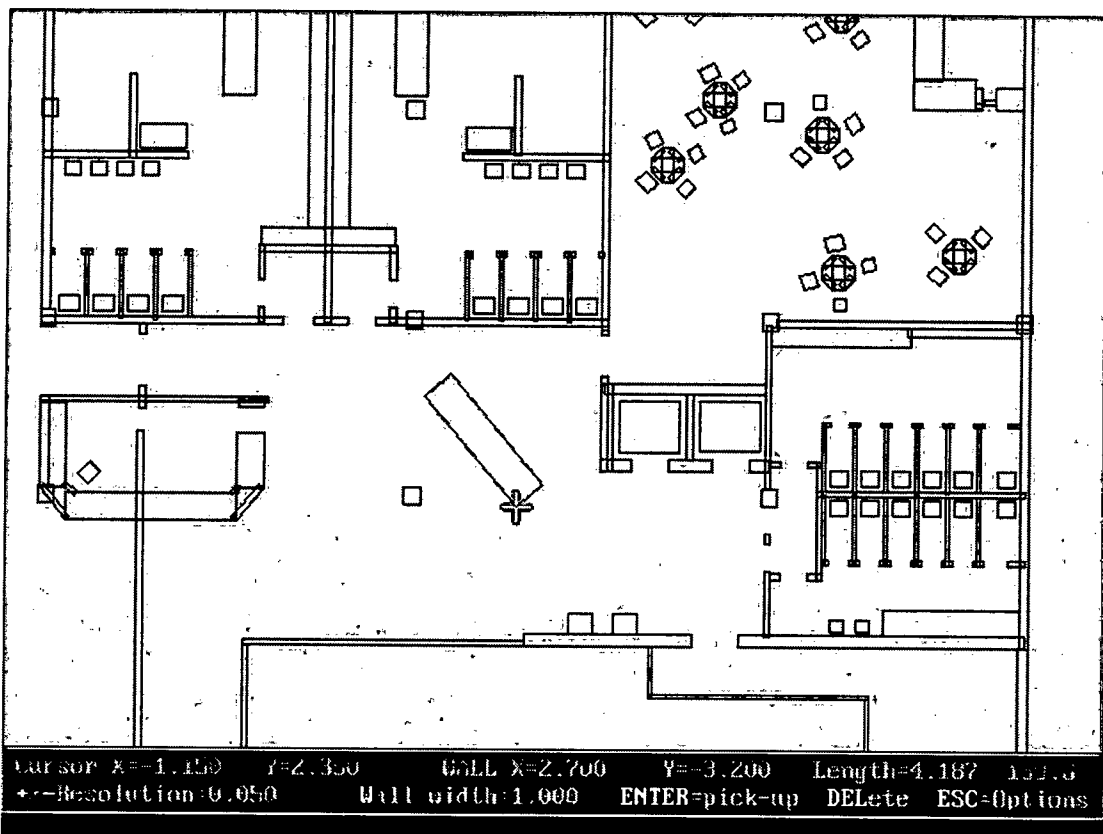


Figure 6.2. A summary of controls, and a sample screen display from DRAWPLAN.

The data file created by DRAWPLAN is given the suffix '.dat'. The prefix is the project name. The format of naming files as '*projectname.dat*', '*projectname.grd*' and similar, is used throughout the suite of programs designed for this thesis. The building plan data file created by DRAWPLAN is used by both the distance analysis tool GRIDFORM, and the evacuation system SIMULEX. The form of this file is described in Figure 6.3. The address labels used are representations of how the numbers are stored, and not the specific addresses in bytes.

Address label	Contents
0000	N = Number of wall units in file
0001, 0002 0003, 0004 0005, 0006 0007, 0008	WALL UNIT 1 (co-ordinates of 4 corners) Co-ordinates of 1st specified corner of wall unit Co-ordinates of 2nd specified corner of wall unit Co-ordinates of 2nd calculated corner of wall unit Co-ordinates of 1st calculated corner of wall unit
0009 - 0016	WALL UNIT 2
0009 - 0016	WALL UNIT 3
	: : : : :
$1 + ((N-1) \times 8)$ to $(N \times 8)$	WALL UNIT N
$1 + (N \times 8)$	End Of File.

Figure 6.3. The order of data storage from DRAWPLAN.

6.2 SEGMENTING THE BUILDING SPACE FOR DISTANCE ANALYSIS

The program GRIDFORM loads in the building plan data file that is created using DRAWPLAN. The maximum and minimum x and y co-ordinates are assessed, and are used to ascertain the dimensions of a rectangle that is capable of containing the entire building plan. GRIDFORM then uses the figures to allocate enough computer memory to represent the plan in terms of total building space. It does this by representing each 0.25×0.25 metre block of space as a single point, that possesses x and y co-ordinates that specify the block position on the building plan. The numerical value of each point defines whether the spatial block that it represents is part of a solid object, or in open space. For example, when the 0.25×0.25 metre points are allocated initially, they are all allocated the value -2. This value is used to represent empty, undefined space. 'Wall units' are plotted by dividing all of the positional co-ordinates by 0.25 to obtain their location on the $\frac{1}{4}$ m spatial grid. Subsequently, areas that are occupied by solid objects are assigned the value of -1. This grid of spatial blocks, represented by numbers, creates an environment where travel distances within a building can be assessed.

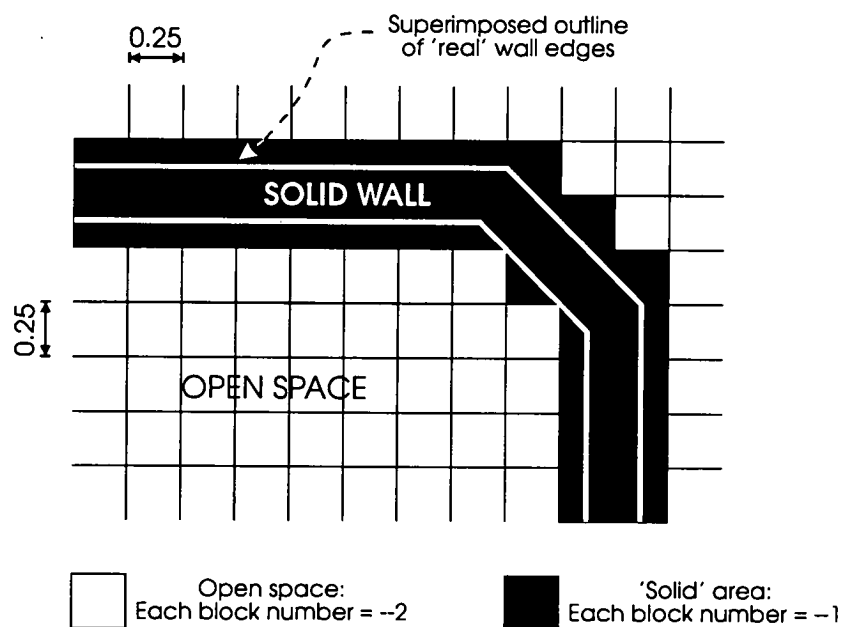


Figure 6.4. The way in which spatial block points represent the building space before distance analysis algorithms are applied.

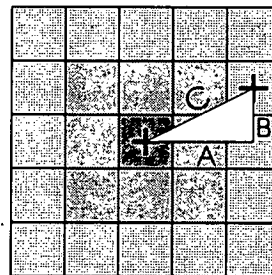
All locations that define exits from the building space are assigned a value of zero at a later stage in the plan development process. The zero value represents 'zero distance to exit' and enables GRIDFORM to calculate the distance to the defined exit from any specific location

6.3 THE USE OF DISTANCE ARRAYS

The following sections of this chapter describe a new method of analysing the space within buildings which was developed by the author. The system was developed to yield a map of travel distances over the entire building plan. This 'distance map' can be used to assess the maximum travel distance required by the ADB1, but is also used by the evacuation program SIMULEX for route-finding methods (Chapter 7). The 'distance mapping' technique is based upon the use of distance arrays which form the basis for all mapping calculations. The examples that are given in this Section 6.3 and the following Section 6.4 use fairly small 5×5 arrays, which enable clear and comprehensive description of the formation of distance maps. GRIDFORM uses larger, more complex forms which are explained later, in Section 6.5. The distance array may be regarded as the 'building block' of the distance mapping technique.

2.8	2.2	2.0	2.2	2.8
2.2	1.4	1.0	1.4	2.2
2.0	1.0	0.0	1.0	2.0
2.2	1.4	1.0	1.4	2.2
2.8	2.2	2.0	2.2	2.8

Simple distance array
 1 step=1 unit
 1 dec. place accuracy



Point distance calculation:

$$\text{(pythagoras), } C = \sqrt{A^2 + B^2}$$

$$\therefore \text{dist} = \sqrt{2^2 + 1^2} = \sqrt{5} = 2.2$$

Figure 6.5. The construction of a 5×5 distance array. Note: each numerical value is equal to the distance from the centre of the array.

One unit of distance is equal to the distance (horizontally or vertically) between two adjacent points in the array. Each array value is equal to the distance from the centre point of that block to the centre of the array. Hence, the centre value of the array is equal to zero, and the value, one grid 'step' away is 1, and so on. The diagonal values of distance from the array centre are calculated by using the pythagoras method.

When distance arrays are combined, the spatial area that can be covered is increased, as illustrated below, in Figure 6.6. Note that the blank squares contain the value -2, but these values are omitted to increase the clarity of the diagram.

			+2.8	+2.2	+2.0	+2.2	+2.8
		2.8	2.2	2.0	2.2	2.8	+2.2
		2.2	1.4	1.0	1.4	2.2	+2.0
		2.0	1.0	0.0	1.0	2.0	+2.2
		2.2	1.4	1.0	1.4	2.2	+2.8
		2.8	2.2	2.0	2.2	2.8	



			4.2	3.6	3.4	3.6	4.2
		2.8	2.2	2.0	2.2	2.8	3.6
		2.2	1.4	1.0	1.4	2.2	3.4
		2.0	1.0	0.0	1.0	2.0	3.6
		2.2	1.4	1.0	1.4	2.2	4.2
		2.8	2.2	2.0	2.2	2.8	

Two distance arrays with identical numerical values are used in this process.

The first array is embedded in the spatial mesh, where zero is regarded as an 'exit' value. A second array is then overlaid, "one step" away from the centre of the first array. However, because of the offset position of the second (overlaid) array, some values are positioned outside the first array, on the spatial mesh. These 'overlap' values are highlighted in the diagram opposite.

The 'overlap' values are distances from the centre of the second (overlaid) array, which is, itself, 1.4 units away from the zero (exit) value in the mesh.

In each case, the nine 'overlap' values are added to the offset value of 1.4 to calculate the *total distance to the exit* at the centre of the first array, via the centre of the second (overlaid) array.

New values are not assigned at the other 16 positions of the overlaid array because the overlaying process would produce numbers larger than those already in the mesh. Points are only overlaid if they are set to -2 (open space), or if a lower mesh distance value is obtained by 'overlaying'.

Figure 6.6. The principle of overlaying distance arrays.

6.4 CREATING DISTANCE MAPS BY THE OVERLAYING PROCESS

A distance map is created by repeatedly overlaying distance arrays onto the spatial mesh. The most mathematically efficient way of doing this is to carry out the overlaying process in a series of 'passes'. Each pass consists of overlaying distance arrays onto a specific range of values in the spatial mesh. Figure 6.7 illustrates a spatial mesh after a 1st pass has been carried out on values in the range 1.0 to 1.9. As a result, the central 3×3 area has been fully 'overlaid' and calculation is complete for this zone.

	4.2	3.6	3.2	3.0	3.2	3.6	4.2	
	3.6	2.8	2.2	2.0	2.2	2.8	3.6	
	3.2	2.2	1.4	1.0	1.4	2.2	3.2	
	3.0	2.0	1.0	0.0	1.0	2.0	3.0	
	3.2	2.2	1.4	1.0	1.4	2.2	3.2	
	3.6	2.8	2.2	2.0	2.2	2.8	3.6	
	4.2	3.6	3.2	3.0	3.2	3.6	4.2	



Base numbers for 1st pass

Figure 6.7. The 1st pass of an overlaying procedure.

This system of overlaying by passes must be repeated with successive base number ranges (2.0-2.9, 3.0-3.9, 4.0-4.9,) to completely transform the spatial mesh into a 'distance map'. In this way, 'overlaying' occurs in bands that successively emanate from the mesh zero value, until the available space has been completely filled and all possible calculations have been executed. Calculations are complete when all available points have been assigned their lowest (or optimal) distance values. The maximum travel distance can then be specifically identified as the largest value on the distance map.

The effect of obstructions in the spatial mesh is accommodated by the way in which the overlaying process is executed. Figure 6.8 illustrates this effect.

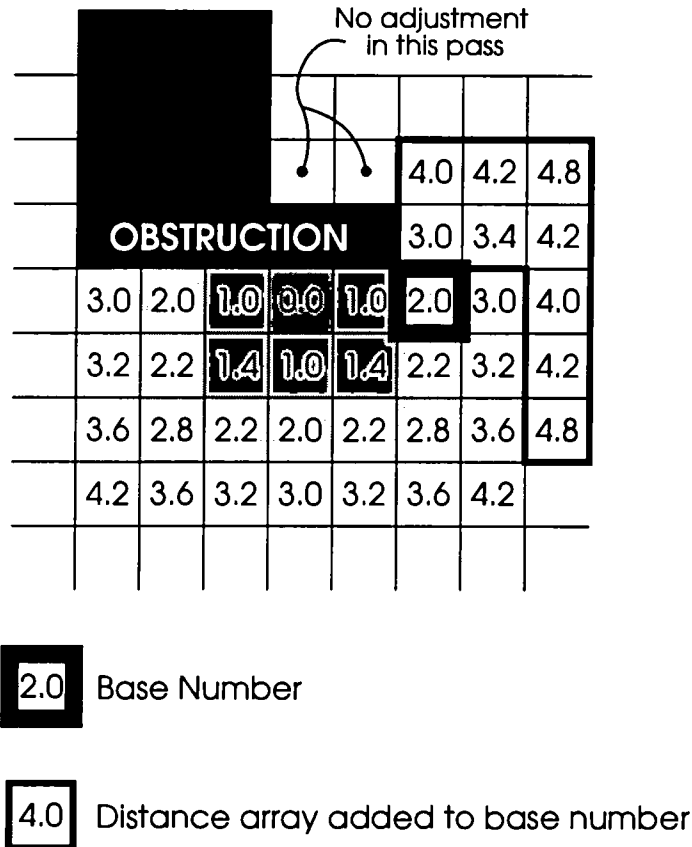


Figure 6.8. The effect of obstructions on the overlaying process.

When one distance array is overlaid onto the mesh, new mesh values are only assigned if there are no obstructing points in a straight line between the base value and the new point identified by the overlaying process. In this way, distance values are routed around obstructing blocks, representing the (possible) way in which a person is routed around an obstruction, rather than the (impossible) route through a solid object. Notice the order in which the numbers 0.0, 1.0, 2.0(base number), 3.0(new), and 4.0(new) occur on the deviated distance pathway. If the pathway had been direct, the total distance value after 4 steps would have been 2.8 instead of 4.0. The difference of 1.2 units represents the amount of deviated distance caused by the obstruction on that particular pathway to the zero point.

6.5 THE USE OF DISTANCE ARRAYS IN 'GRIDFORM'

The program GRIDFORM segments space in the way described in Section 6.3. After the building space has been segmented into a spatial mesh, all points are allocated the number -2, to represent open space. Subsequently, the obstructions are plotted onto the mesh, and the relevant points are reallocated with the number -1, to represent a solid obstruction. After this, the points along the building perimeter still possessing open space values of -2 are reallocated the number 0, to represent a potential exit location. Therefore, at the stage immediately before the application of distance arrays, the spatial points will have been allocated the following values:

- Point value 0 = exit location
- Point value -1 = solid obstruction
- Point value -2 = open, available space

In order to increase the speed of calculations, GRIDFORM uses only integer numbers in the spatial mesh, because the computer takes longer to process floating point calculations. This is done, with no cost to the accuracy of distance calculations, because the accuracy of the technique of overlaying arrays is dependant on the size of the arrays, and not the decimal accuracy of the numbers that are used. The reason for this is that the size of the basic overlaid array determines the angular accuracy of the routes that are calculated. A simple 3×3 array is only capable of allowing route 'steps' in horizontal, vertical, and 45 degree diagonal directions, and is therefore accurate to only 45 degrees. The previous example array, defined in Figure 6.5, allows more directions of route steps for distance calculations, as illustrated below.

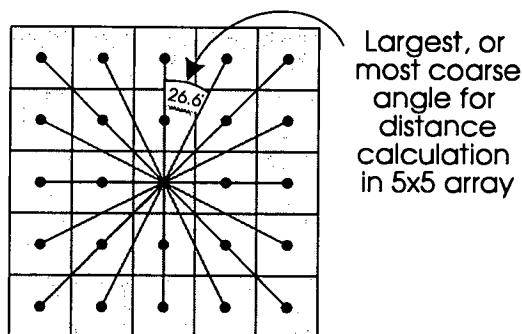


Figure 6.10. The angles of direction for distance calculation in a 5×5 array.

The size of the 5×5 array does not, however, yield enough directional precision for the purposes of accurate distance analysis. Therefore, the distance array used in GRIDFORM is a much larger 21×21 array. This distance array is illustrated in Figure 6.11, below.

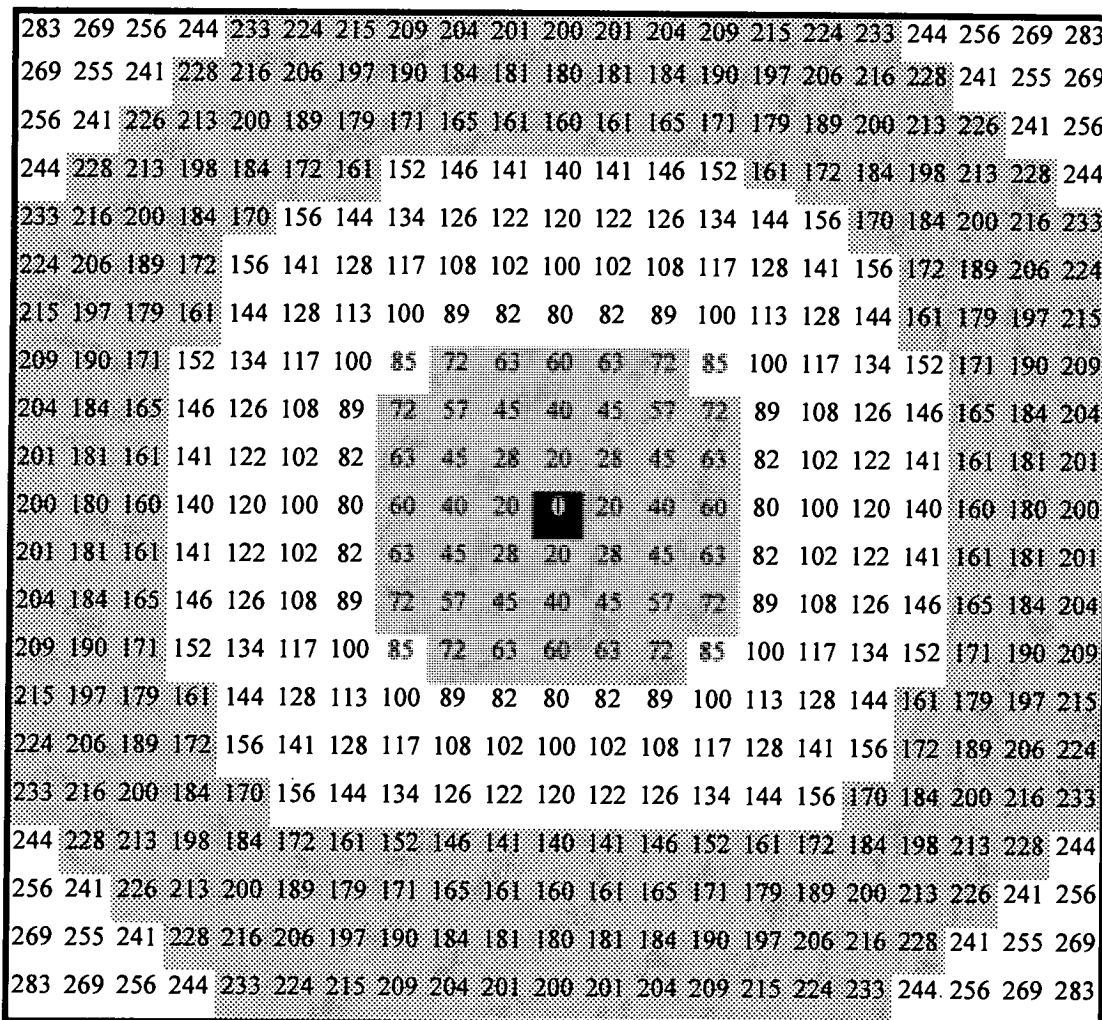


Figure 6.11. The distance array used by GRIDFORM.

Note: Black square is the base point of the array.

Distance between adjacent array points = 20 units (0.25m)

Shaded areas represent bands of 80 units (1 metre contours).

The coarsest directional angle in this 21×21 array is 5.19 degrees. The maximum inaccuracy would be incurred if a travel line bisected this angle. Therefore, maximum angular inaccuracy = 2.60 degrees. Therefore, the maximum inaccuracy

for distance calculations, incurred by the 21×21 total array size = $100 \times (1 - \cos(2.6)) = 0.1\%$. A larger inaccuracy will be incurred by the fact that any position is only defined to an accuracy of 0.25m. Therefore, if a 'real' point was exactly diagonally half way between two mesh points, this would lead to an inaccuracy of $\pm 0.177\text{m}$. The value of 20 units per grid step was used because it was the lowest integer number whose use could maintain a difference in values between all adjacent points. An example where the distance values in the array are very similar is at row 10, column 1 in Figure 6.11. An additional inaccuracy is incurred when the accurate coordinates of obstructions are plotted onto the coarse 0.25m mesh. This inaccuracy will vary from between 0.0 to 0.249m. After applying this system to various geometric layouts, the typical error range was found to be 0 to +3%. This level of accuracy for the analysis of simulated buildings is considered to be acceptable.

6.6 THE APPLICATION OF DISTANCE ANALYSIS TO LARGER AREAS

GRIDFORM can be used to analyse buildings of almost limitless size. If a spatial mesh is larger than the memory available on the computer being used, GRIDFORM will use the free hard disk space as 'virtual memory'. This is possible because the system uses fairly complex memory management techniques, where the whole mesh is segmented into blocks of $5.25 \times 5.25\text{m}$ space. The use of these memory manipulation algorithms will not be described in any detail because the methods used are specific to programming within the DOS environment, and will be fundamentally changed in the course of future development, possibly within a WINDOWS environment. It is the key principles involved in the distance analysis techniques described in this chapter that are of direct relevance.

The clearest way of representing a completed distance map is in the form of 'distance contours'. Figure 6.11 first illustrated this method of representation by identifying distance values that lay within a specific range, and then filling the corresponding spatial blocks with the same colour. This produced coloured bands, or contours of distance that emanated away from the zero distance value. Figure 6.12 illustrates the application of distance analysis to an enclosed area, with one exit, four walls and a rectangular obstruction. The contours of distance emanate from the zero distance line (the exit) and spread through the building space, around the obstruction. In the area behind the obstruction, the contours meet to form a 'ridge' where distance to the exit is equal in opposite directions (left or right).

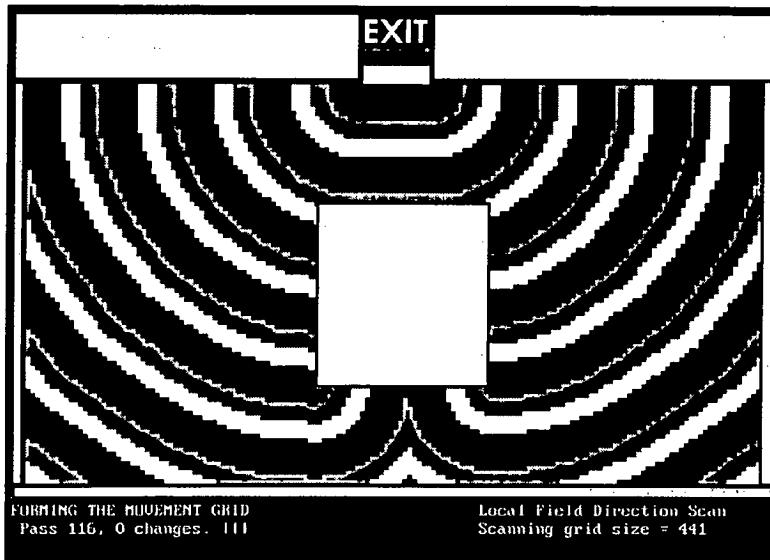


Figure 6.12. Screen display of a simple distance map for a 32.0×22.5 m area.
Note: each shaded band represents 0.8m distance 'contour'.

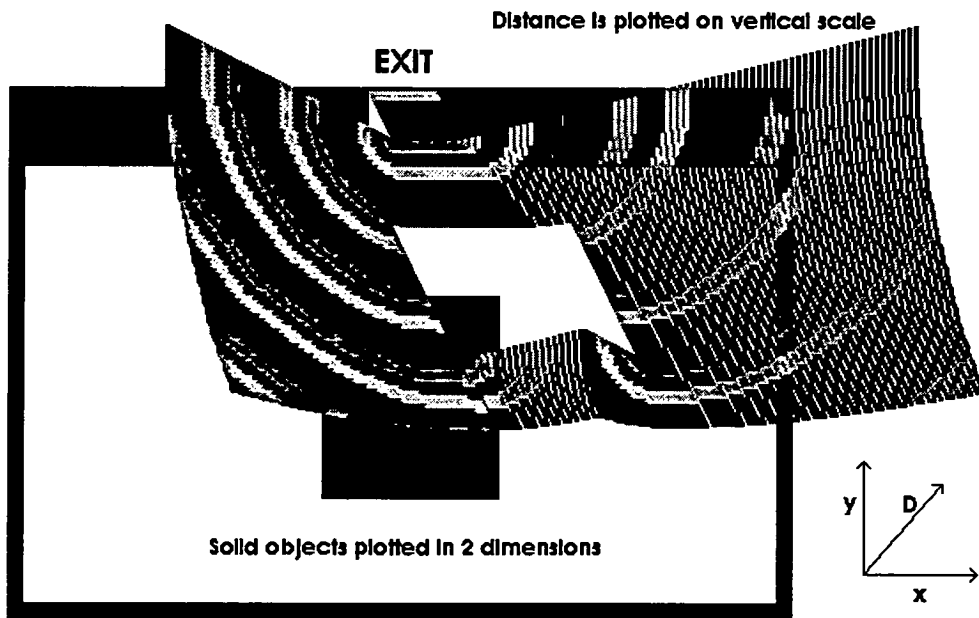


Figure 6.13. Three dimensional representation of a simple distance map.
Note: each shaded band represents 0.8m distance 'contour'.

The three-dimensional representation of a distance contour map is illustrated in Figure 6.13 and can be useful when visualising certain characteristics of distance mapping. The ridge where contours meet after spreading out, around the obstruction becomes clearer. These three-dimensional maps become too confusing, however for more complex spaces. A route out of the space can be calculated by travelling down the slope of this three-dimensional map, at right angles to the contours. Route assessment is discussed in detail in Chapter 7.

An example of the application of distance analysis to slightly larger, more complex spaces is illustrated in Figure 6.14 below. This example depicts some of the complexity that distance mapping can achieve, when analysing building space. One of the advantages of this method of spatial/distance analysis is that the time required for analysis is hardly affected by increasing the complexity of a building space. GRIDFORM took 2 minutes, 42 seconds to process the example below, when executed on a 486 DX2 66 IBM compatible PC.

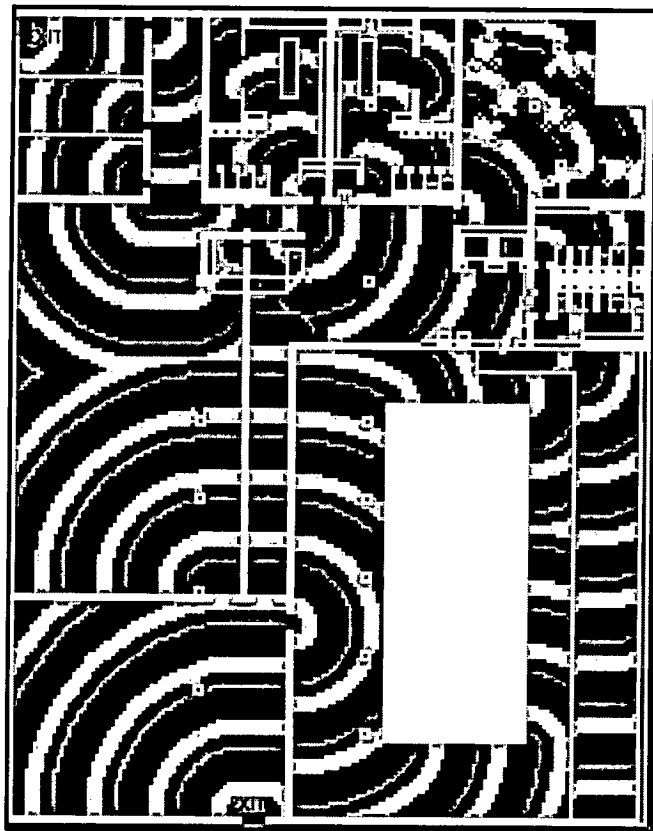


Figure 6.14. Screen display of a fairly complex distance map for a 40.8×52.2m area.

Note: each shaded band represents 1m distance 'contour'.

This chapter has described the principles and application of distance mapping, by overlaying distance arrays. The technique is fast, and only takes a few minutes to analyse building areas as large as 20,000 square metres. The distance mapping system described is unique, and is one of the primary features of this project. Distance maps form the basis for the route-finding processes described in Chapter 7. The automatic analysis of travel distance is very useful when assessing whether or not a building conforms to the Building Regulations. The evacuation program SIMULEX, described in later chapters uses distance map files created by GRIDFORM to automatically assess the maximum travel distance for a building, and informs the user of the result.

CHAPTER 7

WAYFINDING: the assessment of individual routes through the building space

The process by which each individual finds his or her desired route to exit, using the distance map, is described in detail. The method involves the selection of an optimal direction from a number of possible alternatives. The way in which the familiarity of exit routes might effect the choice of direction is also discussed.

7.0 THE SIMULATION OF WAYFINDING

'Wayfinding' is the process by which a person deduces his/her desired route through a building space, based upon previous knowledge of the building and the available audio and visual cues. For the purposes of computer simulation, this 'deduction' process must be emulated by a series of calculations, that make certain assumptions.

Until 1994, no evacuation models attempted to simulate the effects of factors such as the type of emergency alarm used, or the effects of signage. The first piece of work that approached the complexities of modelling such physiological problems was that described by Proulx and Hadjisophocleous (1994). This work involved the development of a model in which occupants were alerted by a variety of auditory, visual, olfactory and tactual cues. The model introduced the Perception - Interpretation - Action process, that was described earlier in Section 2.2.1. The project is in a state of early development, and requires more data from real evacuation studies in order to formulate reliable predictions of human activity in the early stages of the escape process. It is, by far, the most intricate and comprehensive model of it's kind, and will probably form the basis for any future computer models that attempt to simulate similar behaviour. Even this model, however, does not attempt to simulate human actions beyond the early stages of evacuation.

Typically, computer models for evacuation do not attempt to model the effects of signage and the familiarity of occupants with the building environment. All current models, except two, automatically calculate the escape routes through a building to be the shortest pathway to the nearest exit, which is the approach that is adopted by building regulations (such as ADB1) around the world. The models that do not make this assumption are VEGAS (1993) and EGRESS (1993), both of which allow the programmer to describe specific exit routes for building occupants. Neither program, however, is accompanied by documentation that contains any guidance for the use of this facility, and the specification of routes is entirely at the discretion of the user. As a result, it may be possible to produce results that are less accurate than if the model automatically assumed that occupants walked directly to the nearest exit.

Two basic issues create problems in this field. Firstly, it is extremely difficult to collect specific data that quantifies the effects of signage and building geometry upon the choice of exit routes by the building occupants. Some analytical work has

been carried out, such as that by Horiuchi (1986) and Rubadiri (1993), but the results are not extensive enough to be statistically reliable. The results from such studies are useful when formulating qualitative guidance, but the use of the numerical data must be regarded with some scepticism. The second basic issue that must be considered when simulating the assessment of escape routes, is that human decision making can be incredibly complex, especially when considering the range of stimuli available during the evacuation process.

In the light of the complexity of the problems, and the lack of reliable data, it becomes necessary to make certain assumptions about the selection of escape routes. The current version of SIMULEX assumes that building occupants will usually walk to the nearest exit, but does contain the facility to make one exit less 'desirable' than another, simulating poor signage or the infrequent use of such an exit. It should be noted that, although the initial route to exit is in the direction of the 'optimal' route to the nearest exit, the occupant is not 'forced' to travel in this direction. If one exit is severely congested, and another, less congested exit is not significantly further away, an occupant may turn and select this alternative exit. This feature is a result of the overtaking and route deviation algorithms described later in Section 8.6.

SIMULEX assesses the optimal escape routes by using the distance maps created by GRIDFORM. As a result, no input for escape routes is required from the user, but if an exit does not lie on the boundary of the building plan, the position of that exit may be specified, if desired. SIMULEX is the first program that is able to assess escape routes without any specific input required from the user. The speeds of the route assessment algorithms are not affected by the complexities of the building plan, because the route of any individual occupant, at a specific time, is based upon the analysis of 441 surrounding points, extracted from the distance map. A very tortuous route, requiring many changes of direction, requires no longer to calculate than if an occupant was able to walk straight to an exit, with no obstruction.

The method by which SIMULEX calculates individual routes, at specific times is described in the following Sections. The algorithms are unique because of their directional and spatial accuracy.

7.1 THE ASSESSMENT OF OPTIMAL ROUTES AND TRAVEL DISTANCES

When the program SIMULEX is executed, the first option available to the user is the facility to analyse travel distances throughout the building space. An example screen display of this option is illustrated below, in Figure 7.1. The two choices that are available are "Point Travel Distance", and "Maximum Travel Distance". The "Point Travel Distance" option allows the user to point to any position in the building with the 'mouse'. When a point has been specified, SIMULEX draws the optimal escape route from that position, and displays the travel distance for that route. The "Maximum Travel Distance" finds the point that is most remote from an exit by scanning the distance map for the largest value. The escape route and travel distance for this point are then illustrated.

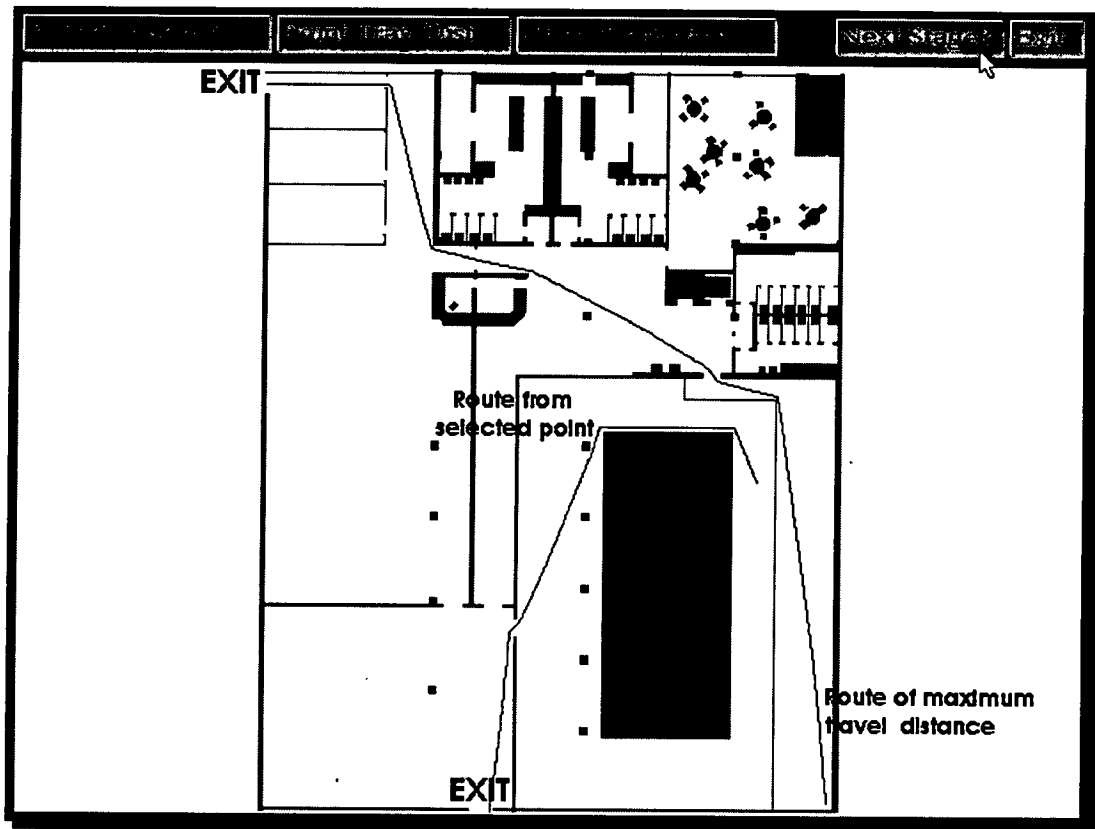


Figure 7.1. Screen Display from SIMULEX, illustrating the assessment of travel distances and routes in a building space

This is an important option, because the calculation of the maximum travel distance for a building space is required by ADB1. The travel distance from any point is generated immediately by extracting the value for that point from the distance map. The calculation and illustration of the total route pathway is much more complex, but the method by which it is achieved is one of the primary features of SIMULEX. The program starts from the specified position, and calculates the initial travel direction by the 'surplus distance method', described in the following sections. The program then 'steps' forward 0.25m, in the calculated angle of direction, to a new position, and draws a line to represent this step. The route is then reassessed, and another step of 0.25m taken. This process is repeated until the new position 'stepped' to possesses zero exit distance. Step distances of 0.25m are used because the distance map is only accurate to 0.25m. The accuracy of the whole process is the same as that described in Section 6.5.

The instantaneous assessment of the direction of travel of an individual is crucial to the simulation of evacuation, as calculated by SIMULEX. During the course of a simulated evacuation, the route of each individual is recalculated at each time step of 0.1 seconds. The value of 0.1 seconds was used because it is small enough for accurate modelling of physical movement at pedestrian walking speeds, and does not incur excessive calculation times for the total evacuation process. The way in which the instantaneous evaluation of travel direction can be processed is described in the following sections.

7.2 PRINCIPLES OF THE 'SURPLUS DISTANCE' METHOD

The method for the assessment of travel direction from any particular 'person' position is based on the analysis of nearby points, and their distance to exit. This system is called the 'surplus distance method' because the total distance to exit through each potential route is calculated, and compared to the optimal distance to exit from the specified 'person' position. The optimal travel direction is defined as the potential direction that yields the same total distance to exit as the known optimal distance to exit from the 'person' position. All of the 'distance to exit' values are extracted from the distance map. The distances from the 'person' position to 'intermediate' points that lie on the potential escape routes are calculated with a simple distance array, described in Chapter 6.

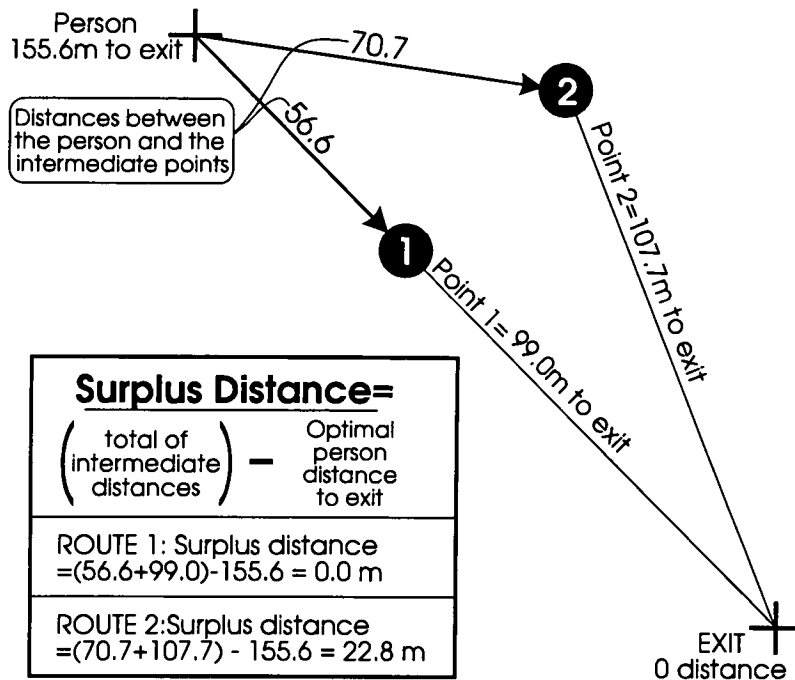


Figure 7.2. An example of route assessment by the analysis of 'Surplus Distance'.

The principles of the 'surplus distance' calculation are illustrated in Figure 7.2. 'Surplus distance' is defined as the difference between the total exit distance along a defined route pathway, and the optimal distance to exit from the position of the person. The route pathway is defined by using straight lines between intermediate points, at which a change of direction may, or may not occur.

The example uses routes that possess only one intermediate point, but there is no reason why the same principle could not be applied to a route that possessed many intermediate points. SIMULEX uses only one intermediate point for the calculation of 'surplus distance' for a particular direction of travel, because the accuracy of the distance map is sufficient to accommodate this, and the distance value at any particular point assumes that distance is measured around obstructions, rather than through them.

This method of route assessment is useful because it can become very accurate, by easily assessing a large number of potential travel directions, and each calculation comprises extremely simple addition/subtraction commands. The optimal route to exit is the one that possesses zero 'surplus distance'.

7.3 USING DISTANCE ARRAYS FOR ROUTE ASSESSMENT

The 'intermediate' distances required for the 'surplus distance' calculation, comprise two distances, when the technique is used by SIMULEX. The two intermediate distances are as follows;

- (i) The distance from the position of the person to the intermediate point, which is calculated using a distance array.
- (ii) The optimal distance to exit from the intermediate point, which is extracted directly from the distance map.

SIMULEX applies this method to a section of the distance map, which is the same plan area as the distance arrays used. It is important that the same size of distance array is used both in the construction of the distance map, and the assessment of route. For the purposes of example, the following sections use 5×5 arrays, both for the distance maps and route assessment routines which are only accurate to 26.6 degrees. It should be noted that SIMULEX actually uses systems based on 21×21 arrays in order to achieve the much greater directional accuracy of 2.6 degrees.

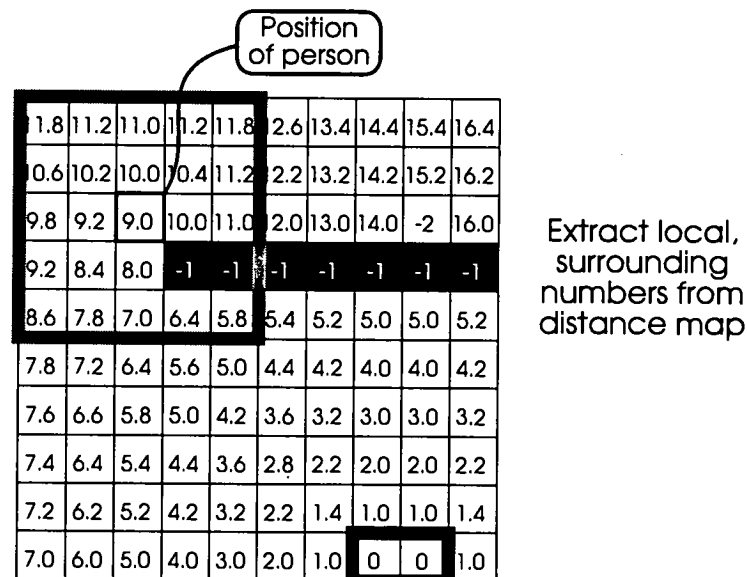


Figure 7.3. Selecting the area of distance map to be analysed for route assessment.

Figure 7.3 illustrates the extraction of a 5×5 section from an existing distance map, where the centre of the extracted section is located at the co-ordinate position of a person whose direction of travel is to be assessed. The value at the centre of this section (9.0) is the optimal, total, distance to exit for a person at that location. The localised distances from the position of the person to each of the surrounding 24 intermediate points are described by a 5×5 distance array. The optimal route is contained within the numerical 'form' of the distance map, and is revealed by adding the distance of *person-to-intermediate-point* to the *total exit distance* at each intermediate point on the extracted section of the distance map.

The addition of the intermediate distances is illustrated below, in Figure 7.4. The distance array values are added to the distance map values to obtain a 5×5 array of total intermediate distance. Total intermediate distance represents the distance to exit that would result if a person walked to the intermediate point, and then to the exit by the optimal route method.

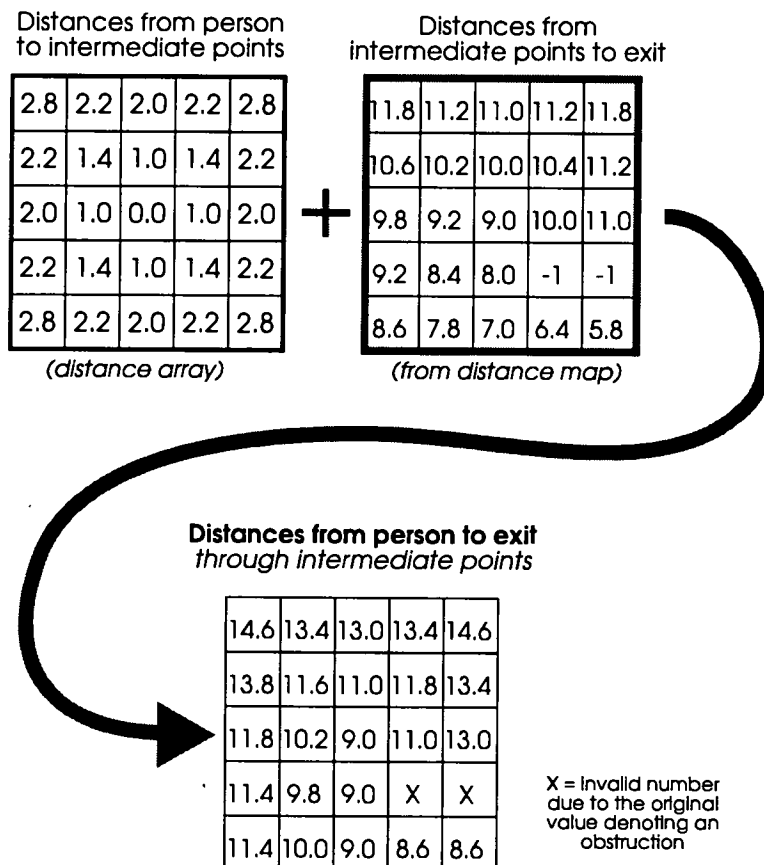


Figure 7.4. Evaluating the total distance to exit through intermediate points

When the total distance to exit through each of the 24 intermediate points has been calculated, the line of blocks that contain the same value (9.0) describes the optimal route to exit.

The 'surplus distance' calculation can be executed when the array of total distances to exit through the intermediate points has been obtained. The 'surplus distance' for the route through each intermediate point is obtained by subtracting the optimal distance of the person to an exit, from each of the exit distances obtainable through the intermediate points. Figure 7.5 shows how this process is carried out, and the resulting 5×5 array that is produced.

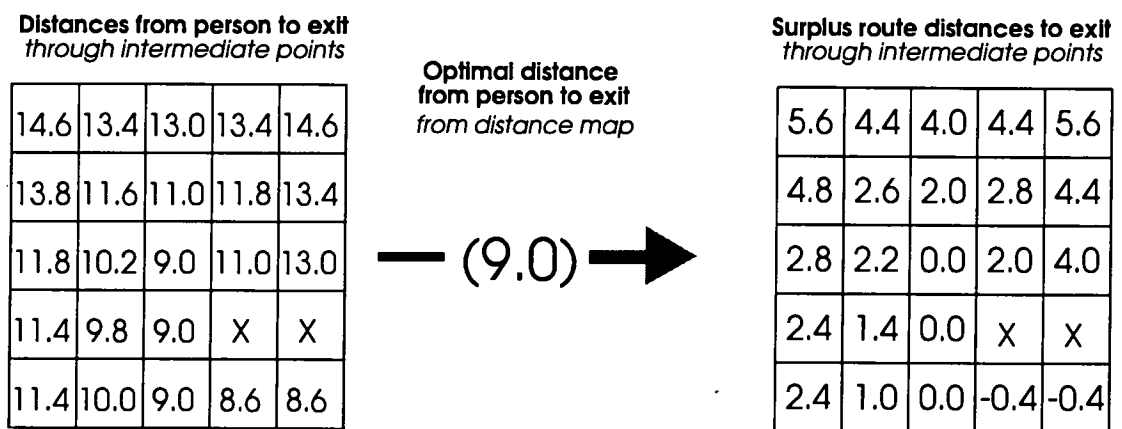


Figure 7.5. The evaluation of 'surplus distances' through intermediate points.

The array that contains all of the 'surplus route distances' is very useful. The array is one way of describing the geometric 'desirability' of the available exit route pathways. All positive numbers represent the additional travel distance required if the person walks to that position, and then to the exit. The 'X' values denote obstructions, and therefore points that cannot be travelled through. The negative values represent points that are unavailable because travel to these points would necessitate movement through an obstruction. The optimal route pathway is defined by the array points that contain the value zero. This pathway describes a route that takes the person around obstructions towards a final exit. The optimal route can be envisaged on distance maps where contours of distance are drawn, by the person moving perpendicularly over the contours, towards the exit.

All of the points that possess zero surplus distance are assessed. The point that is furthest from the centre of the 5×5 array is then selected, because this point will yield the greatest angular accuracy. The angle from the position of the person to the position of the selected 'zero surplus distance' point is therefore calculated and used as the optimal angle of travel, for the person at that position to get to the exit. The process of selecting this angle of travel is illustrated below, in Figure 7.6.

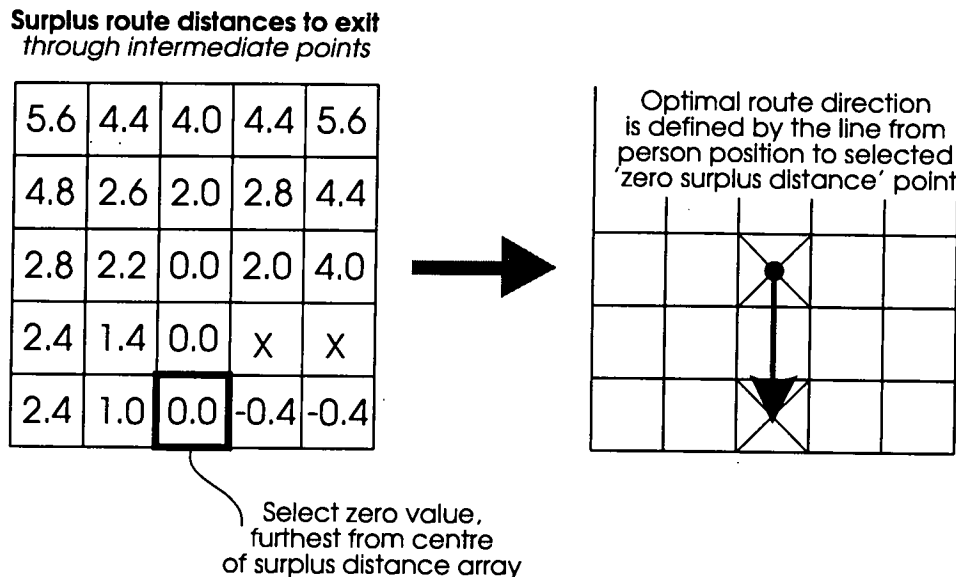


Figure 7.6. Finding the optimal 'surplus distance' point for the optimal route.

The method by which the angle of travel from any positional point on the distance map can be assessed, has now been described. The method must be reassessed, after each small step of distance has been taken, in order that an accurate total exit route can be described. This is because the angle of travel will continually change when a person negotiates his way around the sides and corners of physical obstructions. Note that for typical walking speeds, and the time step of 0.1 seconds adopted by SIMULEX, the usual steps of distance taken between the reassessment of routes are between 0.08 and 0.17 metres. The co-ordinate position within a two-dimensional space is defined with an accuracy of +/- 1mm real scale, and the angle of travel is obtained by calculating the angle between the precise position of the person and the target, which is the 'zero surplus distance' point identified on the spatial mesh. Therefore, the routes and locations of people, relative to each other and to the building space are modelled sufficiently accurately.

The system of assessment > step > assessment > step produces an accurate trace of the total exit route of an individual person through a building space. The total exit route for a person on the example distance map is traced out in Figure 7.7 below.

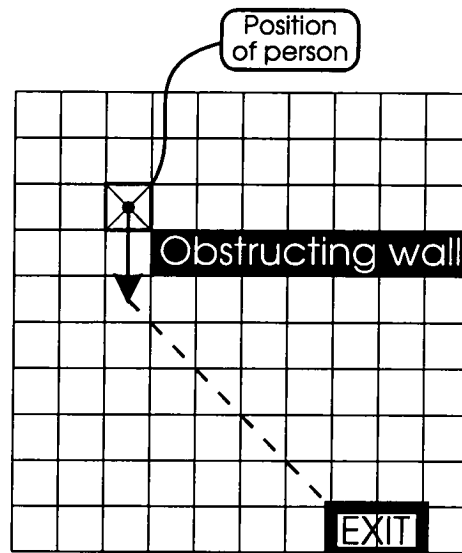


Figure 7.7. The use of repeated route assessment for the total exit route.

In this way, the total exit route from any point in the building space can be calculated. If a person chooses to deviate his or her route to overtake another person, or to traverse a congested area, then the travel direction is automatically reassessed at the next time step. The system is flexible and can accommodate almost infinitely complex building geometries, with no additional calculation time required for the assessment of individual routes.

It is possible that in future versions of SIMULEX, the distance map could be recalculated during an evacuation when an exit becomes obstructed. An exit may become impassable due to toxic fumes, poor visibility, heat from a fire, or the degradation of a building caused by a fire or earthquake. In the event of this occurrence, obstruction values would be placed across the line of the exit, and algorithms from GRIDFORM used to recalculate the distance map. This would immediately affect the routes of all individuals who would have been walking towards that exit, so that they would turn around and head for a viable exit.

7.4 THE FAMILIARITY OF EXIT ROUTES

The subject of the familiarity of the building occupants with the potential escape routes was discussed in Section 2.2. The lack of comprehensive, quantitative data on this subject means that the effects of 'route familiarity' are very difficult to predict. SIMULEX does not allow the normal program user to specify exit routes as being more familiar or desirable than another, but the program can be adjusted if suitable quantitative data is available for that particular building. If an exit is found to be used by those occupants who are initially positioned within close proximity, then this effect can be accommodated. The exit value at this position is therefore set to a value greater than zero distance, before the distance map is formed. As a result, when the routes are assessed by the 'surplus distance method', only the occupants who are close to the exit will use it.

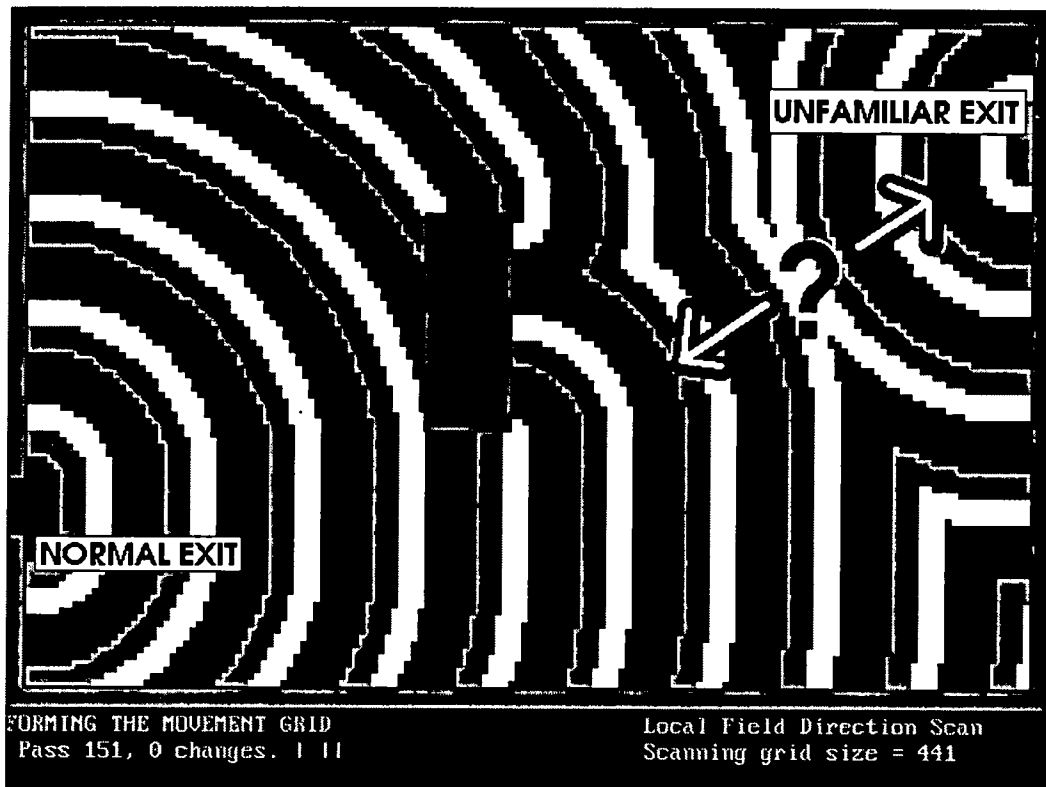


Figure 7.8. The way in which the familiarity of an exit may effect the choice of an escape route, based on directions formed from a distance map.

Note: each shaded contour represents 0.8m distance.

The effect that this 'weighting' of less desirable exits has, is illustrated in Figure 7.8. In this example, the right hand exit has been weighted with a value significantly greater than zero, which reduces the area of the building from which occupants will escape through that exit. The large question mark denotes a distance point at which both exits are equally 'desirable', and either exit could be selected by the 'surplus distance method'. All occupants who are closer to the right hand exit than this distance point will take that exit, and all occupants who are closer to the left hand exit than this distance point will choose to head towards that particular exit. Due to the lack of comprehensive data about this effect in different building types, the method of 'weighting' certain exits could be only applied if specific data about the behaviour of the occupants was available.

7.5 THE USE OF ROUTE ASSESSMENT METHODS IN SIMULEX

The methods for route assessment described in this chapter are used by SIMULEX to calculate the optimal direction of travel for each building occupant at every tenth of a second. They are an integral and crucial part of the way in which the simulation package models individual movement. When the optimal angle of travel is calculated, each person 'looks' forward in that direction to detect the presence of any potential obstructions to movement, such as solid objects or the bodies of other individuals. The way in which these detected 'potential obstructions' affect the movement of a simulated person is described in the following Chapter 8.

CHAPTER 8

INTER-PERSON DISTANCE: speed and movement

The speed of an individual is affected by the proximity of other individuals and solid objects. The way in which speed is affected by inter-person distance, and how this affects the direction of travel is explained. The overall crowd speed and flow relationships are discussed, in terms of general crowd motion and with respect to individual movement in crowded areas.

8.0 THE PREVIOUS ANALYSIS OF MOVEMENT IN CROWDS

All previous analyses of the movement of people in crowds have consisted of measuring general motion parameters, such as the total crowd flow rate and the overall speed of crowd movement. No study has investigated the movement of individuals in crowded situations in any detail or with any degree of accuracy. Initially, this lack of data caused some problems when algorithms for the evacuation program SIMULEX were being formulated. Any model that is to be used both for research and as a design tool for life safety should contain simulation techniques that are based on the analysis of real-life data, and should contain specific parameters extracted from such analyses. The reason that such data has not been collected in the past is that no evacuation model has attempted to simulate the specific movements of each individual in a crowd, while still maintaining the overall crowd flow and speed relationships that have been observed in the past.

Studies such as those carried out by Fruin (1971), Predtechenskii and Milinskii (1969), Ando et al (1988), and Hankin and Wright (1958) were extremely useful for formulating parameters relating to the general crowd motion. The primary aim of such studies was to generate crowd speed and flow data that could be incorporated into design guides and mandatory regulations. The figures produced by these four studies are very useful when examining specific aspects of crowd movement. When the movement of a crowd of people is reduced to the sum total of the movement of the individual crowd members, the overall crowd movement parameters should still correlate well with real-life data.

Previous computer models, specifically those of the network-node type make large approximations about the movement of people through a building. EXIT89 (Fahy - 1991) is one of the most sophisticated models of this type, but even this program makes the large assumption that all individuals in a specific room move at the same speed ! Modern computing power allows much more sophisticated programming techniques, but this advancement of computing power has not been accompanied by a similar improvement in the nature of the available data for crowd movement.

The development of SIMULEX needed to be accompanied by significant improvements in the data available for the movement of individuals in crowds, if the program was to be useful as a tool for research and design. New data was obtained by

the scientific collection of new material (Chapter 10) and by extracting figures from previous studies in such a way that the data could be related to the movement of individual persons. New tests were only carried out after previous studies had been fully examined, and after the important parameters for individual movement had been identified.

This chapter describes the detailed analysis of existing data and the identification of specific parameters for individual movement. This analysis showed that crowd movement characteristics could be analysed in terms of the geometrical distance between individuals, rather than the overall crowd density. As a result of this type of analysis, certain graphs were derived, that eventually formed the basis for most of the motion algorithms written for SIMULEX. It was extremely important that the data for these algorithms was accurate, because any inconsistency in such data could have caused serious problems when the output of the simulation program was later compared with the movement of real people.

8.1. INTER-PERSON DISTANCE

The movement of individual people in crowded areas is primarily affected by the orientation and distances between each person. The 'inter-person distance' forms the basis for much of the discussion and analysis in this chapter. It is crucial to the accurate simulation of individual motion and behaviour.

The spatial area that is of most importance when analysing the movement of an individual 'assessing person' is illustrated in Figure 8.1, overleaf. This figure demonstrates the way in which the algorithms in SIMULEX analyse the space that people move into. Each person is assessed separately, and the forward projected area analysed for the presence of 'obstructing people'. An 'obstructing person' whose body centre is more than the breadth of a body to the side of the 'assessing person' is not generally considered, because the presence of that person creates no immediate physical obstruction to forward movement.

The 'inter-person distance' is defined as the distance from the centre of the body of the 'assessing person' to the centre of the body of the 'obstructing person'. The calculations are currently applicable only to movement that is generally uni-

directional. As a result, the rate of motion is usually referred to as the walking velocity, rather than as speed which is not direction-specific.

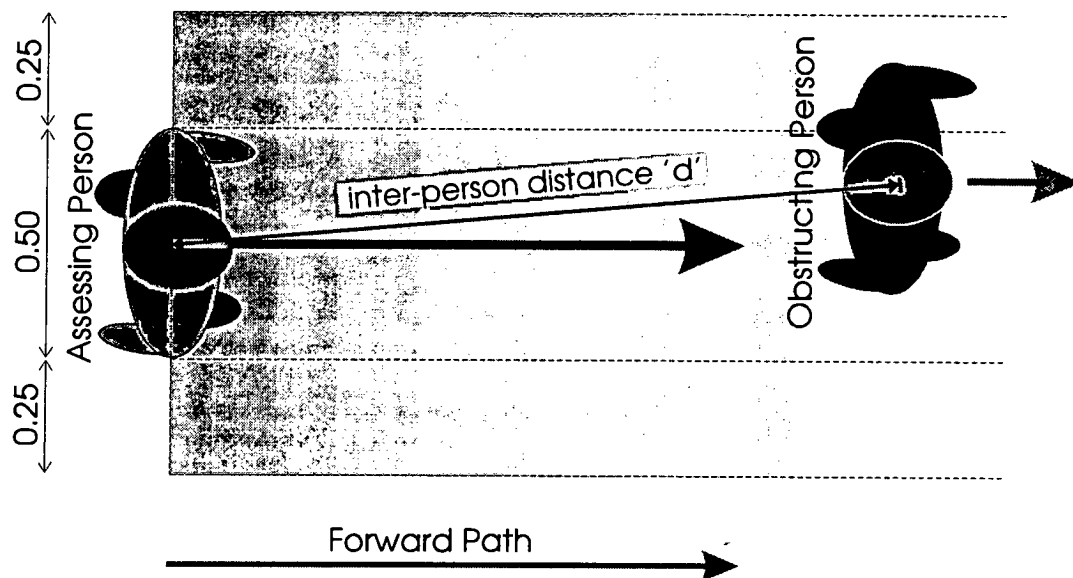


Figure 8.1 The definition of inter-person distance 'd'.

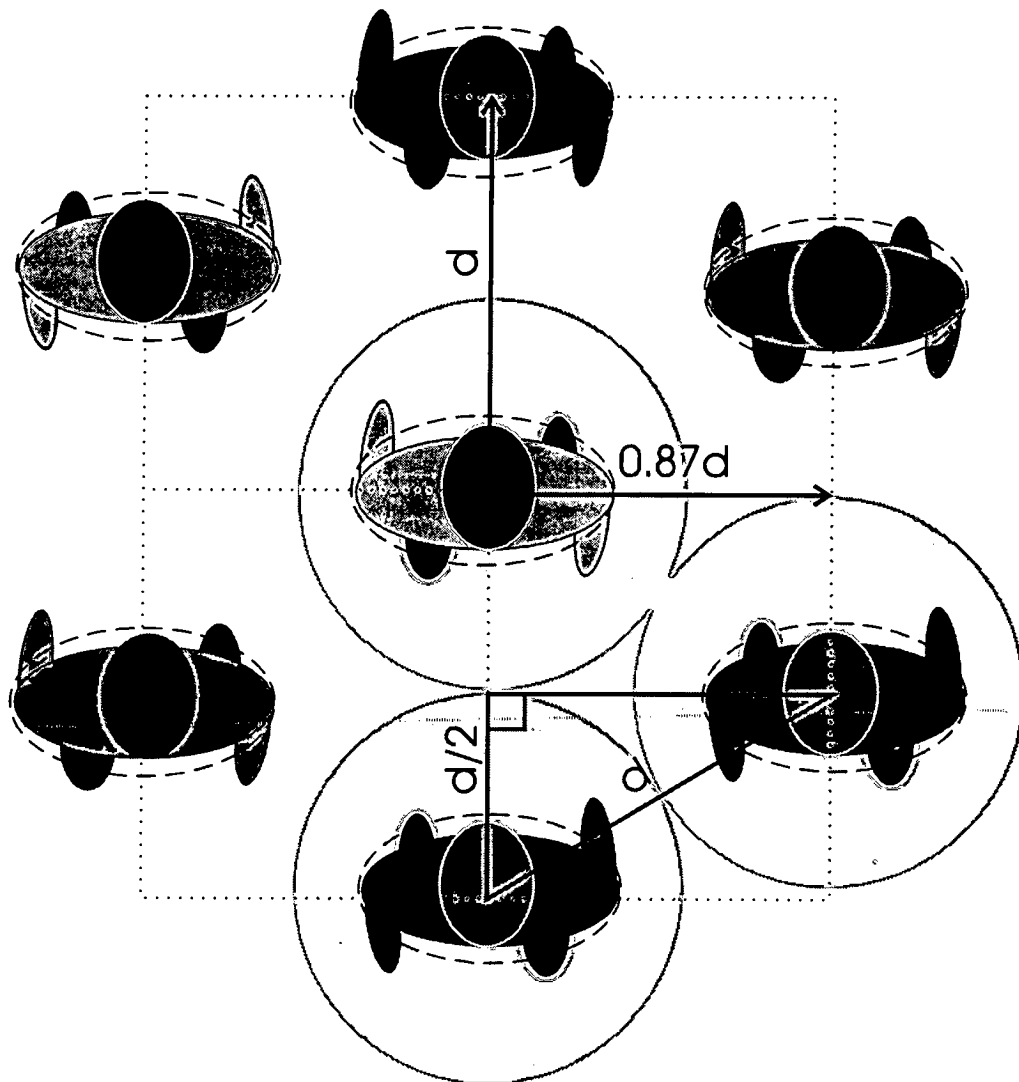
The above Figure is only applicable to individuals with body breadths of 0.5m. Body dimensions are discussed in detail later, in Chapter 9.

8.2 TRANSLATING DENSITY TO 'INTER-PERSON DISTANCE'

Fruin (1971) and Ando et al (1988) observed that in a moving crowd, the positions of individual people generally adhered to a form of circular spacing. These 'space zones' were discussed in some depth by Fruin (Section 3.1). He defined certain 'levels-of-service' for pedestrians that were based upon the radius of personal space around each person (Figures 3.4-3.5). This 'level-of-service' was used as a measure of comfort and ease of movement for the individuals in a crowded area, and the concept was used for various design guides in the United States.

The circular spatial zoning around each individual can be seen only as an approximation of the positions of individuals in a crowd, because individuals are

clearly not going to perfectly conform to such a geometrical situation. This 'average' measure of individual position is however, extremely useful because all of the available data for crowd motion refers to the overall crowd speeds and flow rates. This circular spacing arrangement is therefore the starting point for the analysis of inter-person distance, and the effect that it has on individual movement and crowd motion.



d =inter-person distance

Side spacing = $\sqrt{1^2 - 0.5^2} = 0.87d$
 (by pythagoras)

Figure 8.2. Reducing the circular packing configuration to linear dimensions.

The translation of circular spacing into linear distances is demonstrated in Figure 8.2. If forward spacing is referred to as inter-person distance, ' d ', then the lateral (or side) spacing is equal to $0.87d$. This relationship is derived from simple geometrical analysis, and using the Pythagoras relationship for three sides of a triangle. It is clear that in this situation the quantity of total floor space per person, in a crowded area, is equal to the forward distance d multiplied by the lateral distance of $0.87d$. Using this relationship, the following equations were derived.

$$A = 0.87d^2 \quad \dots\dots\dots (8.1)$$

$$\therefore D = \text{persons per unit area} = \frac{1}{A} = \frac{1}{0.87d^2} \quad \dots\dots\dots (8.2)$$

$$\therefore d = \sqrt{\frac{1}{0.87D}} \quad \dots\dots\dots (8.3)$$

where; A= area per person (m²)

D=crowd density (persons/m²)

d= inter-person distance (metres)

These equations are extremely important, because they enable the translation of data for overall crowd motion such as flow rates and speeds, into figures that relate to the average inter-person distance for individuals in a crowd. It should be noted that the figures derived in this way were verified by further testing, described in Chapter 10. This type of data, describing the speed and movement of individual people was incorporated into SIMULEX at an early stage of the program's development. The algorithms that simulate individual walking motion, and other behaviour such as overtaking, were based upon the figures generated by the method described, using the equations shown above.

8.3 INDIVIDUAL WALKING SPEEDS

Many of the observational studies discussed in Chapter 3 described a relationship between crowd density and overall speed. It was clear that as the space available per person decreased, the speed of movement of the crowd also decreased. Therefore, the application of Equations 8.1-8.3 shows that as the distance between individuals decreases, the overall crowd speed decreases. If the crowd as a whole is slowed, then the individuals within that crowd must have also slowed down. Taking this to its logical conclusion, it is clear that a decrease in the distances between individual people results in a corresponding decrease in speed of those individuals. This relationship is definable, and the analyses carried out in Sections 8.3-8.5 show that it is the single, most important aspect for individual movement in crowded areas. These analyses are concerned with uni-directional movement, so the term walking velocity is used instead of 'speed'.

The results of investigations into the relationship between crowd speed and density by different researchers, described in Chapter 3, were collected together, converted to metric units, and then translated to relate to inter-person distance rather than density. This translation of data was carried out using equations 8.1-8.3, and the results of this process are illustrated by the graph shown in Figure 8.3, overleaf. This is the first time that the relationship between walking velocity and inter-person distance has been defined. Some difference exists between the exact figures from different research sources, but the graphical trend is clear.

One aspect that this graph does not show is the range of data points that each of the original speed/density graphs were based upon. Variations of up to 50-60% from the original graphical curves were observed in some cases. The graph that contained the largest number of data points, by far, was that described by Predtechenskii and Millinskii, although it would appear that the subjects for the 'emergency' tests were not under heavily stressful conditions. The data presented by Hankin & Wright and Ando et al, was obtained from commuters in railway stations who appeared to possess significantly greater walking velocities than the subjects described by Predtechenskii and Millinskii who were under 'emergency' conditions. The data from Fruin was not plotted below 0.8m distance because the graph that was presented in the original research did not possess data points that were applicable in this range.

OBSERVED GRAPH OF VELOCITY AGAINST INTER-PERSON DISTANCE
 -converted from different sources

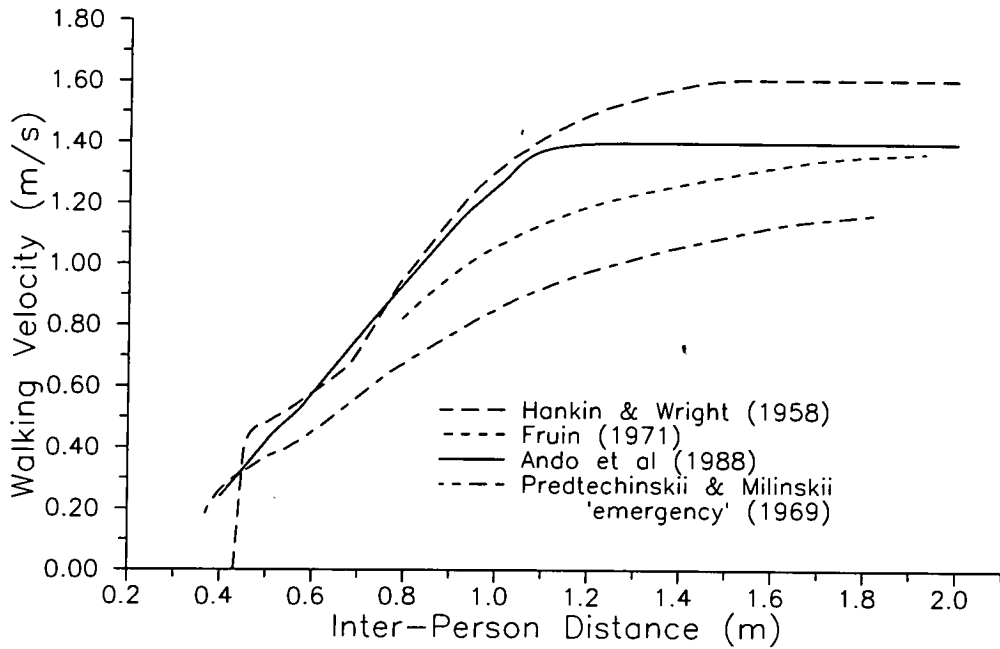


Figure 8.3. Graph of Walking Velocity against Inter-Person Distance.

Note: this graph was derived from the 4 references using Equation 8.2.

'BEST FIT' GRAPH OF VELOCITY AGAINST INTER-PERSON DISTANCE

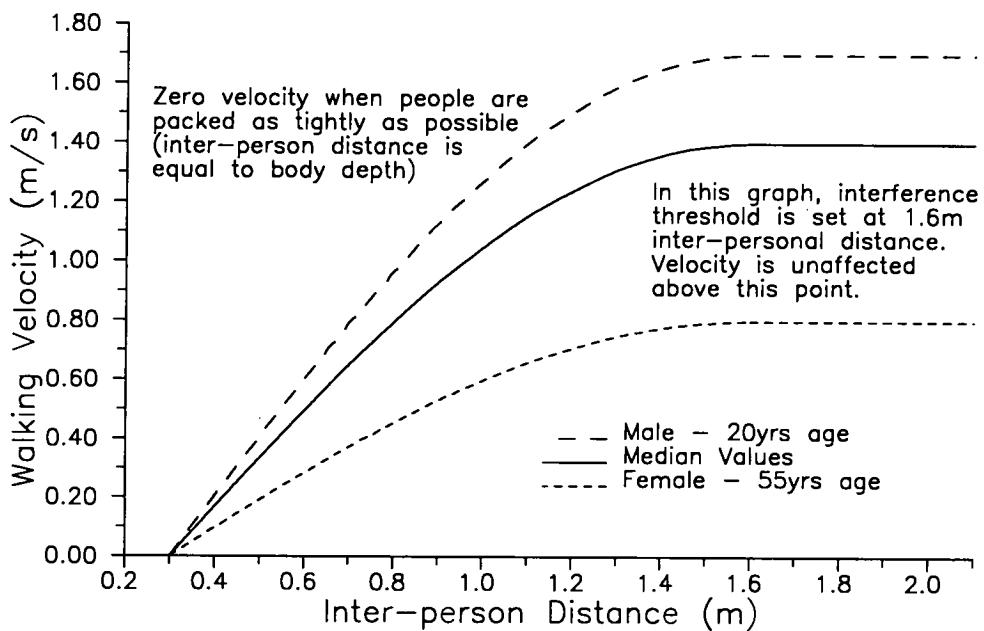


Figure 8.4. 'Best Fit' Graph of Walking Velocity against Inter-Person Distance

The graph in Figure 8.3 possesses certain definite features. It is clear that beyond a certain inter-person distance, the presence of one person has little, or no effect upon the movement of another person. The distance at which the movement of one person is not affected by the proximity of another may be called the 'threshold distance'. The 'threshold distance' for the data derived from Ando et al is clearly defined as 1.1m, but the transition between a person being slowed down, and being completely unaffected is less acute for the other graphical curves. The 'transition distance' for the data derived from Hankin & Wright is 1.6m, but some interference is still observed between individuals beyond this distance, in the data derived from Fruin and Predtechenskii and Milinskii. The transition between 'interference' and 'non-interference' is likely to be less acute than that observed by the curve from Ando et al.

There is a clear relationship between walking velocity and inter-person distance for values below the 'threshold distance'. Some variation between the results from different sources is still observed, but the curves converge as the inter-person distance decreases. The relationship between walking velocity and inter-person distance is approximately linear for distances below 0.7 metres. There is generally a gradual curve between 0.7m and the threshold distance, as movement in the crowd space becomes less inhibited.

The overall relationship between walking velocity and inter-person distance can be fitted to a 'best fit' equation of movement, shown below and illustrated in Figure 8.4, on the previous page.

$$v = V_u \times \sin \left\{ 90 \times \left(\frac{d - b}{t_d - b} \right) \right\} \quad \text{where } b \leq d \leq t_d \quad \dots\dots\dots (8.4)$$

$$v = V_u \quad \text{where } d > t_d$$

where; v =impeded walking velocity (m/s)

V_u =unimpeded (normal) walking velocity (m/s)

d =inter-person distance (m)

t_d =threshold distance=1.6 (m)

b =body depth=0.3 (m)

Equation 8.4 is applied to the closest person in front of the 'assessing person' whose body presents a potential obstruction to physical movement. The threshold distance t_d is set to 1.6m, and body depth is assumed to be 0.3m. The dashed lines in Figure 8.4 represent the graphical curves for the (optimal) figures of a male, aged 20 years, and the (minimal) figures of a female, aged 55 years. These curves are based on the relationship between age and unimpeded walking speed, identified by Ando et al, and illustrated in Figure 3.16. The median value line is based on the unimpeded walking speed of 1.4m/s which is the average of the unimpeded walking speeds at 1.8m inter-person distance in Figure 8.3.

It should be noted that movement can become highly irregular when small inter-person distances (0.3-0.5m) are encountered as friction and crowd pressure may be encountered due to the unavoidable contact between individuals. Hankin and Wright observed complete stagnation of movement when distances approached 0.43 metres, but Ando et al and Predtechenskii & Millinskii observed that movement was still achieved at inter-person distances of 0.35 metres. Due to the variation in body size within a population, it is probable that the larger members of the observed crowds were in permanent physical contact with the bodies of other people, making movement almost impossible. The presence of crowd members with luggage would also affect this figure of minimum 'inter-person distance'. Predtechenskii & Millinskii produced figures that predicted laden individuals could possess effective body depths from 0.4 to 0.8 metres, making movement for people in close proximity impossible because inter-person distances cannot be less than the body depth of the individuals concerned. It is also possible that cultural and psychological differences accounts for some of the graphical variation in Figure 8.3, because commuters who are travelling to work in a hurry may be more anxious to continue movement when in close proximity to other individuals, compared with relaxed students leaving a lecture hall. Both of these types of data are included in the work presented. The 'anxiety level' or state of stress of the individuals will affect the walking velocities, and the inter-person distances at which movement is sustainable.

Equation 8.4 was incorporated into SIMULEX to assess individual walking velocities. The equation is applied to the closest 'obstructing person' in the 1 metre wide forward projected area illustrated in Figure 8.1. The forward extent of this projected 'interference area' is the 'best fit' threshold distance of 1.6 metres. The accuracy of this 'best fit' equation is crucial to the overall performance of SIMULEX when attempting to correlate simulations with real-life behaviour.

8.4 ANALYSING CROWD VELOCITY AND DENSITY

A graph relating average walking velocity to crowd density is presented in Figure 8.5, overleaf. This graph was created by converting the source data to metric units, and plotting the results from the work of different researchers on the same graph. The corresponding graph that was derived from the 'best fit' Equation 8.4, is presented in Figure 8.6. This graph was plotted by converting the average inter-person distance back to crowd density by using Equation 8.2. The graph of observed results illustrates the variation in results from different researchers, possibly due to differences in location; body sizes, culture, and psychological state. The derived 'best fit' graph bears a reasonable relationship to the observed data.

Certain regions of the graph in Figure 8.5 are important. The low density region of 0 to 1 person/m² is the region in which the movement of individuals becomes less affected by the presence of other people. In the data presented by Ando et al, the crowd density does not affect the velocity of the crowd at all, below 0.8 persons/m². Hankin and Wright observed that there was a negligible effect on crowd velocity for densities below 0.5 persons/m². Fruin observed a reduction in the effect of density on velocity at low crowd densities, but this was not recognised on the graphs produced by Predtechenskii & Milinskii. This is surprising because some of the individual studies that Predtechenskii & Millinskii based their findings upon, did notice the reduced effect of density on velocity in fairly dispersed crowds, especially on staircases. The effect of this 'levelling off' of velocity was possibly concealed by the large spread of data plotted by the Russians. The fact that this was not recognised should be viewed as an oversight, because the graph that was produced implies that people are slowed down by their physical presence, when they are 20 metres apart (at a density of 0.05 persons/m²). This is clearly not the case. There exists a 'threshold density' below which the walking velocity of people is unaffected. The 'best fit' graph predicts this 'threshold density' is 0.67 persons/m².

The region from 1 to 4 persons/m² on the velocity/density graph conforms to a definite curve where crowd velocity is increasingly impeded by density. When densities are greater than 4 persons/m², the relationship continues but crowds have a tendency to shuffle, and movement becomes gradually more irregular until the crowd becomes too densely packed to sustain motion. The maximum physical packing density of people (depending on body size) is generally 7-8 persons/m².

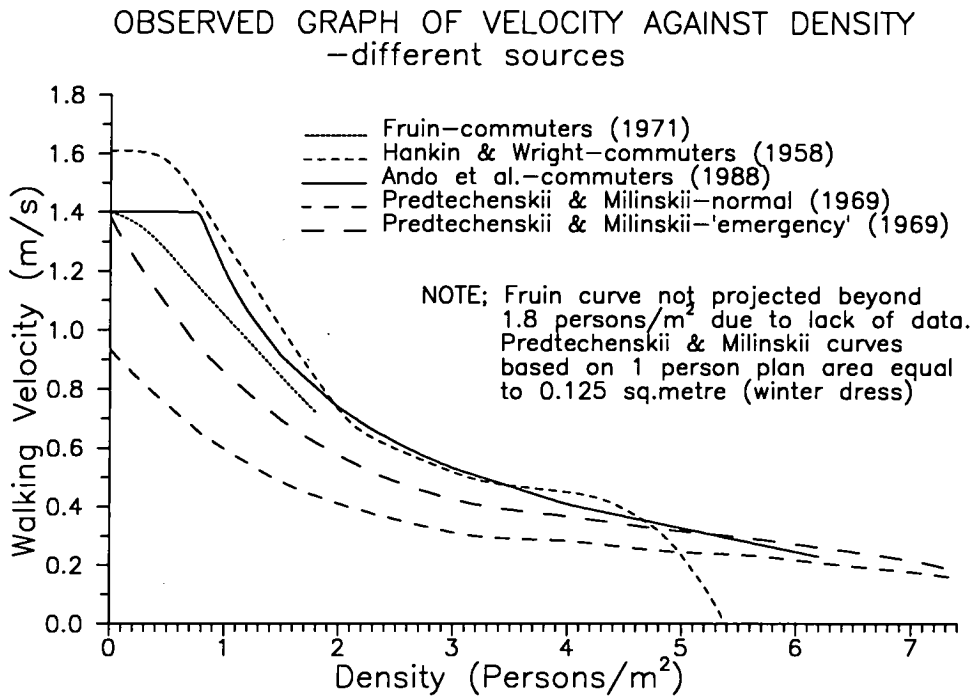


Figure 8.5. Observed Graph of Walking Velocity against Density,

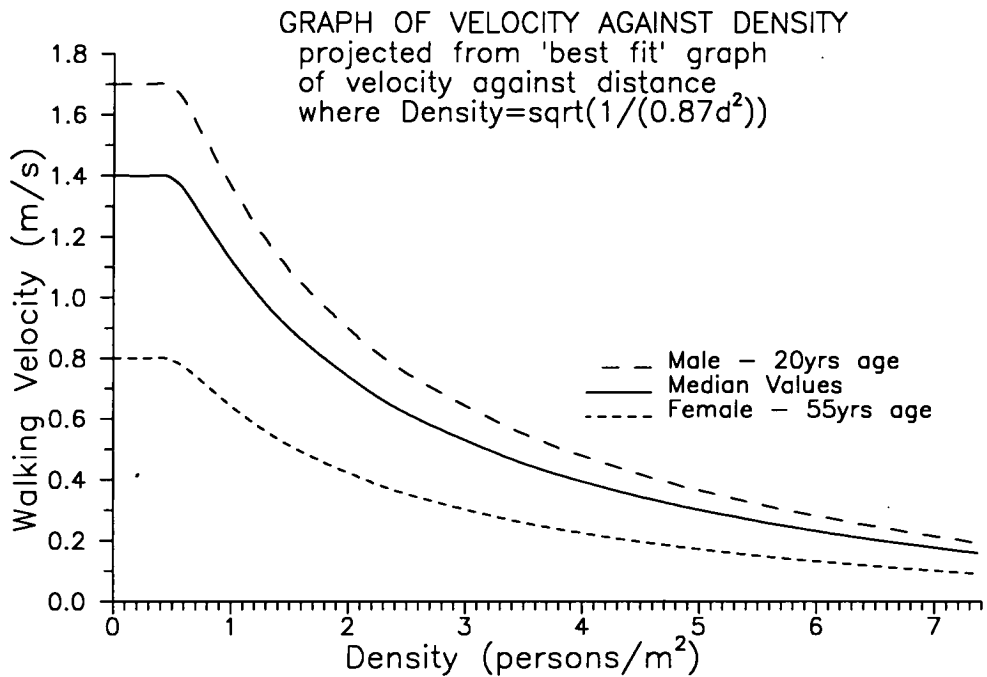


Figure 8.6. Graph of Walking Velocity against Density, projected from 'best fit' graph

8.5 ANALYSING FLOW RATE AND CROWD DENSITY

The overall crowd flow rate is usually regarded by the building designer as the most important factor for crowd movement. ADB1 details guidelines that relate the width of a passageway to the total number of evacuees that can escape through that passageway over a period of 2.5 minutes. The usual measure of flow rate is persons per metre width per second, although some regulations such as the 'Green Guide' (HMSO, "The Guide to Safety at Sports Grounds - 1990") assess flow rate in terms of number of persons per whole unit of exit width over a set period of time. One unit exit width is 0.55m which is the average body breadth of a person, plus a small allowance for body sway. The measurement of flow rate in terms of whole numbers of unit exit width leads to the development of a 'step' function, where the capacity of an exit is only increased when the width increased by a multiple of 0.55m. There appears to be little experimental or observational basis for this form of 'stepped flow' function. Although Hankin & Wright only produced graphs for passageway widths in multiples of 2 feet, they did not specify any particular reason for this. Predtechenskii and Millinskii collated readings for many passageways of different widths, and did not observe any form of 'stepped flow'. The relationship between flow capacity and increases in passageway width was therefore identified as a possible area for investigation by SIMULEX. This investigation is described in Chapter 11. The majority of research indicates that the flow capacity of passageways is linearly proportional to the passageway width. This is assumed for the rest of this chapter.

The relationship between crowd flow rate and density is illustrated in Figure 8.7 using data compiled, and converted from different sources. This compilation of flow rate curves highlights the different results obtained by different researchers, which must be due, in part, to the different types of crowds analysed, and the different locations at which the observations were carried out. Except for Ando et al, all of the flow curves were obtained by converting the original flow rate graphs to metric units. The flow rate curve from Ando et al was calculated for this thesis by multiplying the velocity and density values (from Figure 8.5) together to obtain flow rates for specific densities. Some of the other, original graphical curves were obtained in a similar way. As a result, the differences in the original velocity/density graphs were magnified by the calculation process when obtaining the flow rate/density graphs, resulting in slightly different graph shapes.

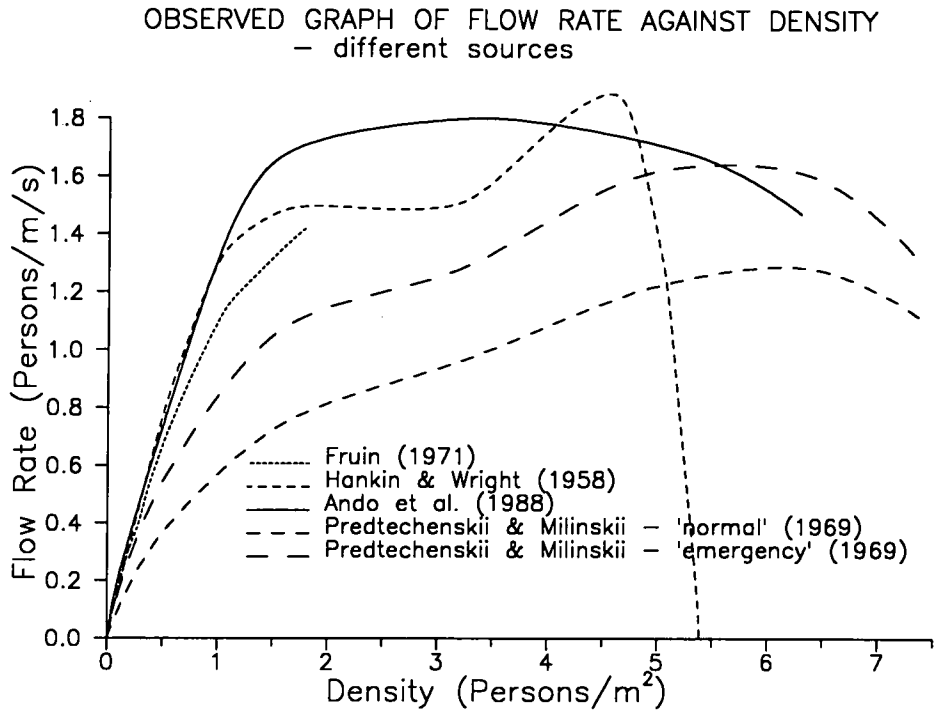


Figure 8.7. Graph of Crowd Flow against Density, converted from 4 references.

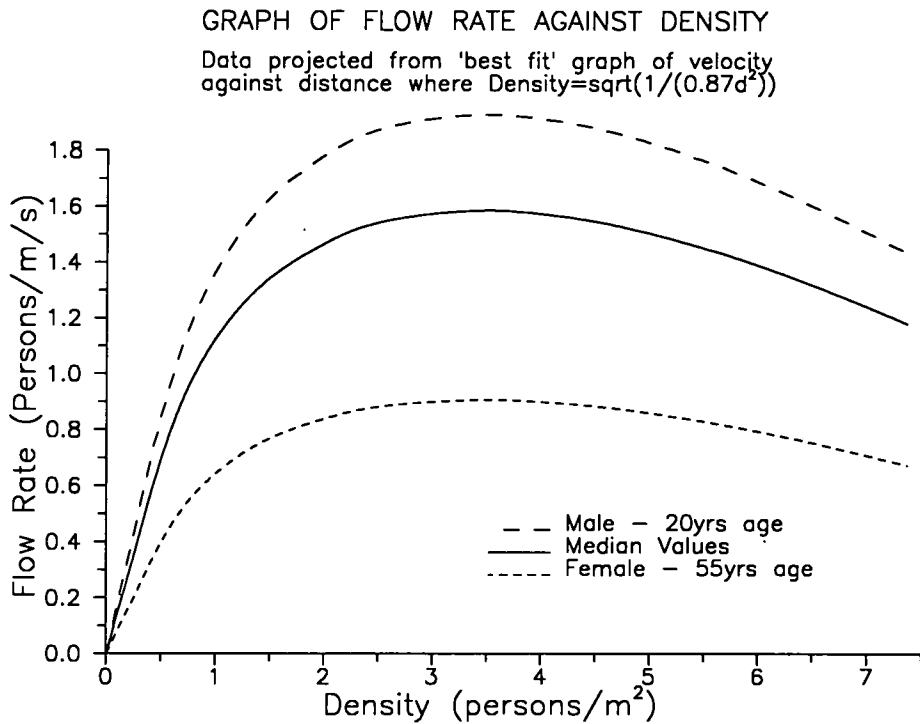


Figure 8.8. Graph of Crowd Flow against Density, projected from 'best fit' graph.

The graphical curves in Figure 8.7 observe similar trends at lower densities, but the differences become more exaggerated at the higher densities. Hankin & Wright recommended maximum design flow rates that corresponded to densities of approximately 1.6 persons/m², indicating that flow rates for densities above this value became gradually more inconsistent and unpredictable due to increased 'shuffling' in the observed crowds. The data derived from Ando et al indicates that beyond 1.6 persons/m², the flow rate almost levels out, and then falls gradually as higher densities are achieved. Predtechenskii & Millinskii and Hankin & Wright predicted a 'surge' in achievable flow rate at the higher densities, possibly due to pressures in the crowds forcing people forward.

The flow rate graph presented in Figure 8.8 was derived from the 'best fit' Equation 8.4, and the 'median line' produces values that are generally mid-way between the extremes of the curves produced in Figure 8.7. This is again encouraging because the 'best fit' method appears to correlate well with the overall speed and flow rate characteristics for crowd movement. The 'best fit' method for relating inter-person distance to the walking velocity of each individual was therefore considered suitable for use in SIMULEX.

8.6 OVERTAKING AND LOCALISED ROUTE DEVIATION

To model the movement of individual persons accurately, and to simulate the invasion of personal space, SIMULEX was required to model localised route deviation in the form of overtaking. Little specific data was available for this process, so the process of overtaking was approached in terms of geometry and available space.

The action of overtaking is only assessed when one 'obstructing' person impinges on the forward projected area of the 'assessing person', illustrated in Figure 8.1. When an obstructing person is less than 1.6 metres away from the 'assessing person', and less than 0.5m to the side, a potential obstruction to movement is created, and the 'assessing person' then decides on an appropriate course of action. When the overtaking algorithm encounters crowd densities greater than 2 persons/m² in the forward projected area, overtaking is no longer considered viable due to the close inter-personal spacing of the crowd. Overtaking only occurs in reasonably low crowd density situations.

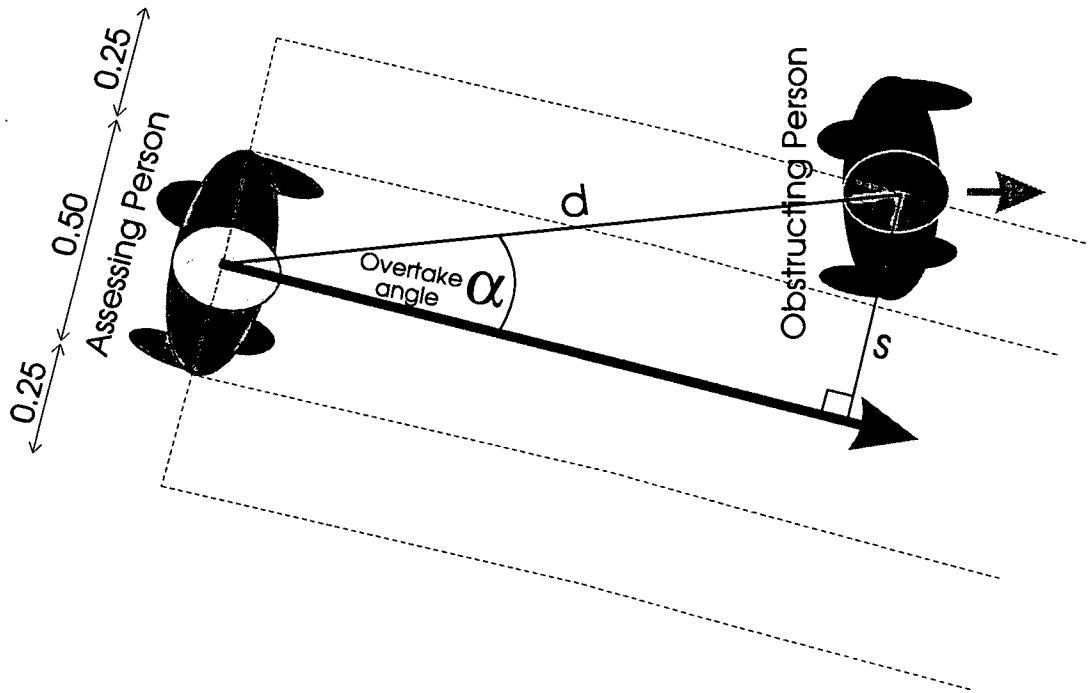


Figure 8.9. The geometrical analysis of overtaking.

The geometry of overtaking, illustrated in Figure 8.9 above, is fairly simple. The angle required for the assessing person to move around the obstructing person is calculated by the simple trigonometric calculation give in Equation 8.5 below.

$$\alpha = \sin^{-1}\left(\frac{s}{d}\right) \quad \text{..... (8.5)}$$

where; α = overtake angle (degrees)
 s = lateral, side distance (metres)
 d = inter-person distance (metres)

The side distance, s is equal to half of the body breadth of the obstructing person plus half of the body breadth of the assessing person plus an allowance for body sway and clearance of movement. For an average body breadth dimension of 0.5m, s is set to 0.6 metres, allowing 0.1m for body sway and clearance of movement.

The overtaking algorithm assesses a deviation of α degrees both to the left and right of the line of inter-person distance. The deviation that incurs the least change of direction from the optimal direction to exit is first assessed. If the walking velocity in this new direction is less impeded than in the original, optimal direction, then this direction is chosen, and the 'assessing person' adopts the new deviated route. If no improvement in velocity is achievable, due to the proximity of a second person, then a deviated route to the other side of the inter-person distance is assessed, and adopted if desirable. In this way, deviations both to the left and right hand sides are possible. The angle and route of deviation is re-assessed at each time step. The continued application of the overtaking algorithm, over successive time steps of 0.1 seconds, to the route of an assessing person is illustrated below in Figure 8.10.

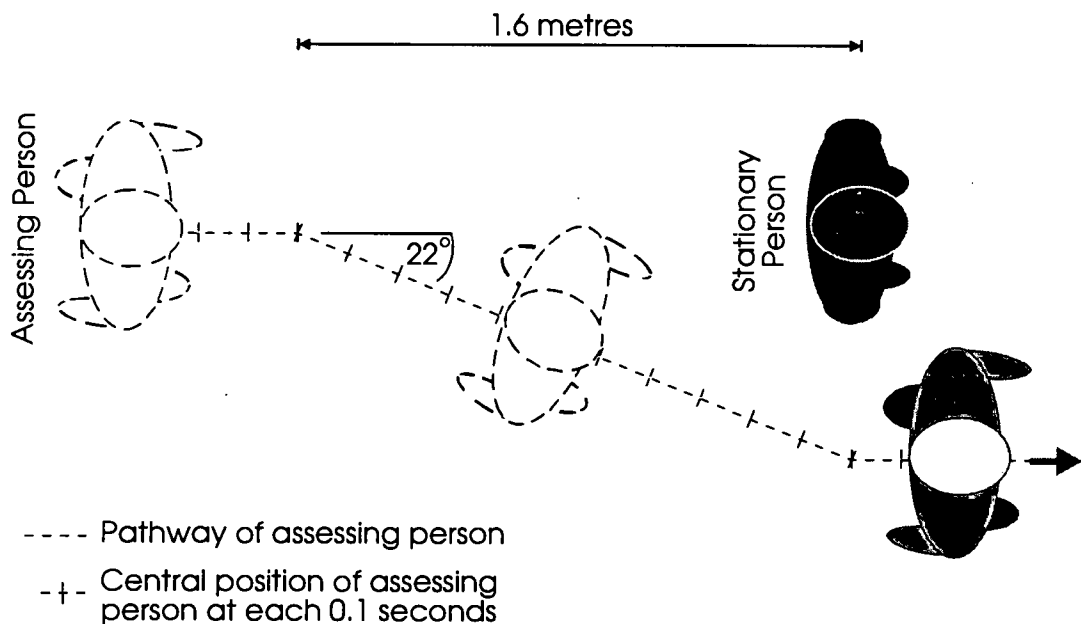


Figure 8.10. The application of the overtaking algorithm.

The adoption of this type of individual movement in SIMULEX maintains the fairly static positioning of individuals in densely packed areas, but allows overtaking when a reasonable amount of space is available for the process to take place. One encouraging aspect is that when a group of people pass through a narrow doorway leading to a fairly wide passageway, the individuals spread out across the width of the passageway. As this 'spreading out' occurs, the individual people adopt spatial

positioning configurations, relative to each other, that are reasonably similar to the circular packing configurations observed by Fruin (1971) and illustrated in Figure 8.2. It may be concluded, therefore, that the application of this process of localised route deviation by SIMULEX simulates human movement in a manner which is reasonably realistic, but may require further testing at a later date, if more specific data becomes available. The walking velocity and direction of movement of an individual is also affected by the presence of solid, immovable obstructions. The following chapter describes the simulation of further aspects of individual motion in detail.

CHAPTER 9

PHYSICAL DEFINITION OF INDIVIDUAL MOVEMENT

This section provides an overview of how the population is defined in the evacuation simulation program. Individual sections describe characteristics such as position, body size, age and orientation and explain how the data is stored in computer memory. A description is given for the mechanism by which physical contact between people is simulated, and also the contact between bodies and solid objects. Other attributes such as body shape and possible 'twisting' are also investigated.

9.0 THE NEED FOR ACCURATE PHYSICAL DEFINITION

The size and shape of the bodies of individual crowd members will affect the overall flow rate of the crowd through passageways and openings. The accurate definition of the physical dimensions of each person is therefore important and may significantly influence the general crowd motion. Most network-node computer models make large assumptions about crowd movement, and few attempt to define the physical presence of individual people, or the potential contact of their physical forms. The only computer program that defines the size and shape of individual people with any real degree of accuracy is VEGAS (Still - 1993). This program models body forms in three dimensions, to an accuracy which includes the size of feet and hands. This degree of accuracy is likely to be excessive, because it is only necessary to define certain critical body dimensions that affect general crowd movement by simulating the mutual interaction and obstruction of individual people.

Predtechenskii and Millinskii (1969) stated that the critical dimensions, when determining individual physical form, were body breadth and body depth, which could be defined by using the 'body ellipse', illustrated in Figure 3.1. A list of different body dimensions for different people is presented in Table 3.1. Fruin (1971) also recognised that shoulder breadth was significant, and some regulatory codes such as the 'Green Guide' (HMSO, 1990) use the average shoulder breadth as a basis for flow calculations applied to passageway widths. These types of calculation are usually based on a unit shoulder width between 0.55-0.6 metres (with some allowance for body sway).

The definition of the physical form of individual people by using a body ellipse can be achieved by using mathematical formulae. These formulae are defined later, in Section 9.2. The use of this type of physical definition requires significantly less computer processing time than the three-dimensional approach adopted by VEGAS. Different body forms can be defined by adjusting the mathematical equations to model people with different shoulder breadths, body depths and orientations. The definition of the tangible shape of each building occupant by plan dimensions in SIMULEX has proved to be accurate when analysing the overall flow rates of groups of people (see Chapter 11).

9.1 BODY SIZE, SHAPE AND DEFINITION

The body ellipse, as used by Predtechenskii and Millinskii, is defined by the mathematical formula;

$$x^2 + ay^2 = c^2 \quad \text{..... (9.1)}$$

where: a=shoulder breadth / body depth

c=shoulder breadth / 2

This equation is only valid for a non-rotated ellipse, of the type illustrated below in Figure 9.1. Pauls (1980) stated that the 50th percentile U.S. male possessed a body width of 0.5m, and Predtechenskii and Millinskii (1969) stated that the shoulder breadth for an adult in winter dress was 0.5m. From Table 3.1, the corresponding body depth is 0.32m. These values are therefore used as the average dimensions for body sizes in SIMULEX.

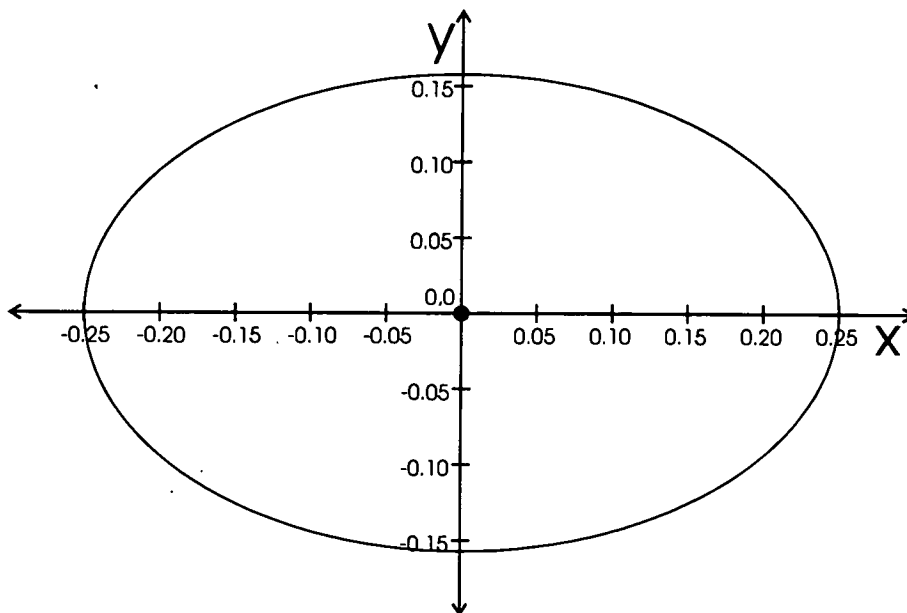


Figure 9.1. Average dimensions for the body ellipse (metres)

This non-rotated ellipse is formed by using a simple equation, which can be easily solved for x or y. However, SIMULEX accommodates the movement of individuals at any angle of travel, so an equation relating x, y and the angle of orientation is required. The equation for a rotated ellipse, below, was developed by taking Equation 9.1, and rotating the co-ordinates through θ degrees by applying trigonometric sine and cosine functions.

$$y = \frac{-2 \sin\theta \cos\theta(1-a) \pm \sqrt{[2 \sin\theta \cos\theta(1-a).x]^2 - 4(\sin^2 \theta + a \cos^2 \theta)[x^2(\cos^2 \theta + a \sin^2 \theta) - c]}}{2(\sin^2 \theta + a \cos^2 \theta)} \dots\dots\dots (9.2)$$

- where: a=shoulder breadth / body depth
- c=shoulder breadth / 2 (metres)
- θ =angle of rotation (degrees)
- x=horizontal co-ordinate, relative to centre of ellipse (metres)
- y=vertical co-ordinate, relative to centre of ellipse (metres)

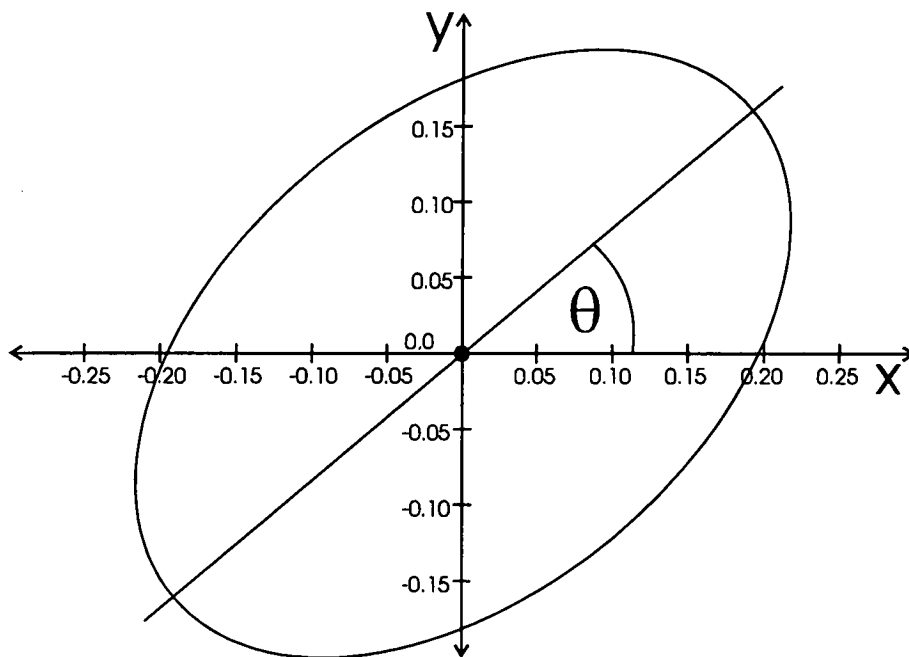


Figure 9.2. Rotating a body ellipse, by angle θ .

The formula given in Equation 9.2 is fairly complex, but can be solved almost instantaneously by computer. It is fairly simple therefore, to define the shape of a rotated body ellipse, but this is just the first step in analysing the physical contact between two bodies. To analyse whether or not two bodies are touching, the intersection points at which the outlines of the two ellipses cross, must be evaluated. This is usually done by equating the y values of the two intersection points in the Figure 9.3, below.

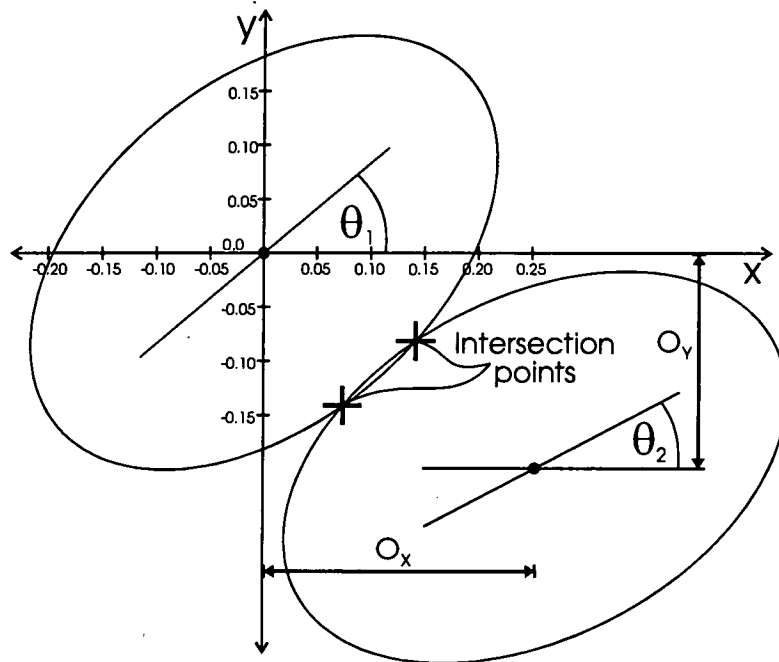


Figure 9.3. The intersection of two body ellipses.

The solution for the y values of the two intersection points is;

$$y = \frac{-F_1x \pm \sqrt{(F_1x)^2 - 4E_1(D_1x^2 - c)}}{2E_1} = \frac{-F_2(x - O_x) \pm \sqrt{[F_2(x - O_x)]^2 - 4E_2[D_2(x - O_x)^2 - c]}}{2E_2} + O_y \quad \dots\dots\dots(9.3)$$

where: θ_1, θ_2 are angles of ellipse rotation (degrees)

a =shoulder breadth / body depth c =shoulder breadth / 2 (metres)

$$D_1 = \cos^2 \theta_1 + a \sin^2 \theta_1 \qquad D_2 = \cos^2 \theta_2 + a \sin^2 \theta_2$$

$$E_1 = \sin^2 \theta_1 + a \cos^2 \theta_1 \qquad E_2 = \sin^2 \theta_2 + a \cos^2 \theta_2$$

$$F_1 = 2 \sin \theta_1 \cos \theta_1 (1 - a) \qquad F_2 = 2 \sin \theta_2 \cos \theta_2 (1 - a)$$

The solution of Equation 9.3 for a value of 'x', involves the solution of four squared complex roots which cannot be simply evaluated. The only way of solving the equation is by a method of repeated iteration, such as Newton-Rhapson. This involves a long, complex calculation process for what should be a fairly simple process of assessing whether two bodies are in contact. Mathematically, it is much easier to analyse the contact of shapes if circles are used. For this reason, SIMULEX does not use ellipses to define the body form, but instead uses three linked circles of the form described in Figure 9.4 below.

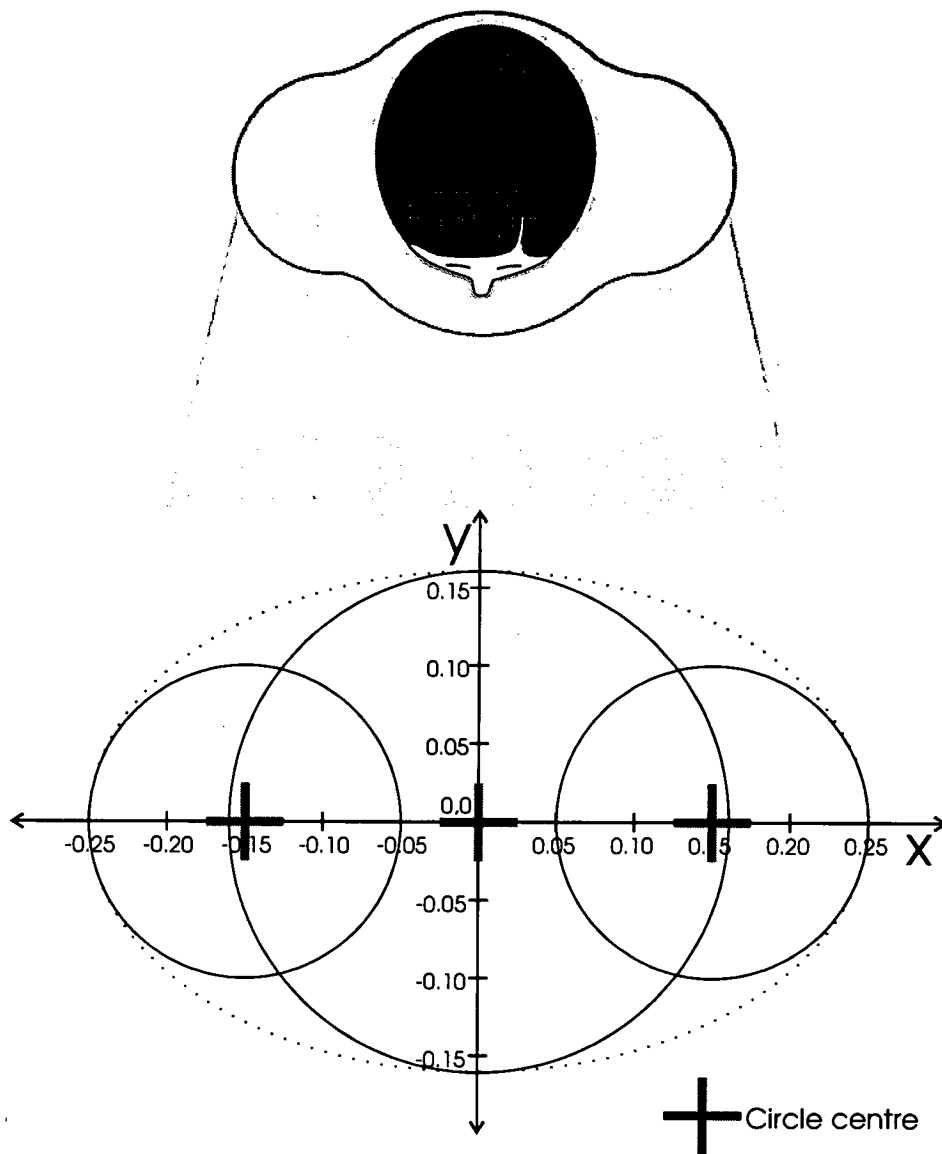


Figure 9.4. The body shape defined in SIMULEX as 3 linked circles (dims. metres).

This three circle system was used because it modelled the plan view of a body sufficiently accurately, and used no complex equations. The major advantage is that when the body form is defined in this way, the contact between two bodies can be evaluated without assessing intersection points by solving equations, but by simple distance calculations described in Section 9.6. The body dimensions are easily adjusted by changing the distance between the left and right circles, or by changing the circle radii. The other reason for adopting the three circle system was that rotating the body shape was much simpler than for the elliptical form, because the only adjustment required was to change the co-ordinate positions of the left and right circles, rather than to solve a complex mathematical equation. This process is described in Section 9.3.

9.2 CO-ORDINATE POSITIONING

SIMULEX assesses the positions of solid objects and the bodies of individual people by using floating point x and y co-ordinates, in a similar way to a graph. The co-ordinates are specified in terms of metres with an accuracy of 7 digits. Positions are therefore defined to an accuracy of thousandths of a millimetre. This accuracy might be regarded as excessive, but is required so that the sine, cosine, tangent and pythagoras calculations maintain sufficient digital accuracy for the mathematical operations to be executed in the C++ package. To reduce the positional accuracy to whole millimetres would actually incur an increase in computer processing time, and is therefore regarded as unnecessary. The body centre co-ordinates are stored in computer memory in the order shown below.

Order Number	(Person.x) number stack	(Person.y) number stack
0	X co-ordinate of person furthest from exit	Y co-ordinate of person furthest from exit
1	X co-ordinate of person 2nd furthest from exit	Y co-ordinate of person 2nd furthest from exit
:	:	:
:	:	:
$n-1$	X co-ord. of person nearest exit	Y co-ord. of person nearest exit

Table 9.1. The storage of positional co-ordinates for n people by SIMULEX.

All individual attributes are stored in this way (from the person with the longest travel distance at the bottom of the stack, to the person with the shortest travel distance at the top of the stack). This order of storage was selected so that when the movement of each individual is assessed at each time step, the assessment routines start at the top of the stack and work their way down to the bottom. People are therefore assessed in order of how far they have left to travel to exit. When this order of movement assessment is adopted, forward 'shuffling' is possible. The reason for this is that if two people are waiting in a queue that is slowly moving forward, the person in front must be assessed first, to make space for the person behind to move in. However, the speed of movement of the 'behind' person will be significantly reduced because of the proximity of the person in front.

Tests were carried out to assess the effect of the order of person assessment, and it was found that there was a slight effect on the flow rate. Assessment of people in the order [from shortest travel distance first, to longest travel distance last] achieved flow rates approximately 5% greater than [from longest travel distance first, to shortest travel distance last]. The order described in Table 9.1 was used because it produced a more realistic form of group movement.

9.3 ORIENTATION AND TWISTING

The orientation of each individual is assessed in degrees, as a 7 digit floating point number which is accurate to more than a hundredth of a degree. This accuracy is required for the same reason given for co-ordinate positioning, in the previous section. The orientation is measured relative to vertical, in the way shown in Figure 9.5, overleaf. This angular convention is the standard for C++ when using trigonometric functions such as sine and cosine, and is therefore used throughout SIMULEX when executing calculations for angular assessment.

The route assessment and overtaking routines produce an almost infinite number of angular orientations for individuals, and the orientations of different people are stored and assessed very accurately. However, the graphical representation of each individual, as an approximation of the elliptical form, is accurate to steps of 10 degrees. More accurate graphical representations are unnecessary because the difference is almost imperceptible on the monitor, which has a limited number of pixels in the viewed screen.

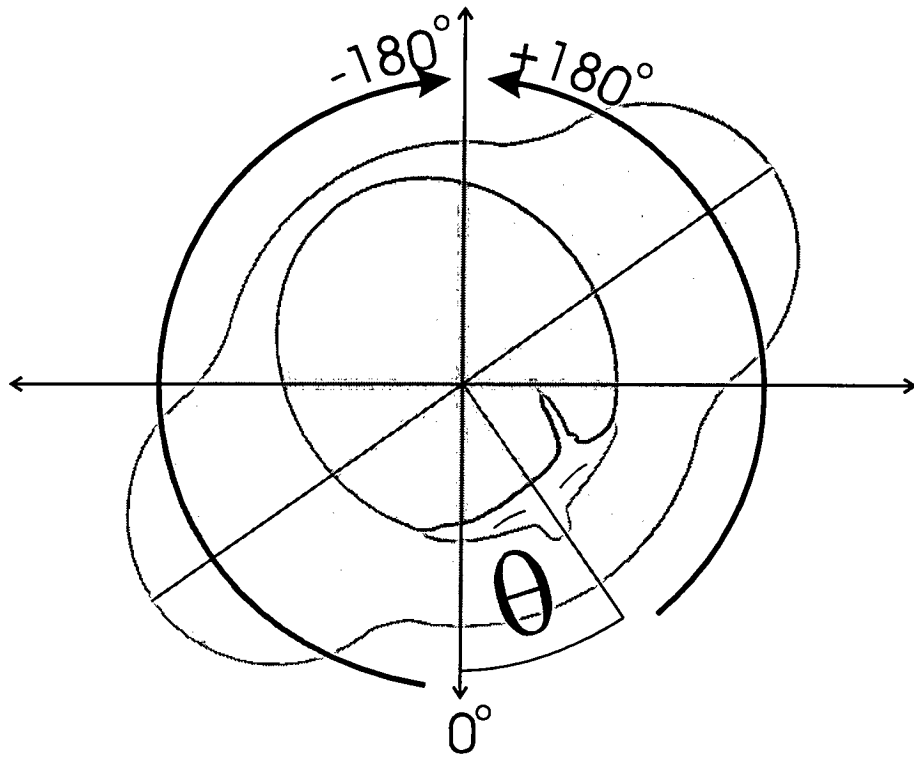


Figure 9.5. Angular orientation of the body of an individual person.

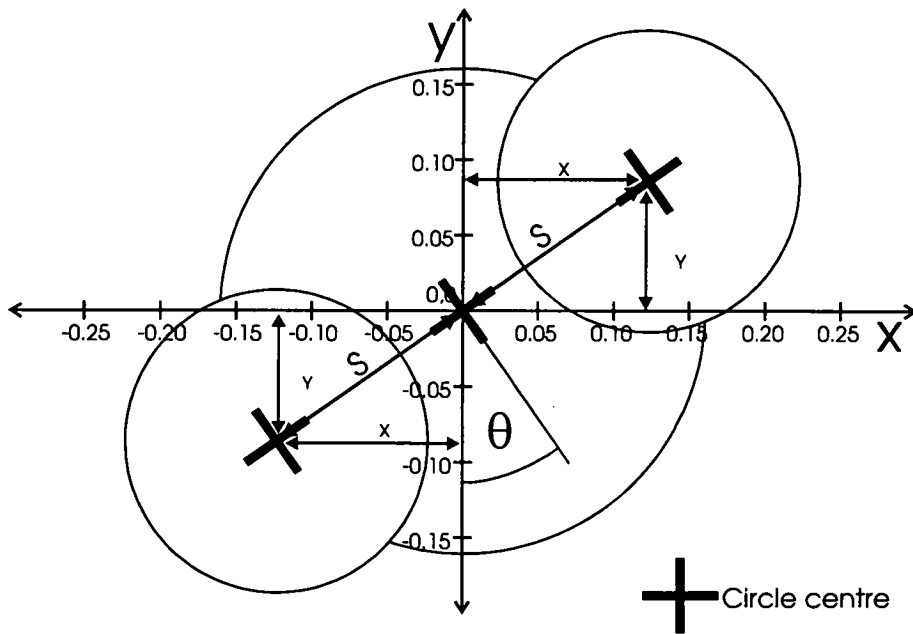


Figure 9.6. Offsets for left and right shoulder circles, for a rotated '3 circle' body.

Figure 9.6 illustrates the way in which the 'three circle' body is rotated by an angle θ . The distance from the body centre to the centre of a 'shoulder' circle, S , is 0.15m for the average body used by SIMULEX. The calculations for the offset values of the shoulder circles are detailed below.

$$L_x = S \cdot \cos\theta \quad \dots\dots\dots (9.4)$$

$$L_y = S \cdot \sin\theta \quad \dots\dots\dots (9.5)$$

$$R_x = -S \cdot \cos\theta \quad \dots\dots\dots (9.6)$$

$$R_y = -S \cdot \sin\theta \quad \dots\dots\dots (9.7)$$

where; L_x =horizontal offset from body centre to centre of left shoulder circle (m)

L_y =vertical offset from body centre to centre of left shoulder circle (m)

R_x =horizontal offset from body centre to centre of right shoulder circle (m)

R_y =vertical offset from body centre to centre of right shoulder circle (m)

θ =angle of orientation (degrees.)

S =distance from body centre to centre of either shoulder circle (m)

Although the angle of orientation is calculated from the route assessment and overtaking algorithms, it is also affected by a 'limited twist' angle. The 'limited twist' angle is the maximum angle that a body can turn through in one motion time-step. One of the conclusions of the research detailed in Chapter 10 concludes that the 'limited twist' rate is 100 degrees per second. The duration of one time-step in SIMULEX is set to 0.1 seconds, so the 'limited twist' angle used by SIMULEX is 10 degrees per time-step. The 'limited twist' angle is crucial to the realistic modelling of the movement of individual people because in reality, people cannot turn through a large angle instantaneously. When a large change in body orientation is required by the route assessment and overtaking algorithms in SIMULEX, the rotation of the body occurs by changing the angle of orientation by 10 degrees at each time step, producing a smooth, realistic turning action. SIMULEX is the only evacuation model to limit the rate of turning of the escaping individuals. Chapter 11 discusses the significance of the 'limited twist' angle on the flow rates achieved by different groups of people when they pass through restricted openings, such as doorways.

The angles of orientation of each individual, after each time step are stored in the order shown below in Table 9.2. The positions in this stack are reassessed after each time-step, and may change when one person overtakes another and hence becomes closer to an exit than the person that has been overtaken.

Order Number	(Person.angle) number stack
0	Orientation of person furthest from exit
1	Orientation of person 2nd furthest from exit
:	:
:	:
$n-2$	Orientation of person 2nd nearest to an exit
$n-1$	Orientation of person nearest to an exit

Table 9.2. The storage of angles of orientation for n people by SIMULEX.

9.4 CONTACT WITH SOLID OBJECTS

In order to simulate the movement of people in close proximity to solid objects, such as walls, SIMULEX defines a 'body circle' around each person. This 'body circle' represents the space available to a moving person without being impeded by contact with solid objects. The 'body circle' diameter is equal to the sum of the shoulder breadth and the side-to-side body sway. The average shoulder breadth used by SIMULEX is 0.5m, and the body sway is 0.1m. The body sway figure is based upon the observation by Bryan (1985) that the total lateral movement of individuals in crowded corridors could approach 101mm (50.5mm sway to both the left and right sides).

The circular form is used so that an individual who walks towards an immovable object will leave enough space to turn and select a route around the object. The route-finding algorithms will never select a direction that takes a person directly towards the middle of an obstruction, but there is sometimes a possibility that the physical space of a wall may impinge on the body form when a person moves around corners and through doorways. The contact of the 'body circle' of an individual with the surface of a wall is illustrated overleaf, in Figure 9.7. In this example, a person is moving forward towards the end of a wall, where he will

eventually turn left. The 'initial body circle' occupies the position of the person after the last time-step of movement. The 'projected body circle' represents the position that the person would move into if he walked in the optimal direction (angle of travel) at his normal walking speed.

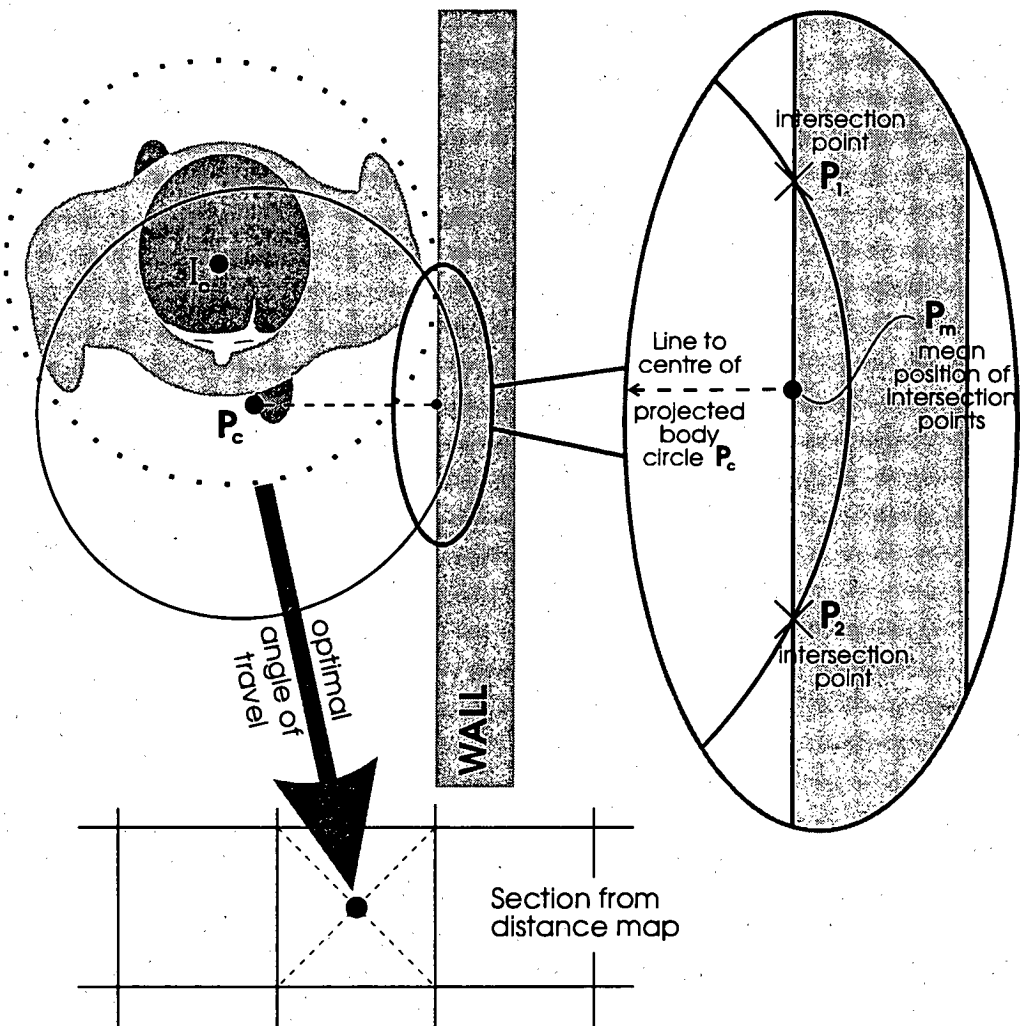
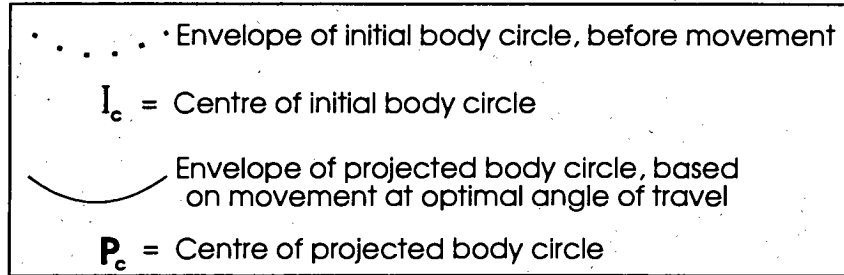
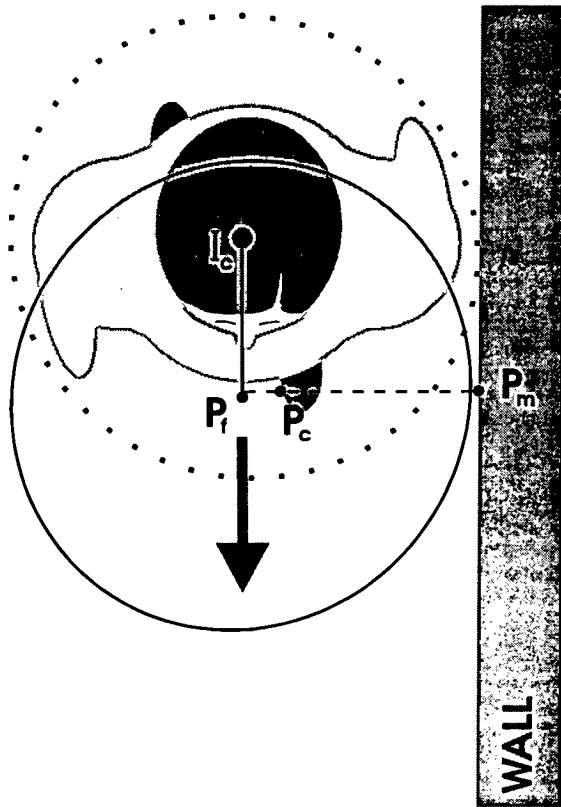


Figure 9.7. The intersection of a body circle with a 'wall unit'.



KEY:

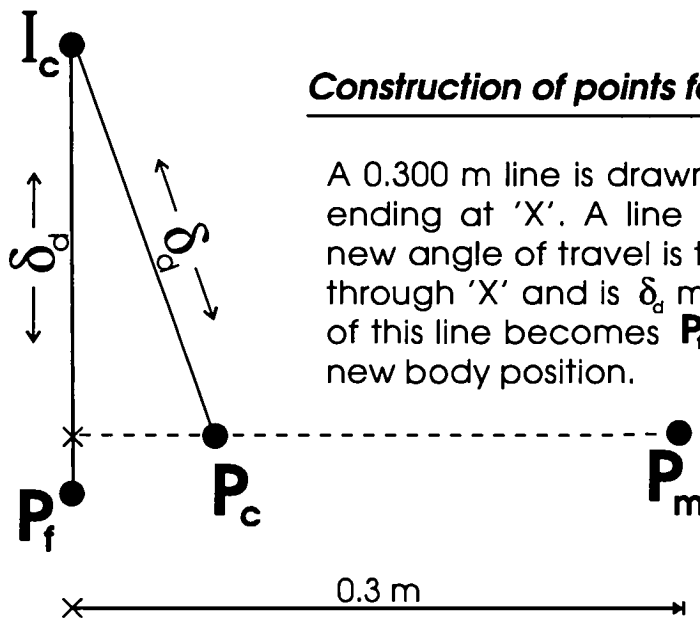
I_c = Centre of initial body position

P_c = Centre of projected body position

P_f = Final, corrected centre of body position

P_m = Mean position of intersection points

δ_d = Total travel distance over one time step



Construction of points for corrected position

A 0.300 m line is drawn from P_m through P_c ending at 'X'. A line that represents the new angle of travel is then drawn from I_c through 'X' and is δ_d metres long. The end of this line becomes P_f , the centre of the new body position.

Figure 9.8. The development of a corrected body circle position, from the mean intersection point.

The intersection points P_1 and P_2 , in the magnified section of Figure 9.7, are the points at which the projected body circle crosses the surface line of the 'wall unit'. The co-ordinate points are calculated by equating the mathematical equation of the body circle to the equation that defines the wall surface line, in order to obtain the x and y offsets from the body circle centre. The x co-ordinate of P_1 is added to the x co-ordinate of P_2 and the sum is divided by two to produce a mean x co-ordinate. This process is also applied to the y co-ordinates. The resulting mean x and y co-ordinates specify the mean position of the intersection points, P_m .

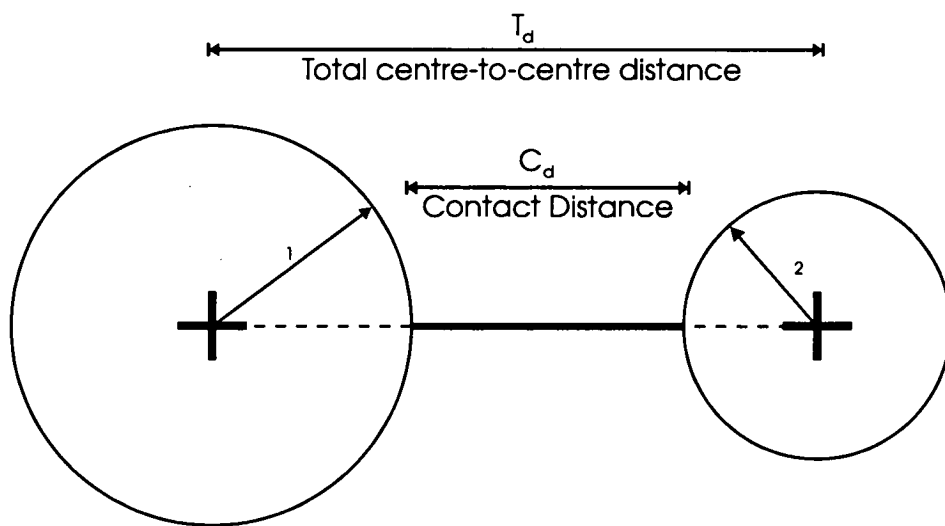
Figure 9.8 shows how the calculated points are used to correct the angle of travel of the walking person. In this diagram, three points are used to construct the line that describes this new, corrected, angle of travel. The actual calculations for this process are based on the interception of the equations of various straight lines, whose solutions are, mathematically, fairly simple. The process begins by creating a straight line that starts at P_m , passes directly through P_c , and terminates when a length of 0.3 metres is achieved. The termination point is denoted with an 'x'. The line length of 0.3 metres is equal to the radius of the body circle, which ensures that the final, corrected, body circle will just touch the surface of the wall. The 'angle of travel' line is then constructed. It originates at the centre of the initial body position, I_c , passes through the 'x' point and terminates at a length which is equal to the walking distance δ_d , covered over that one time-step. The termination of this line is the point P_f which is used as the centre of the final, corrected body position. The orientation of the line linking I_c and P_f becomes the new angle of travel and orientation for the person being assessed.

The whole positional correction process is based on simple geometrical relationships, and need only be applied once to fully correct the situation in Figure 9.7. However, if the two intersection points P_1 and P_2 are either side of a wall corner and therefore lie on two separate lines, the process must be repeated iteratively 2-3 times to obtain a correct result. The correction process is therefore repeated in all situations until the centre of the new, corrected, body position is 0.3m from the furthest extent of any immovable object. The calculations may appear complex, but only require a fairly small amount of computing time. The action of slight positional correction combined with the limited twist angle, produces a smooth, realistic simulation of the movement of an individual walking around the edges of walls and doorways, during his escape from a building. The whole algorithm should accommodate any geometry of obstruction.

The way in which all of the movement algorithms combine to simulate individual movement is described in more detail later, in Section 11.1, and a flow chart of the interaction of the various decision processes is presented in Figure 11.2.

9.5 PHYSICAL CONTACT BETWEEN INDIVIDUAL PEOPLE

The adoption of the 'three circle body' requires significantly less complex calculations than if the elliptical body form is used. The position of the centroid of each of the three circles is calculated by using the simple Equations 9.4-9.7. When these centroids have been located, the exact distance between two bodies can be calculated by simple addition and subtraction of the individual distances between points. When two circles, of different radius, are located by their centre positions, they can be analysed in terms of the direct distance between their circumferences. This distance is called the 'contact distance', and the calculation principles are illustrated below, in Figure 9.9.



To calculate the Contact Distance:

$$C_d = T_d - (R_1 + R_2)$$

Figure 9.9. The calculation of the 'contact distance' between two circles.

The 'contact distance' is equal to the total distance between centroids, minus the sum of the circle radii. The total distance, T_d , is calculated by applying the pythagoras theorem to the difference in co-ordinate positions of the two centroids. The application of the 'contact distance' calculation to the 'three circle body' is illustrated below in Figure 9.10.

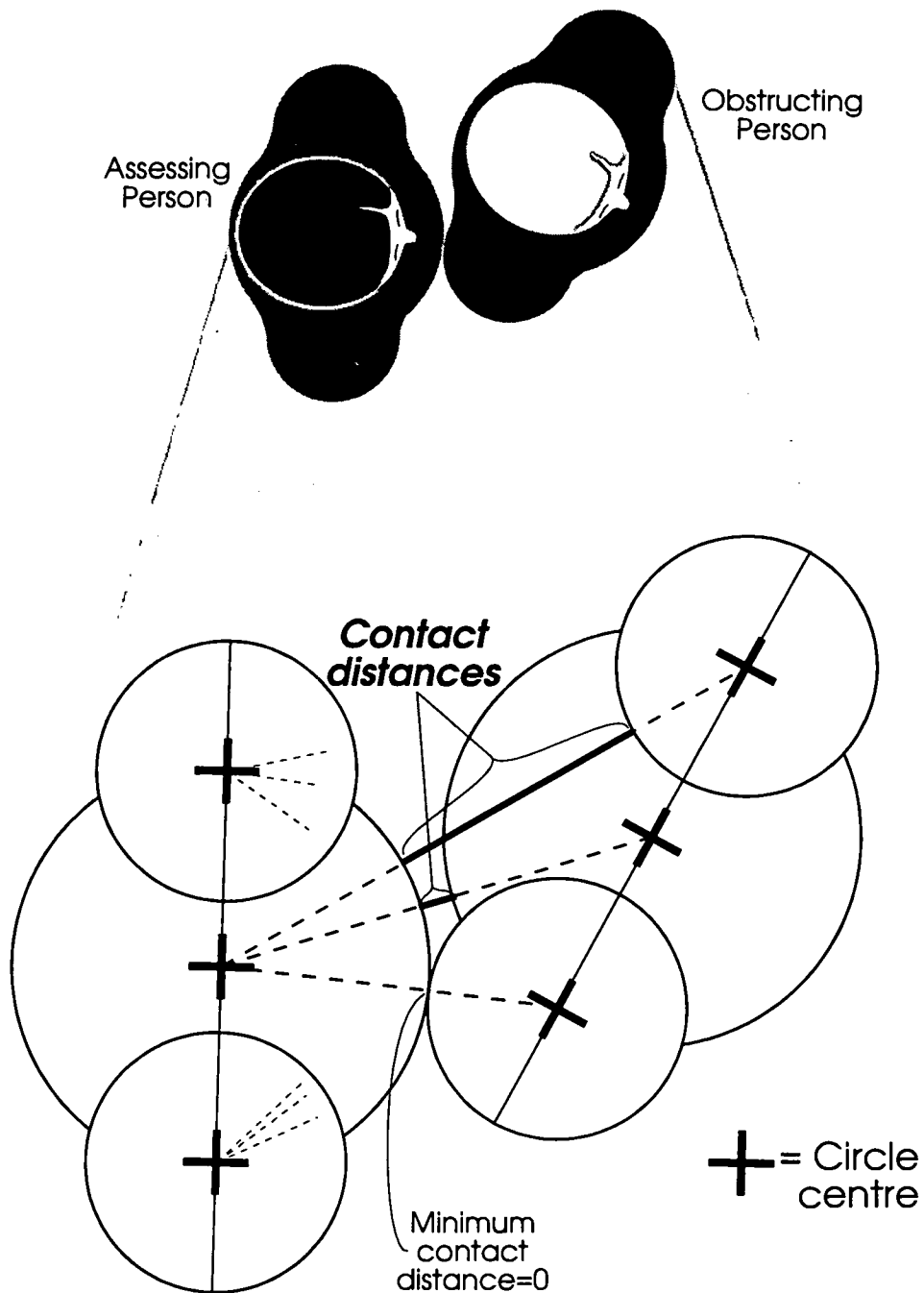


Figure 9.10. The 'contact distance' between the bodies of two individual people.

The body of each person contains three circle centres. Each calculation takes a pair of circles, one from each body, and executes the 'contact distance' calculation. Figure 9.10 shows the three contact distances from the centre circle of the assessing person. The contact distances are also calculated from each of the two shoulder circles to all three of the circles that comprise the body of the obstructing person. Hence, a total of nine contact distances are calculated. The minimum contact distance is the most important, because it represents the shortest distance between any point of the assessing person's body and any point of the body of the obstructing person. When the minimum contact distance is equal to zero, the two bodies are just in contact. If it is negative, then the body of the assessing person overlaps the space of the body of the obstructing person, and must be moved backwards by a distance equal to the minimum contact distance. Although this 'stepping backwards' facility has been written into SIMULEX, it is rarely invoked because the speed calculations cause the assessing person to stop when a minimum contact distance of zero is achieved.

The minimum contact distance is an accurate representation of the amount of forward distance that is available to the assessing person for movement. The calculation is applied to all obstructing persons in the forward projected area described in Figure 8.1. The value that is used for later calculations is the smallest 'minimum contact distance' achieved by assessing all people in the forward projected area.

9.6 ADJUSTMENTS TO WALKING VELOCITIES

The two distances that affect the walking speed of individuals are the distance to the nearest immovable object, and the minimum contact distance to the nearest person.

When SIMULEX considers the proximity of solid objects, it scans forward in a 0.25m wide strip from the circumference of the body circle of the 'assessing person' for a length equal to the threshold distance of 1.6m. The distance to the nearest immovable object in this scanned strip, O_d , is then used in Equation 9.8 overleaf. No data is available for the reduction of speed incurred as person approaches a solid object, so the threshold distance used is the same as for the velocity calculation applied to moving people. The calculation may be regarded as

substituting a block of solid, stationary individuals for a solid immovable object, and may require some future verification, although the analogy seems reasonable. A linear relationship is used to relate distance and velocity in Equation 9.8 which will return slightly pessimistic values for the velocity of an individual. The reason for this is that the analogy of a wall to a line of non-moving people has not been verified, and if SIMULEX is to be used for testing building designs, figures that are slightly pessimistic are preferable to optimistic values when designing for life safety.

$$v = V_u \times \left(\frac{O_d}{t_d - r} \right) \quad \text{where } r \leq O_d \leq t_d \quad \dots\dots\dots (9.8)$$

$$v = V_u \quad \text{where } O_d > t_d$$

where; v = impeded walking velocity (m/s)

V_u = unimpeded (normal) walking velocity (m/s)

O_d = distance from the edge of the body circle to the nearest solid object (m)

t_d = threshold distance = 1.6 (m)

r = body depth = 0.3 (m)

The walking speed calculation given in Equation 8.4 is adjusted to use the minimum contact distance, which produces a more accurate calculation, when considering the potential contact between individual people whose body forms are defined by the three circle method..

$$v = V_u \times \sin \left\{ 90 \times \left(\frac{C_d}{t_d - 2R_s} \right) \right\} \quad \text{where } 0 < C_d < 1.6 - R_s \quad \dots\dots\dots (9.9)$$

$$v = V_u \quad \text{where } C_d > 1.6 - R_s$$

where; v = impeded walking velocity (m/s)

V_u = unimpeded (normal) walking velocity (m/s)

C_d = minimum contact distance (m)

t_d = threshold distance = 1.6 (m)

R_s = radius of shoulder circle = 0.1 (m)

Equations 9.8 and 9.9 are the only two equations used by SIMULEX for the assessment of individual velocity. If both equations return a value which is less than the unimpeded walking velocity, then the lowest value is adopted.

9.7 FURTHER DEVELOPMENTS FOR PHYSICAL DEFINITION

It is intended that in the future, SIMULEX will have a facility to allow the user to specify population characteristics such as age and disability, rather than the population being randomly assigned different unimpeded walking velocities, as at present. Although this would require some adjustment to the menu systems and options, the movement algorithms would require little adjustment because most body forms can be approximated with either three or two circles that envelope the body shape. Figure 9.11 below shows how the shape of a disabled person in a self-propelled wheel chair could be approximated by a 'two circle body', instead of the 'three circle body' discussed earlier. The dimensions are based on Table 23.2 from Goldsmith (1976).

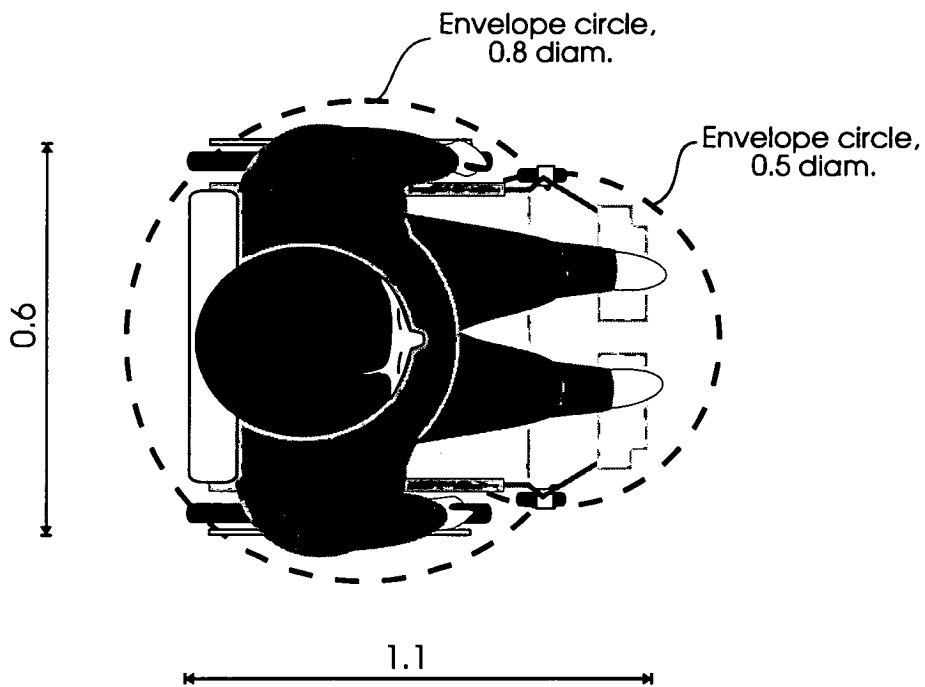


Figure 9.11. The use of 2 envelope circles to approximate the shape of a wheelchair.
Dimensions in metres.

If people in wheelchairs are to be modelled, they will be assigned slower movement velocities and a slower angle of twist per time-step, because they are far less manoeuvrable than healthy, unimpeded people. One area of prime interest would be to simulate the way in which a few people in wheelchairs impede the movement of other, upright people through constrictions such as doorways. Other possible disabled forms to consider would be people on crutches (0.95m wide), and with walking aids (0.75-0.90m wide). Different possible body shapes for healthy people are described in Table 3.1.

At present, SIMULEX usually moves people forward in the same direction as the angle of orientation of their bodies. The movement algorithms might possibly be developed to allow individuals to move sideways through narrow gaps, and pivot around the ends of their shoulders to achieve movement in very densely packed situations.

CHAPTER 10

COLLECTING DATA FOR INDIVIDUAL MOTION

In the latter stages of this project, specific parameters of movement were identified that had not been researched before. This chapter summarises the process by which people were filmed, and the way in which the footage was processed by "image analysis" to obtain data relating to parameters for individual movement.

10.0 THE NEED FOR NEW DATA

The development of SIMULEX highlighted certain parameters for the movement of individuals where no experimental data was available. The most important areas that required investigation were: (i) the maximum rate of turning (body twist) achieved by escaping individuals; and (ii) the relationship between inter-person distance and walking velocity

Previous studies, such as those carried out by Fruin (1971), Predtechenskii & Millinskii (1969), and Hankin & Wright (1958) were primarily concerned with the quantification of a moving group of people as a whole, unified 'flow', rather than as a collection of individuals with different characteristics. The general measurement of large numbers of people to obtain the average flow rate and speed is very useful for the purpose of design, but such figures are of little use to a computer package that attempts to model the movement of each individual within a group of people as accurately as possible. By carrying out a number of test runs of SIMULEX, the two parameters for individual movement, mentioned above, were shown to have a significant effect on the overall flow rate through an exit achieved by a group of escaping people.

The main reason that the movement of each individual has not been measured or modelled previously, is that the quantification and simulation of such movement requires a fairly large amount of computing power. Image analysis packages that allow individual frames of video footage to be captured as bitmapped image files, have only become readily available in recent years. It is necessary to analyse still images, captured with a short time span between them, to obtain the accuracy required for the calculation of individual parameters of motion. Although time-lapse photography could have been used before image analysis techniques were developed, the manual calculation of data from the photographs obtained would have been extremely laborious. This form of data would not have been of much use because the computing power was not available to take advantage of it. For example, SIMULEX would not be able to operate on any PC more than 5 years old because of the limitations in operating speed and available memory. SIMULEX demanded the development of specific parameters because the accurate simulation of individual motion would be impossible without a realistic data base for the algorithms involved in the simulation process.

10.1 A SUMMARY OF THE PROCESS OF DATA COLLECTION

Modern image analysis techniques facilitate the repeated capture of many individual frames from any length of video footage. Therefore, part of this project involved the filming of different groups of people as they left or entered a building space. The footage was then processed by the University Audio-Visual Department to superimpose a time label onto each frame of the film, accurate to $\frac{1}{25}$ of a second. The film was then played through the image-capture package Media Pro HiRes (on a 486 PC) to obtain a series of individual screen images in the PAL format (672×512 screen pixels). However, no standard software was available for the subsequent analysis of the images to obtain the specific motion parameters that were desired. The author therefore developed the program PICSCAN which analysed a sequence of captured screen image files, recognised the perspective of the camera shot, and then allowed the user to identify the positions of certain individuals in each frame. When the position and orientation of specific individuals had been identified in more than one screen image, PICSCAN analysed the change in positions and orientations and then calculated certain parameters for motion. These parameters were then fed into Microsoft Excel 4.0 & 5.0 to plot the relevant graphs. The graphs were originally plotted by Ricketts (1994).

Two people were involved in the data analysis described in this chapter. The author devised the methods of computer analysis, wrote the analysis tool PICSCAN, and made up one half of the 'film crew' at each test location. Gordon Ricketts, a 4th year Honours student at Edinburgh University who was the other half of the 'film crew', arranged most of the visits to film locations, used Media Pro HiRes and PICSCAN and plotted the original graphs. This process was supervised by the author. The original graphs were used in an Honours thesis (Ricketts - 1994). Some of these graphs are represented in this chapter, which is a only a brief summary of the work carried out.

Several months of work was involved in the development of the systems and processes involved in this complex, but accurate form of motion analysis.

10.2 DESCRIPTION OF VENUES

The video footage was taken between March and May 1994 at locations that were in and around the city of Edinburgh. Each venue was chosen because the passage of groups of people through constrictions, such as doorways, could be observed clearly from an elevated vantage point. The vantage points used were in positions that were reasonably unobtrusive, so that the presence of the video camera did not become a distraction for the people that were observed.

APPLETON TOWER

This location was on the ground floor of an Edinburgh University building where the exits from five lecture theatres led into an open concourse area. This concourse had one primary exit route, through a set of double doors where the exiting students converged. Footage was recorded when at least three of the lecture theatres emptied, and 100 - 200 people left through the main exit.



Figure 10.1. Captured video image from Appleton Tower footage.

The students were mostly in their first and second years of study, so individual ages ranged from 18 to 20 years old. The students were in no great hurry, and often talked to each other, so the type of movement might be described as casual, non-directed. The personal space of many students was invaded frequently by others and there were large fluctuations in walking pace when people at the front of a group stopped to open the door, and hence slowed down members that were walking immediately behind, in the following group.

EASTER ROAD STADIUM

Easter Road is the home of Hibernian Football Club. The stadium has a maximum capacity of 21,000 although the average attendance is usually 6000 to 10,000. The only suitable vantage point was from the third floor of the club's administration building, opposite the main exit and the turnstiles for the South Terracing and South Stand. Filming took place on the day of a Hibernian vs. Motherwell game at 2:45 - 3:05 p.m. when people were queuing at the turnstiles before the match started, and 4:45 - 5:00 p.m. when the crowds left the stadium.



Figure 10.2. Captured video image from Easter Road footage.

It was hoped that the number of people at the stadium would create congested movement, but this was rarely the case because of the large concourse area available for people to 'mill about' in. Either queues formed at turnstiles, or fairly unimpeded movement occurred in the area as people emerged from the exit gate. The movement might be described as slightly more aggressive than at Appleton Tower.

McEWAN HALL

This building is one of the main University halls, and was the location for a 'Behavioural Science' examination (suitable enough !) which was attended by 216 students. The camera was positioned at an ideal vantage point that looked down onto the start of the exiting staircase, which consisted of twelve shallow steps. Filming occurred over the 15 minute period that the students took to leave the main hall area.



Figure 10.3. Captured video image from McEwan Hall footage.

The students, aged between 17 and 19 were well acquainted, and talked to each other as they left. The invigilator directed the students to the exit, and stood at the top of the exit staircase for much of the period of filming. There were many

fluctuations of individual walking speeds and changes of direction due to the high crowd densities achieved. The movement was generally comfortable, directed and uni-directional. In Figure 10.3, the person standing in the centre of the staircase, facing in the opposite direction to flow is the invigilator, who was actually responsible for some of the obstruction to movement.

ROYAL LYCEUM THEATRE

The Royal Lyceum is one of the largest theatres in Edinburgh, and seats over 2000 people. It was chosen because fairly congested passageways could be observed from above, and the occupants of the building possessed a wide range of ages from around sixteen to sixty. The camera was positioned above one of the staircases that served the main exit from the Grand Circle. After the performance ended, fairly high crowd densities were observed as the occupants walked down the staircases. The flow movement was irregular, and sometime stopped completely, especially when an elderly person was negotiating the stairs. The test area that was viewed was on the level surface of an intermediate landing.

SALTIRE COURT

Saltire Court is a recently built office complex, which is occupied by a number of companies. The companies are predominantly large financial and legal practices. The offices are served by a large atrium area with 5 doors, side by side at the main entrance. For these tests, the camera was positioned on a balcony at first floor level which overlooked the exit doors. Most of the employees left the building at the end of the working day, between 4:50 and 5:20 p.m. when filming took place. People slowed down as they walked through the exits, but high crowd densities were rarely observed. The movement was casual and non-directed, although most of the people maintained a fairly brisk walking pace.

* Footage was also recorded at Craigmount High School when students walked down a staircase after leaving classes. The students became aware of the camera however, and were severely distracted by it. This footage was therefore not used for analysis.

10.3 METHOD OF DATA COLLECTION

The same method for the collection of data was used at each venue. Firstly, the 'film crew' walked around the venue to find a suitable position to locate the video camera. The optimal position of the camera was at least one storey above the area that was to be filmed, no more than 40 - 50 metres away from the edge of the 'Test Area', and unobtrusive enough not to distract the person being filmed. The camera was located at the chosen position and supported by a tripod.

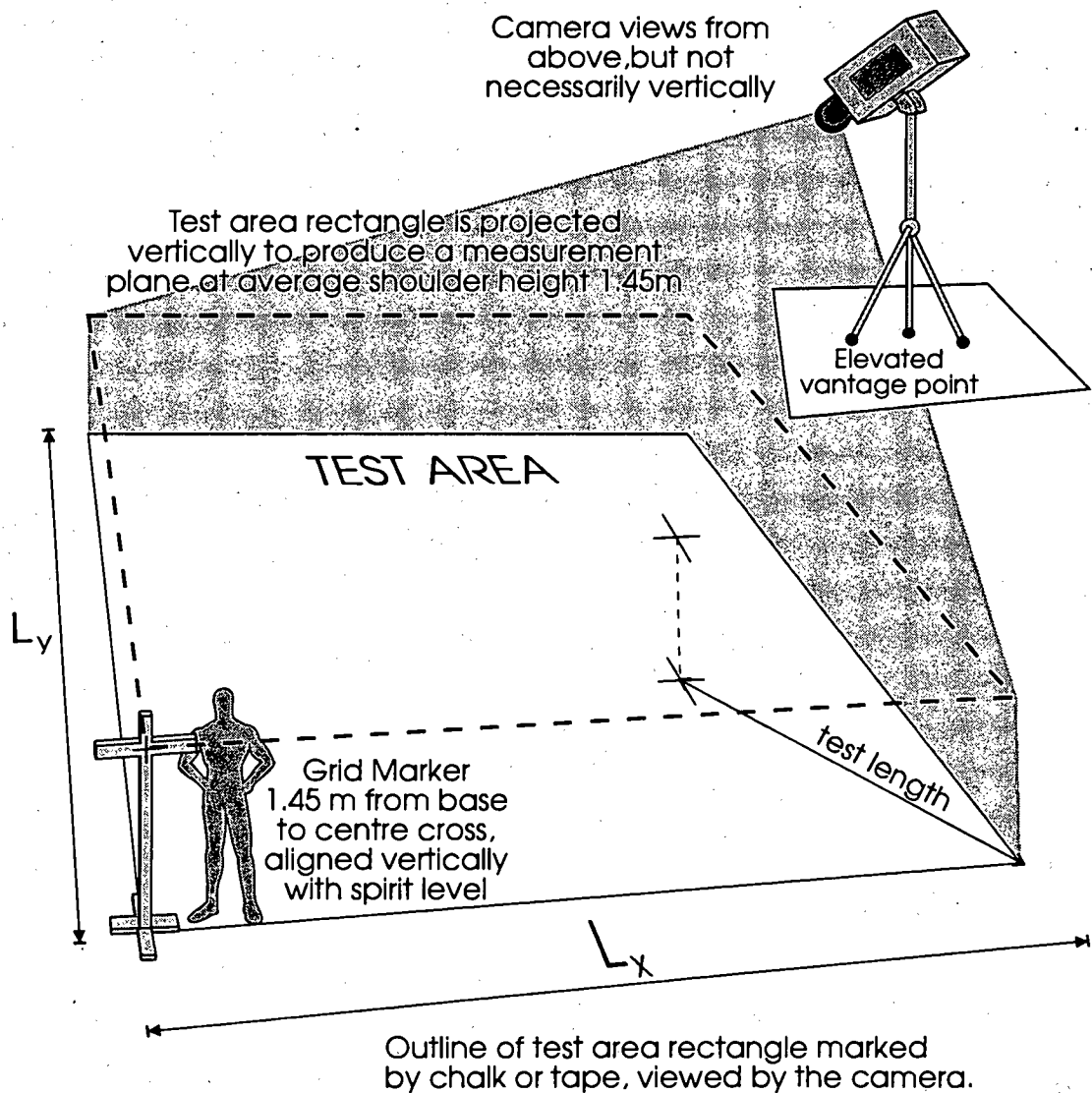


Figure 10.4 Definition of a Test Area, and projection of a measurement plane.

A rectangle was then drawn (with chalk or tape) to encompass the majority of the Test Area, and an arbitrary point within the rectangle was defined for later use. The dimensions of the rectangle were measured to the nearest mm, and the diagonals of the rectangle were also measured to ensure that all corners were square. All dimensions were noted.

One of the 'film crew' then took up his position at the camera and filmed the next stage, which was the projection of the Test Area rectangle to shoulder height. The population at most of the venues consisted of healthy, reasonably young, adults. An average height of 5'8" was therefore assumed, resulting in an average shoulder height of 1.45m. A marker, of the shape and size described in Figure 10.4 was then placed at each of the corners of the Test Area, and was also placed at the previously defined point within the rectangle. This additional point was used later to check any errors that might have occurred in the analytical calculations. When all of the five points had been identified with the marker, filming was stopped and all Test Area markings were removed.

Filming was resumed about half an hour later, when both of the 'film crew' were behind the camera, and all equipment and markings had been removed from the Test Area. The exact camera position, angle of view and percentage of 'zoom' were maintained from the previous stage, when the Test Area was defined. The duration of filming was typically 20 minutes, although the duration did vary, depending on whether the 'film crew' judged that enough suitable footage had been collected. When filming was complete, all equipment was packed away and the taped footage was taken to the University Audio-Visual Services Department, where the progression of time (to $\frac{1}{25}$ of a second) was overlaid onto the film images.

10.4 METHOD OF IMAGE ANALYSIS

The footage obtained from the five venues was initially processed by using the Media Pro HiRes package on a 486 PC to capture individual frames from the output of a standard VHS video recorder. Firstly, one frame for each of the five positions of the Test Area marker were captured and stored as a PAL format (672×512 screen pixels) bitmap file. The four corner positions were used to define the Test Area rectangle, which becomes a quadrangle when viewed in perspective. The standard construction of a perspective view is given in Figure 10.5.

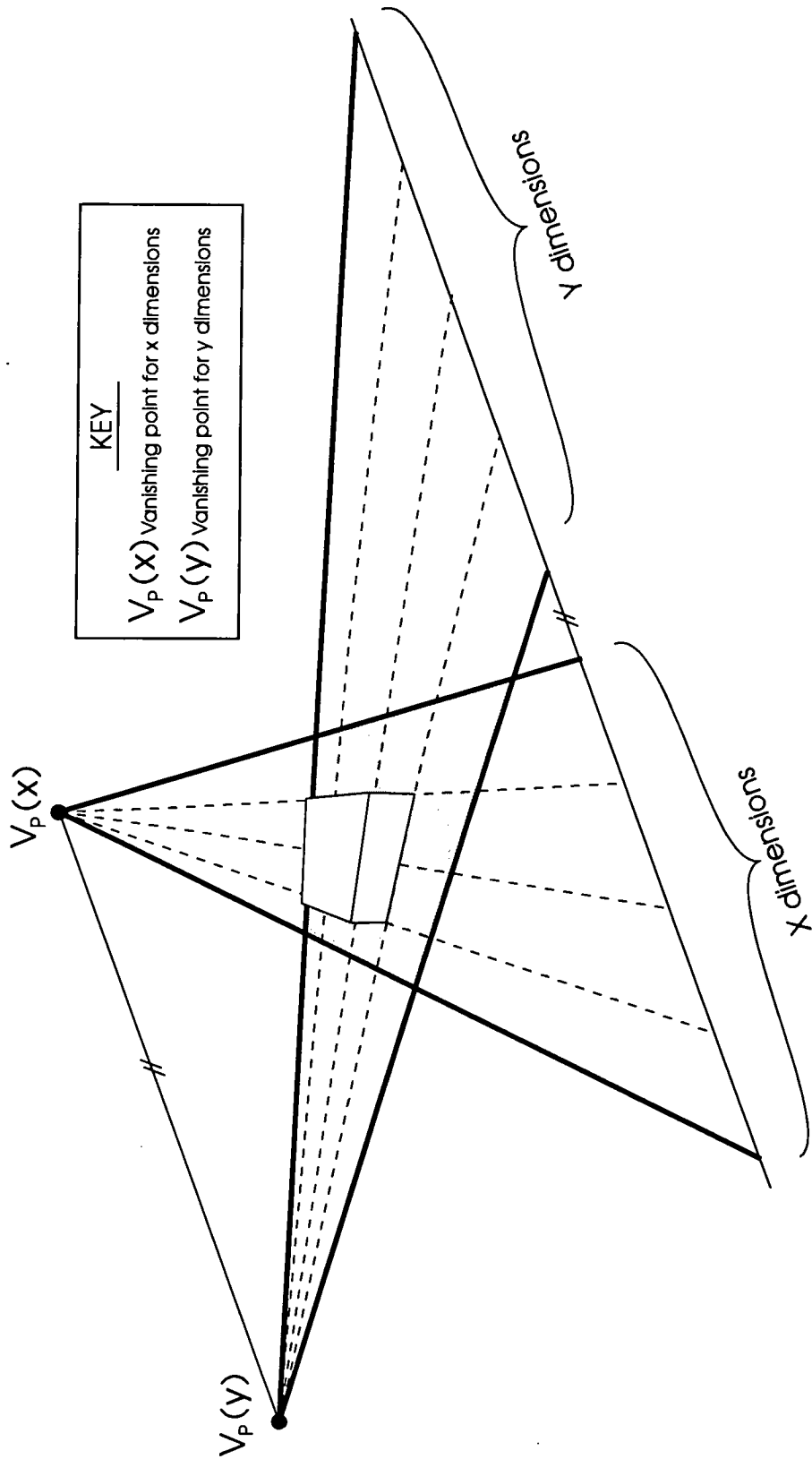


Figure 10.5 Construction of perspective with linear dimensions.

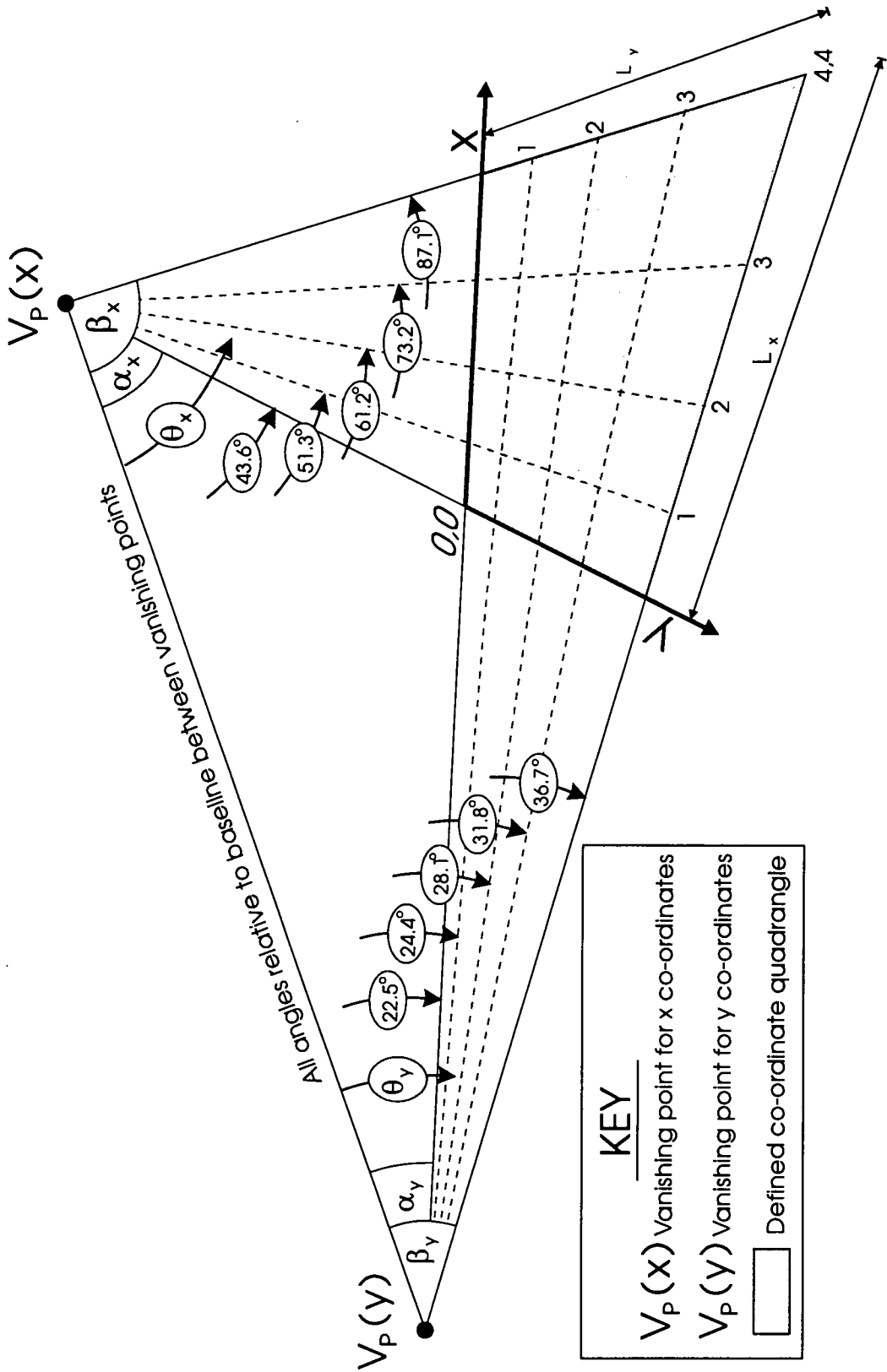


Figure 10.6 Perspective analysis by angular calculation (with example values)

The standard construction of perspective views for dimensional specification uses the projection of straight lines to two vanishing points. The dimensions are initially measured and marked onto a line which is parallel to the line linking the vanishing points. This form of line projection is suitable when constructing drawings by hand, but requires complex mathematical equations if it is to be used by a computer program.

The computer program PICSCAN, which was written specifically for this project, uses the angular technique described in Figure 10.6 instead of the standard method of perspective construction. The method of reducing a perspective form to a series of angles which are subtended from two vanishing points, significantly reduces the complexity of the calculations that are executed by the program. The method was devised by the author and produces exact perspective values.

The principles of the angular calculation method are, geometrically, fairly simple. The positions of the four corners of the Test Area quadrangle are identified at shoulder height by using the captured screen image for each position. Each corner point is fixed on the screen by locating the cross near the top of the vertical marker. The four lines that link the corner points of the quadrangle are then defined. These lines are projected back to form two intersection points. The two intersection points become the perspective vanishing points. When the vanishing points have been located, and the quadrangle dimensions known, then the angular calculations can be executed. The equations for these calculations are given below.

$$C_x = \frac{L_x}{\left(\frac{1}{\tan \alpha_x} - \frac{1}{\tan \beta_x} \right)} \quad \text{..... (10.1)}$$

$$C_y = \frac{L_y}{\left(\frac{1}{\tan \alpha_y} - \frac{1}{\tan \beta_y} \right)} \quad \text{..... (10.2)}$$

$$x = C_x \left(\frac{1}{\tan \alpha_x} - \frac{1}{\tan \theta_x} \right) \quad \text{..... (10.3)}$$

$$y = C_y \left(\frac{1}{\tan \alpha_y} - \frac{1}{\tan \theta_y} \right) \quad \text{..... (10.4)}$$

where: C_x = scaling factor for x dimensions (m.)

L_x = total length of x dimensions described between α_x and β_x (m.)

α_x = angle subtended at $V_p(x)$ between baseline and zero x dimension (deg.)

β_x = angle subtended at $V_p(x)$ between baseline and final x dimension (deg.)

x = x dimensional co-ordinate value (m.)

θ_x = angle subtended at $V_p(x)$ between baseline and a co-ordinate point (deg.)

C_y = scaling factor for y dimensions (m.)

L_y = total length of y dimensions described between α_y and β_y (m.)

α_y = angle subtended at $V_p(y)$ between baseline and zero y dimension (deg.)

β_y = angle subtended at $V_p(y)$ between baseline and final y dimension (deg.)

y = y dimensional co-ordinate value (m.)

θ_y = angle subtended at $V_p(y)$ between baseline and a co-ordinate point (deg.)

Example: Calculation of the 'y' co-ordinate in Figure 10.6, for $\theta_x = 73.2^\circ$

$$C_y = \frac{4.0}{\left(\frac{1}{\tan 22.5} - \frac{1}{\tan 36.7} \right)} = 3.73 \text{ m} \quad \text{..... (10.5)}$$

$$y = 3.73 \times \left(\frac{1}{\tan 22.5} - \frac{1}{\tan 31.8} \right) = 2.99 \text{ m} \quad \text{..... (10.6)}$$

The measured value of 'y' is 3.00. The accuracy of the final value of 2.99 m was restricted by the fact that the angles were only defined with one decimal place. PICSCAN uses an accuracy of 5 decimal places. When PICSCAN is executed, C_x and C_y are calculated at the outset. All further co-ordinate calculations can then be carried out by using one simple equation (Equation 10.3, or 10.4). In this way, any

position can be located in the Test Area with two co-ordinates (x and y), which are relative to the 0,0 corner position. These positional calculations are used later to ascertain the positions and angles of orientation of individual people, at specific times.

10.5 USING PICSCAN

All of the screen image files produced by Media Pro HiRes were converted to black and white image bitmaps to reduce the size of each file from 0.35 Mb to 0.04 Mb, so that a large number of images could be stored onto the hard disk. For each location, the first four screen images converted were those that allowed the corner points of the Test Area to be defined. Although this produced some degradation of image quality, individual people could still be identified sufficiently accurately for the purposes of these analyses. Each corner point was located by clicking onto the marker cross with the user-controlled 'mouse'. This process is illustrated in the PICSCAN screen display shown below in Figure 10.7.



Figure 10.7 Screen display from PICSCAN, showing the construction of a test area.

When the program is used, the 'Adjust Perspective' option saves any changes to the perspective quadrangle onto the hard disk, so that the positions and factors calculated are automatically loaded by PICSCAN for future analysis. The accuracy of the perspective calculations are then checked by 'clicking onto' the marker at the test point, and checking the calculated 'test length' to that measured on site. This type of accuracy check was done because the percentage errors were different for each screen position at a specific location. As points are identified further away from the camera position, the percentage error increases, as the same 'real' length is viewed as a shorter length in the two dimensional perspective image file. The percentage errors for these test lengths were found to be typically +/- 5%.

When the perspective quadrangle has been defined and checked, PICSCAN allows the user to process a sequence of still, black and white, screen images. When each image is loaded from hard disk, the user locates a 'base' person and the nearest 'obstructing' person by positioning a 'T' shaped 'body marker' on the shoulders of each individuals that is to be assessed. The positioning of these 'body markers' is illustrated in Figure 10.8, below.



Figure 10.8 Screen display from PICSCAN, showing the identification of positions.
White marker = 'Base' Person : Black marker = 'Obstructing' Person

The long side of the body marker is positioned across each person's shoulders, and is fixed in position by clicking the left mouse button. The marker is then rotated by moving the mouse and holding down the right mouse button, until the stem of the marker points in the forward direction of that person. More than one 'obstructing person' can be identified if the user desires. The time value of that screen image is also entered. The next screen image, recorded 0.33 seconds (8 frames) later is then loaded, and the process of identifying the same individuals repeated for their new positions. The time value on the second screen is also entered by the user.

The time duration of 0.33 seconds is chosen because it allows the accurate analysis of the changes in body position, but produced forward 'steps' large enough to be accurately measured on the screen. When the new positions have been located, and the time duration between screen images specified, then a number of parameters can be computed. PICSCAN calculates the velocity, distance travelled, average angle of orientation, and rate of body twist of each person. The distance between the base person and the obstructing person is also calculated. All data is saved as a text file on the hard disk. The output data from PICSCAN is contained in Appendix 3, at the end of this thesis.

The method of processing described above, was applied to all five venues. The data obtained was then used to plot the desired graphs, using Microsoft Excel 4.0.

10.6 RESULTS AND DISCUSSION

The development of SIMULEX for realistic simulation required specific data for rates of body twist and the relationship between inter-person distance and individual velocity. These were therefore the first areas to be investigated using the data obtained by PICSCAN from analysing the movement of people at the five venues. Each venue used a different size of Test Area and contained people with different characteristics. Unfortunately, all of the observations were of people who were walking in 'comfortable' conditions, and with no extraordinary degree of haste. Although there were some differences in the general psychological state of the people at each venue, all of the data collected may generally be regarded as applying to individual movement under comfortable conditions with no threat of danger, and certainly no risk to life. The parameters obtained should be applicable to the

simulation of individual movement of people leaving a building after hearing a normal fire alarm bell, when there is no clear evidence of any threat to life. The graphs presented in this section are a representative selection of the many that were plotted by Ricketts (1994) in his original Honours project. 'Best fit' curves have also been added by the author.

The Relationship between Velocity and Inter-person Distance:

This relationship was first investigated, at length, in Chapter 8 by converting the velocity/density data from different sources to velocity/distance data that could be used by SIMULEX. The velocity/distance data was therefore based on certain assumptions about the packing configuration and inter-person spacing of individuals moving in a tested group. It was important to measure the relationship between individual velocity and inter-person distance directly, so that there were no pre-judged assumptions about the movement, and to check whether the graphs used by SIMULEX were realistic.

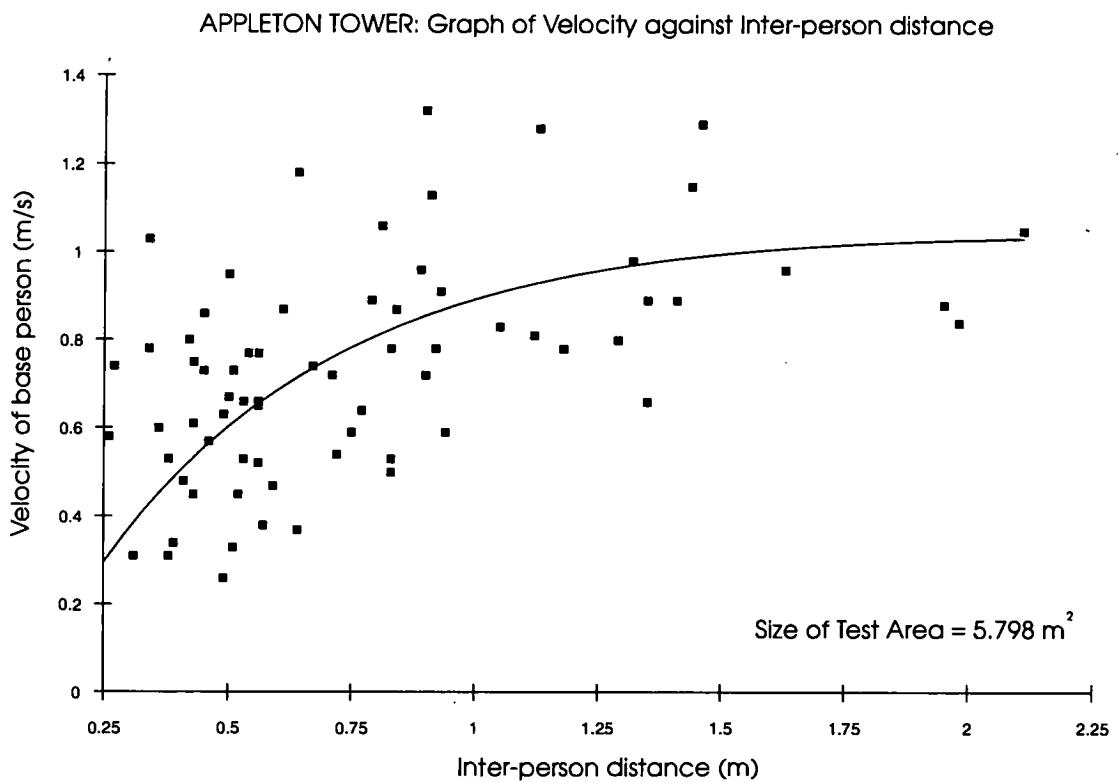


Figure 10.9. Graph of Velocity against Inter-person distance at Appleton Tower

Figure 10.9, on the previous page, and 10.10 below are typical examples of the graphs that were obtained. The general shape of the 'best fit' curves are similar to the graphical form derived previously in Figure 8.4, from other sources. The Appleton Tower graph however, indicates that movement may still be possible for inter-person distances as low as 0.25 metres. This is possibly due to the fact that the students at Appleton Tower were well acquainted and generally had quite slim bodies, with body depths which were possibly less than the normal values of 0.25 to 0.3 metres. The Saltire Court data could not be used to confidently predict whether or not movement was still possible at very low inter-person distances. It does however, indicate that if such movement was possible, it would probably be extremely slow and irregular.

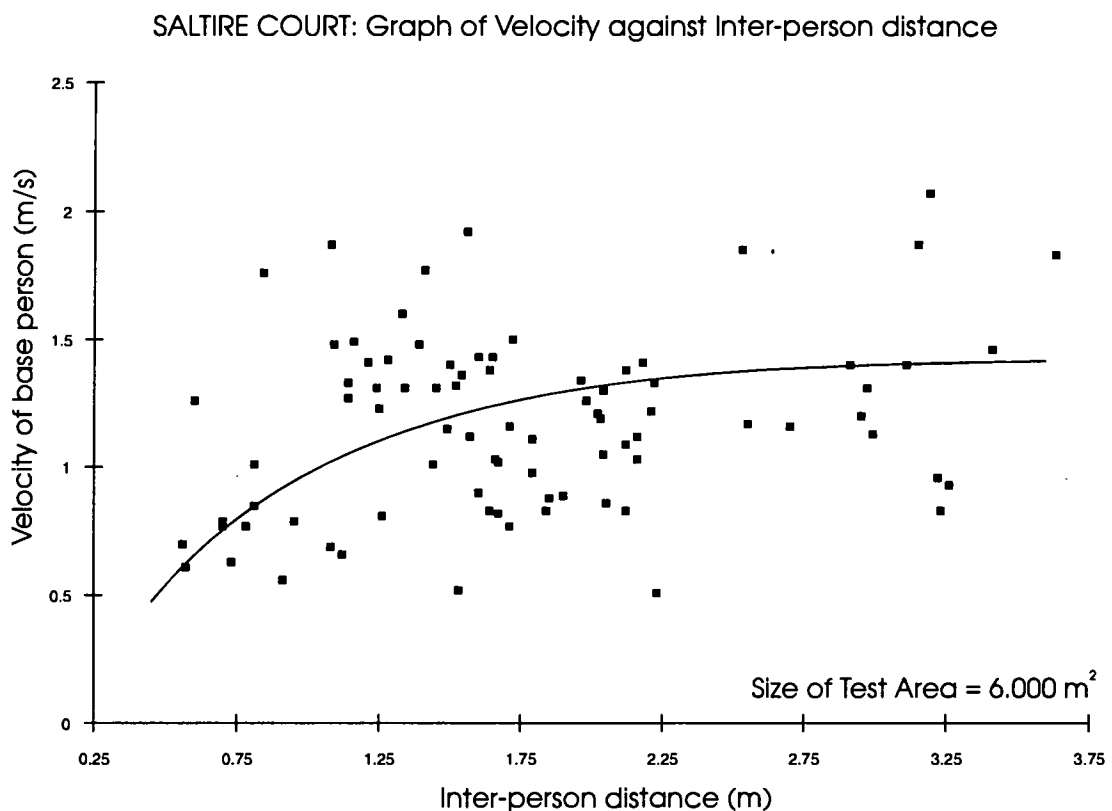


Figure 10.10 Graph of Velocity against Inter-person distance at Saltire Court

Both graphs contain a wide range of data points, which sometimes made the construction of 'best fit' lines rather difficult. The range of data points encountered is

not unusual when measuring the movement of people in close proximity to each other. For example, the original data points plotted by Predtechenskii & Millinskii (1969) for values relating average speed to crowd density displayed almost as much percentage variation from a best fit line, as the variation observed for the data points in the graphs above. A large range of data was fully expected because each individual person has a different normal walking speed and body shape. Also, at Appleton Tower and Saltire court, some people carried baggage such as brief-cases or rucksacks, which might affect movement.

The relationship between Flow Rate and Density:

The data for this relationship was obtained in a different way from that described earlier in this chapter. Each data point was obtained by counting the number of people in the Test Area, both at the start and at the end of a five second period. The number of people leaving the Test Area through an identified passageway, over the five second period was also noted.

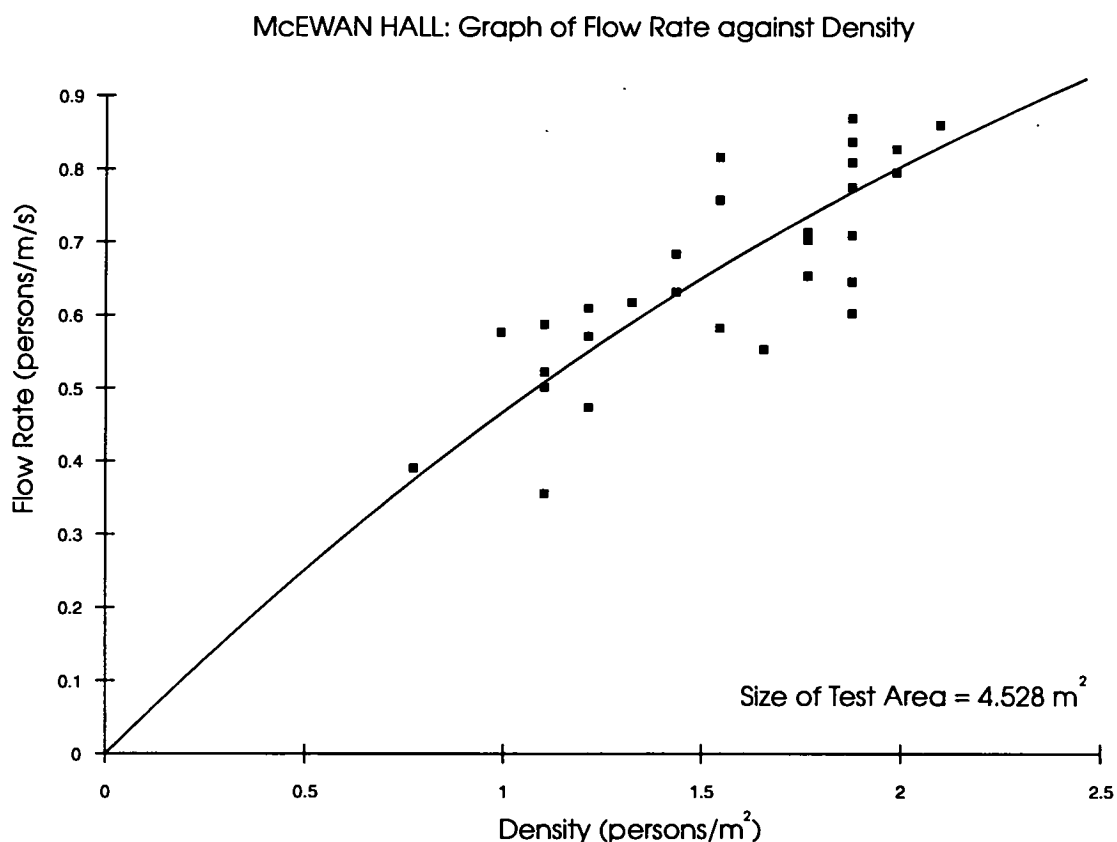


Figure 10.11 Graph of Flow Rate against Density at McEwan Hall

The average number of people in the Test Area, and the size of the Test Area were used to calculate the average density. This average density represented the density of the group at the approach to the exit. The flow rate was calculated by dividing the number of people that left, by the width of the exit and by five seconds to obtain the value in terms of number of persons per metre width per second.

The results obtained from this form of analysis produced graphs that were slightly different from the majority of graphical curves produced by other researchers, which were illustrated previously in Figure 8.7. This is primarily due to the different geometries of the space in which the people were moving. Both of the graphs in Figure 10.11 and 10.12 represent the movement of individuals on a level surface at the approach to a set of steps on a staircase. The graphs show that for this spatial geometry, there is no early peak of flow at 1.5 persons/m². The flow rate increases almost linearly as density increases. This flow behaviour is similar to that observed by Predtechenskii & Millinskii, in the 'comfortable' category.

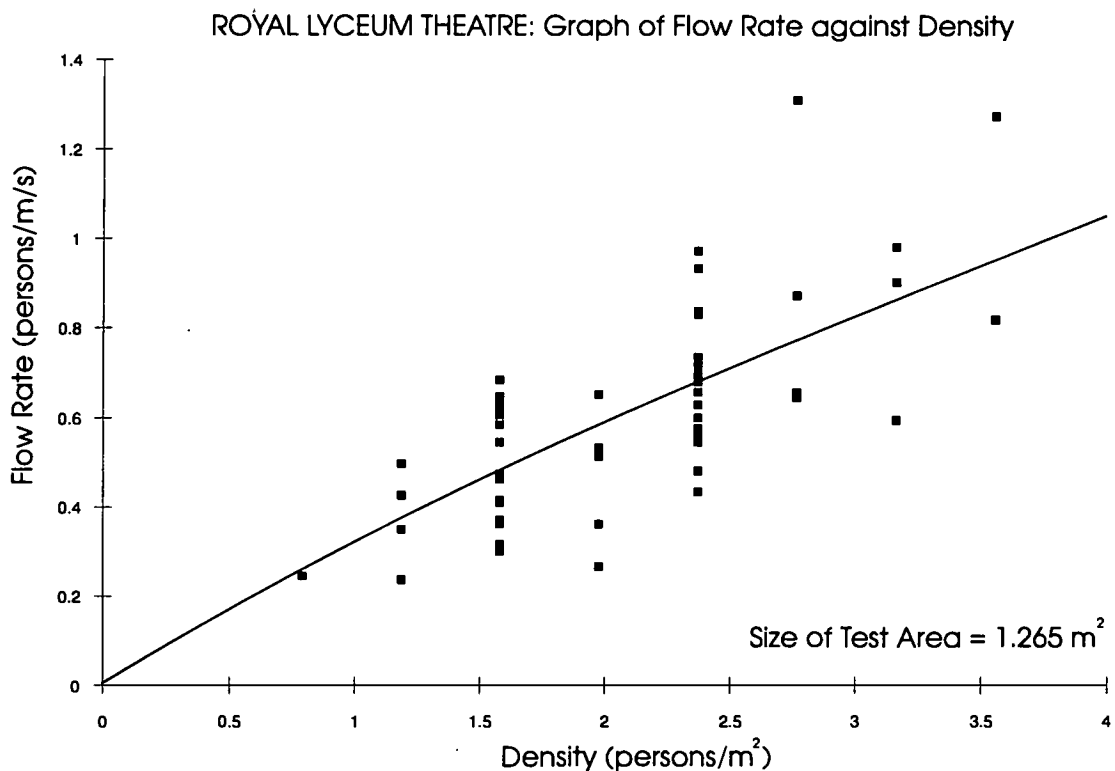


Figure 10.12 Graph of Flow Rate against Density at The Royal Lyceum Theatre
 - data obtained for movement on a staircase landing.

The flow rates observed were quite low because the people in the Test Areas were not under any psychological pressure to escape, and their movement was impeded by the presence of others on the staircase. Although the flow/density graphs were plotted for the Appleton Tower and Saltire Court, the average densities over the Test Areas rarely exceeded 1 person/m², and the data obtained was of little use. At the Easter Road stadium, people either queued at turnstiles (before the match) or emerged from exits at low crowd densities (after the match), so the images were of little use when analysing the relationship between group density and flow rate.

General parameters for movement at all five venues:

PICSCAN was used primarily to analyse movement at the five venues in order to obtain values for individual rates of forward motion, and rates of body twist. These figures are summarised in Figure 10.13 below, and Figure 10.14 overleaf, in the form of two 'bar charts'.

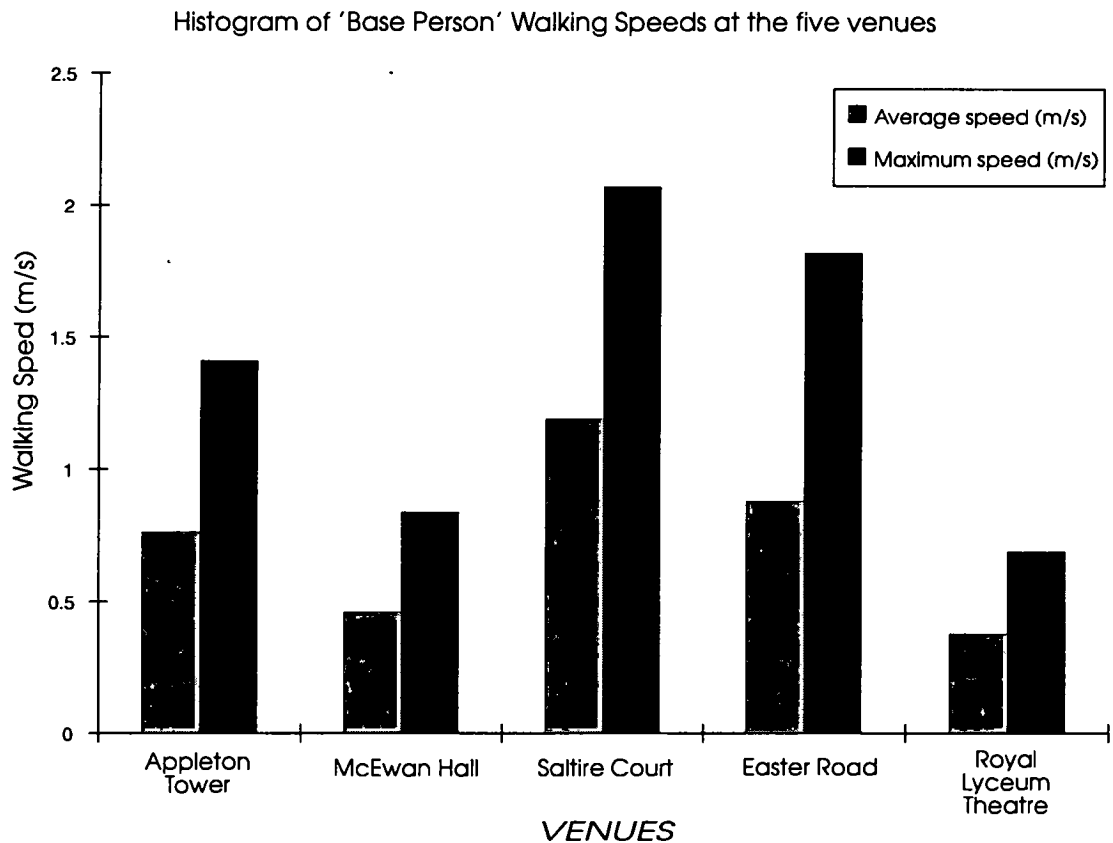


Figure 10.13 Summary of Walking Speeds at the five venues

Histogram of Average and Maximum 'Body Twist' at the five venues.

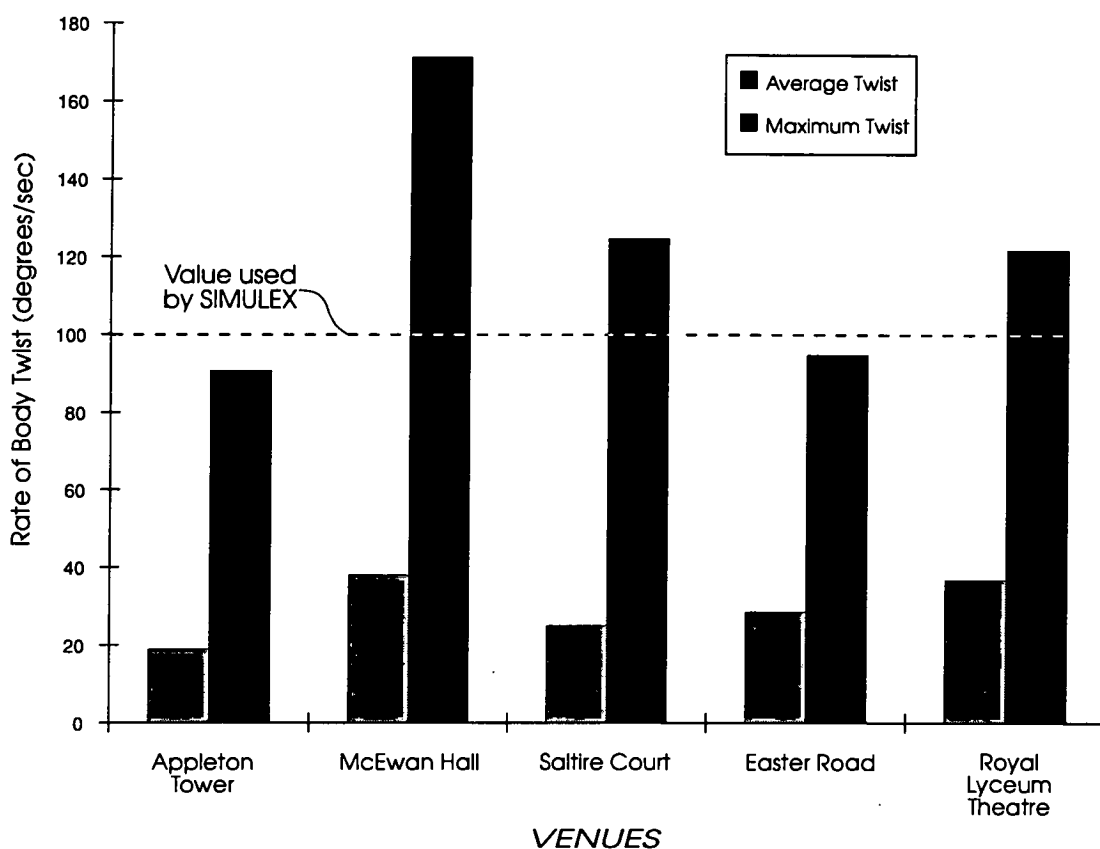


Figure 10.14 Summary of 'Body Twist' at the five venues.

The results of the analyses generally conformed to the expected mathematical trends. At locations where the concentration of people per unit area was low, such as at Saltire Court, the walking speeds of individuals was quite high, and there was generally little obstruction to movement. In such areas, the average rate of body twist was also quite low, indicating that individuals did not have to change direction very often, because people did not often invade the personal space of others. In contrast, the locations where high crowd densities were observed, such as at the McEwan Hall, individual walking speeds were significantly slower, and the average rate of body twist was much higher.

The 'maximum' values that are shown do not indicate any particular trends, simply because they represent exceptional values, rather than the overall pattern of movement. They are however, very useful when ascertaining the maximum limits for

individual motion. The maximum rate of body twist at any venue was observed to be 170° /second, which was regarded as an exceptional value. The exact average of the five maximum values is 118° /second, but the slightly more conservative value of 100° /second was used by SIMULEX. This conservative figure was used because it has always been the intention to use SIMULEX for design, and for the purposes of safe design it was preferable to simulate slightly less mobile individuals than to simulate people who were extraordinarily athletic.

SIMULEX assigns a range of 'maximum' unimpeded walking speeds to individuals from between 0.8 to 1.7m/s, based on the data from Ando et al (1988). These values seem reasonable when compared to the values in Figure 10.13. Only one exceptional maximum value, at Saltire Court, exceeds this range. The low values for walking speeds at the McEwan Hall reflect the high crowd densities, and the fact that the motion of almost every person was significantly impeded by the proximity of others.

The two most important conclusions from this area of research were that the relationship between inter-person distance and individual velocity (derived previously in Figure 8.4) was sufficiently realistic, and that a maximum rate of 100° /second was appropriate for limiting the rate at which the body of each simulated 'person' could twist. The techniques developed for this form of perspective-image analysis will be used in the future at Edinburgh University to measure forms of motion that were not previously quantifiable to any accuracy, such as the rapid rate of flame spread across a burning material.

CHAPTER 11

SIMULEX: A Summary of Systems, Processes and Application

The chapter details the process by which SIMULEX integrates the various analytical algorithms, discussed individually in Chapters 5 to 9. The application of SIMULEX to specific problems is described and a series of tests are executed to assess the accuracy and overall performance of the system. The application of the program to the design of a department store is also illustrated.

11.0 THE PRIMARY FUNCTIONS OF SIMULEX

The program DRAWPLAN allows the user to define the building plan, and GRIDFORM constructs the distance map for the building space. Chapter 6 described the individual algorithms that comprise these programs, and the final output files which are required by SIMULEX for complete and successful operation. The various techniques described in Chapters 7 to 9 are implemented by SIMULEX, the primary functions of which are to assess travel distances, define the building population and simulate the evacuation of the occupants. These functions allow user-defined input and display results on three distinct screens, that are processed in the order shown in Figure 11.1, overleaf. The overall performance of the functions that produce each screen are described below.

11.0.1 SCREEN 1 - "Assess travel distances"

In this first screen, SIMULEX uses the pre-defined building plan and the distance map to display information about travel distances. The two options available to the user are "Point Travel Distance" and "Maximum Travel Distance". The first option, "Point Travel Distance", allows the user to specify any position on the building plan with the computer mouse. The second option "Maximum Travel Distance" scans the entire distance map to find the highest value, which therefore represents the position in the building that is most remote from any exit. When the initial starting position has been defined by either option, SIMULEX uses the wayfinding techniques described in Chapter 7 to plot the optimal escape route out of the building. The travel distance from the initial starting point is displayed in metres, and is obtained from the value contained by the distance map at that point. The typical accuracy of travel distances is 0 to +3%, when the distance map is based on the distance array illustrated in Figure 6.11.

Travel distance is an essential feature of building design. ADB1 defines travel distance as "The actual distance to be travelled by a person from any point within the floor area to the nearest storey exit, having regard to the layout of walls, partitions and fittings". The specified maximum values for travel distance in enclosed buildings range from 9 metres to 45 metres, depending on building usage and number of escape routes.

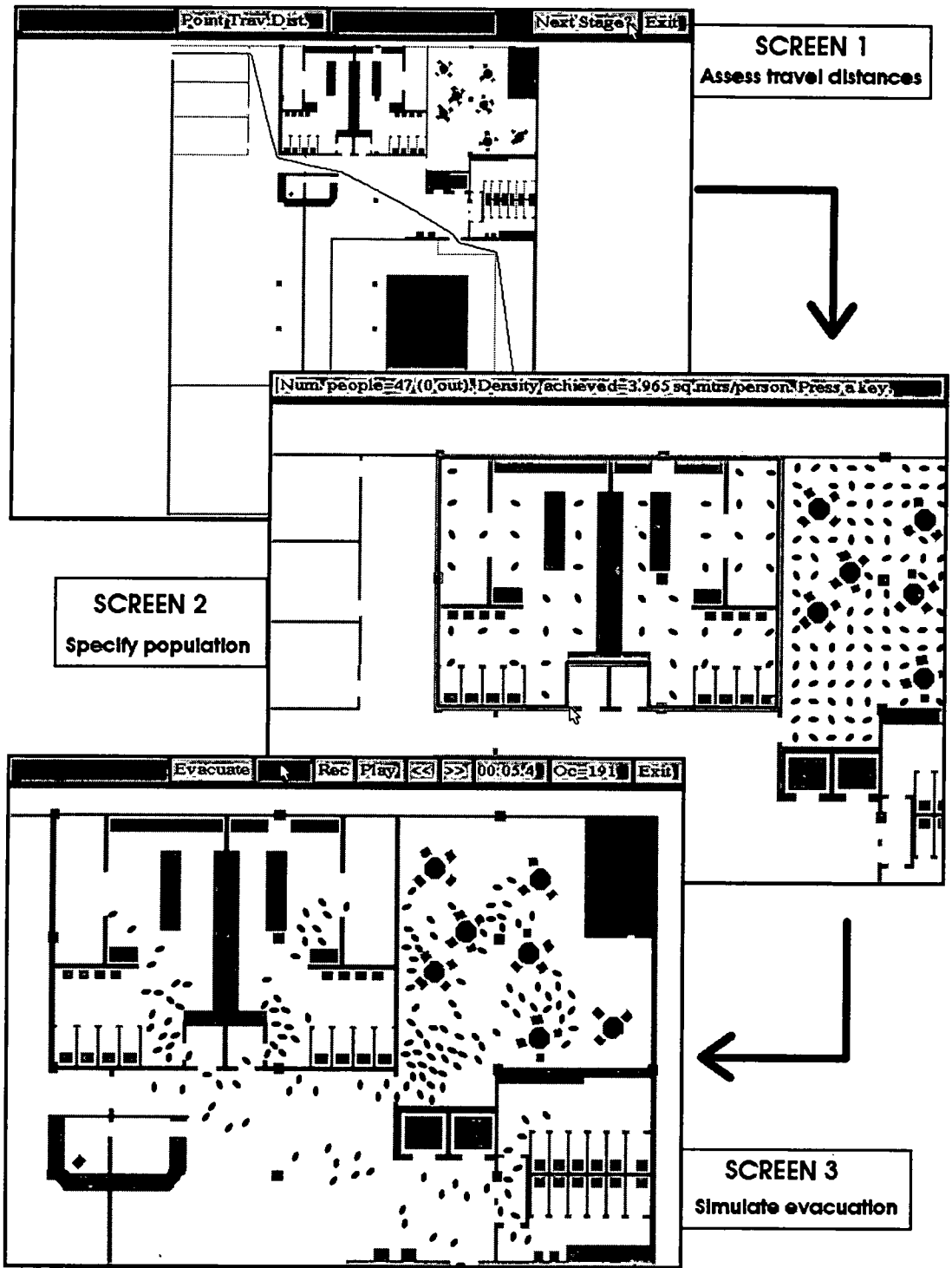


Figure 11.1. The Three Primary Screens in SIMULEX.

Travel distance is regarded as important because it is one of the primary contributory factors for overall evacuation time. For example, in a large office space with a maximum travel distance of 45 metres the travel distance may be much more important than the flow capacities of the exits. If the space contains just one occupant, who is female, 55 years old and positioned at the point that is most remote from an exit, the travel distance and walking speed of the occupant are the only figures that need to be considered to predict the time to evacuate. Time is equal to distance divided by speed, therefore evacuation time = $45/0.8 = 56$ seconds (0.8 m/s derived from Figure 3.16). The flow capacity of the exit does not affect the evacuation time in this case, because only one occupant is considered. The above calculation assumes that the occupant responds immediately to the alarm and walks at an even, unimpeded pace.

A frequently used approximate calculation for the prediction of evacuation time is described in Equation 11.1 below.

$$T = T_{\text{walk}} + T_{\text{flow}} = \frac{D}{v} + \frac{N_{\text{occ}}}{Q_{\text{max}}} \quad \dots\dots\dots (11.1)$$

where: T = Total evacuation time (sec.)

T_{walk} = Maximum time to walk to exit (sec.)

T_{flow} = Time taken for all occupants to move through exits (sec.)

D = Maximum travel distance (m)

v = individual walking speed (m/s)

N_{occ} = Total number of building occupants

Q_{max} = Total combined flow capacity of all exits (persons/sec.)

In large, sparsely populated buildings T_{walk} is very important when regarding the overall performance of the building in terms of its capacity for evacuation. Alternatively, in small, densely populated buildings T_{flow} becomes much more significant than T_{walk} because the flow capacity of the exits becomes the dominant feature. The capability of SIMULEX to accurately calculate travel distances is therefore useful when determining the impact of the building geometry on the total evacuation time, and whether the maximum travel distance conforms to that specified by ADB1. SIMULEX is the only computer program with this capability.

11.0.2 SCREEN 2 - "Specify Population"

SIMULEX allows the user to define the occupancy in different areas of the building plan. The user can change scale by 'zooming in' and 'panning out', and can move around to different areas and rooms. At any location, the user defines a populated zone by moving the mouse and clicking onto the points of an area (square, rectangular, or any polygonal shape). When the co-ordinate points have been specified, the shape is reduced to the minimum number of triangles that can define the geometric form. The sum of the areas of the triangles are used to calculate the total area of the polygonal shape defined. The technique of repeated triangulation for area calculations is not new, and is based on standard mathematical principles. For this reason, the complexities of the area calculation algorithm are not described in any detail. The program has been tested for many multi-sided shapes and is mathematically accurate.

When a populated zone has been defined, and the area calculated, the user is asked for the density of the population that is to occupy that section of the building space. Equations 11.2 and 11.3 are then used to calculate certain parameters.

$$N = \frac{A}{D} \quad \text{..... (11.2)}$$

$$d = \sqrt{D} \quad \text{..... (11.3)}$$

where: N = number of people in populated zone (persons)

A = area of populated zone (m²)

D = population density (m²/person)

d = lateral spacing (m)

A grid of occupants is then located in the populated zone, where the distance between individuals in both the x and y directions is equal to the lateral spacing 'd'. An occupant is not located if the intended grid position is occupied by a solid object, such as a table, shelving rack, or wall. If the number of actual occupants located is different from that originally calculated for the zone, then the lateral spacing in the grid is adjusted. A new 'adjusted density' is calculated by using Equation 11.2 with N equal to the number of occupants actually located. The lateral spacing is then recalculated, and a new potential grid of occupants is tested. This adjustment of

density and lateral spacing is repeated until the number of occupants located is exactly equal to the number originally calculated for that populated zone. The adjustments are usually necessary when the shape is non-rectangular, or solid objects are present within the defined area. The adjustment process is repeated for a maximum of 20 times. If, after 20 grid adjustments, the exact number of occupants is still not achieved due to the complexity of the space, then the lateral spacing that yielded the closest number of occupants to that desired is used. If there is a difference between the original number of people calculated, and that actually positioned in the building, then the difference is displayed.

When a dimensional grid has been calculated, the occupants are located and their co-ordinate positions are stored in memory. Each person is randomly assigned an angle of orientation and a normal, unimpeded walking speed of between 0.8 and 1.7 m/s, representing a population that contains an even distribution of males and females, with ages ranging from 12 to 55 years, based on data from Figure 3.16. The optimal travel distance of each person is obtained from the value in the distance map for that co-ordinate position. These attributes are all stored into computer memory.

When the user specifies that the definition of the population is complete, the program processes the data. Firstly, the data is re-arranged into 'stacks', in order of how far each person is away from the nearest exit. The most remote person's attributes are placed at the bottom of the stacks, and the attributes of the person who is nearest an exit are placed at the top of the stacks. These attribute stacks are then saved as a population file onto hard disk. As a result, when SIMULEX is executed again for the same building, the population is automatically loaded into memory without the user having to define the population zones again. It is also possible to adjust a pre-defined population to test the effect of different occupancy scenarios on a building evacuation.

11.0.3 SCREEN 3 - "Simulate Evacuation"

When the population has been specified, the final stage of SIMULEX uses all of the data previously generated to produce a detailed simulation of the evacuation of a building. The user clicks onto the "Evacuate" menu box to start the evacuation, and can use the "Pause" option to temporarily halt the movement process. At any time, the user can change the scale of the viewed image by pressing the left or right mouse

buttons to 'zoom in' or 'pan out' around the whole building plan. As the evacuation progresses, the program updates the display of the number of occupants in the building and the time from the start of the evacuation, to one tenth of a second. If "Record" is selected before "Evacuate", the progress of the individuals is recorded onto the hard disk, to be replayed using the "Play" option at any stage in the future. The "Record" and "Play" options are limited to fairly small numbers of people because of the limitation on accessible dynamic memory to 0.6 Mb caused by programming under DOS. The future development of SIMULEX for use under Windows will solve this problem because the Windows provides much more direct access to all areas of computer memory. Under the Windows environment, the "Record" and "Play" options will be developed so that the evacuations of large numbers of individuals can be replayed from the hard drive at real-time speed, producing a form of playback animation.

The repeated processes that simulate the movement of each individual occupant through the building space are discussed in detail in Section 11.1, overleaf. The evacuation proceeds with the continuous repetition of the movement simulation algorithms until the last single person arrives at a point of zero exit distance on the distance map. At this point, the last occupant has arrived at the exit point and the evacuation ceases. The total evacuation time is displayed. When the user then selects "Exit" to return to DOS, SIMULEX processes the data that has been stored about the number of occupants present in the building (at every 5 second interval) to obtain the flow rates of occupants leaving the building .

FLOW RATES OF OCCUPANTS LEAVING THE BUILDING (5 sec. periods)		
0->5: 1.2 pers/sec	5->10: 16.6 pers/sec	10->15: 33.0 pers/sec
15->20: 34.6 pers/sec	20->25: 37.2 pers/sec	25->30: 38.8 pers/sec
30->35: 31.8 pers/sec	35->40: 29.4 pers/sec	40->45: 26.4 pers/sec
45->50: 26.4 pers/sec	50->55: 23.8 pers/sec	55->60: 18.6 pers/sec
60->65: 12.8 pers/sec	65->70: 11.2 pers/sec	70->75: 12.8 pers/sec
75->80: 10.2 pers/sec	80->85: 6.2 pers/sec	85->90: 5.4 pers/sec
90->95: 4.0 pers/sec	95->100: 2.2 pers/sec	100->105: 1.0 pers/sec
105->110: 0.2 pers/sec		

Table 11.1. An example of the final output flow rate data from SIMULEX.

An example of the output data is given in Table 11.1. For each 5 second step the program calculates the number of occupants that have left the building. This number is then divided by 5 to produce the flow rate of persons leaving the building per second. This data is very useful when evaluating the evacuation characteristics of a building to observe the efficiency of use of the exterior exits. After the calculations are complete, the program terminates and passes control back to the DOS prompt, with the flow rate table remaining on the screen.

11.1 THE PROCESSES INVOLVED IN SIMULATING EVACUATION

The simulation of the evacuation movement of a specific number of individuals requires a combination of many processes. Each particular process is modelled by using computer algorithms to generate the correct form of escape motion. The mathematical procedures that occur in the primary algorithms were described in previous chapters. These primary algorithms include the calculation of an optimal direction to exit (Chapter 7); speed calculations related to the proximity of individuals and solid objects (Chapter 8); overtaking and localised route deviation (Chapter 8); and the obstruction to individual movement by the presence of solid objects and the bodies of other building occupants (Chapter 9).

The whole process of evacuation occurs in time-steps of 0.1 seconds. The figure of 0.1 seconds was used because over this period of time, the fastest person will only move forward 0.17 metres, which is only slightly more than half the body depth of one person. This prevents the possibility of a person 'stepping through' a solid obstruction without his/her body encountering the presence of that obstruction. It produces a real time for overall computer processing that is acceptable to the user, while maintaining the necessary accuracy for the simulation of individual movement.

At every time-step, the entire range of movement algorithms are invoked. The outcome of the calculations executed by each algorithm will affect which algorithms are subsequently processed. The numerical output of each process is therefore very important because it affects the entire mechanism of simulated, individual, movement. The way in which the algorithms interact produces a form of artificial intelligence where the actions of a person are affected by a complex process of decision making. A summary of the way in which decisions are made by each individual, at each time-step is given in figure 11.2, overleaf.

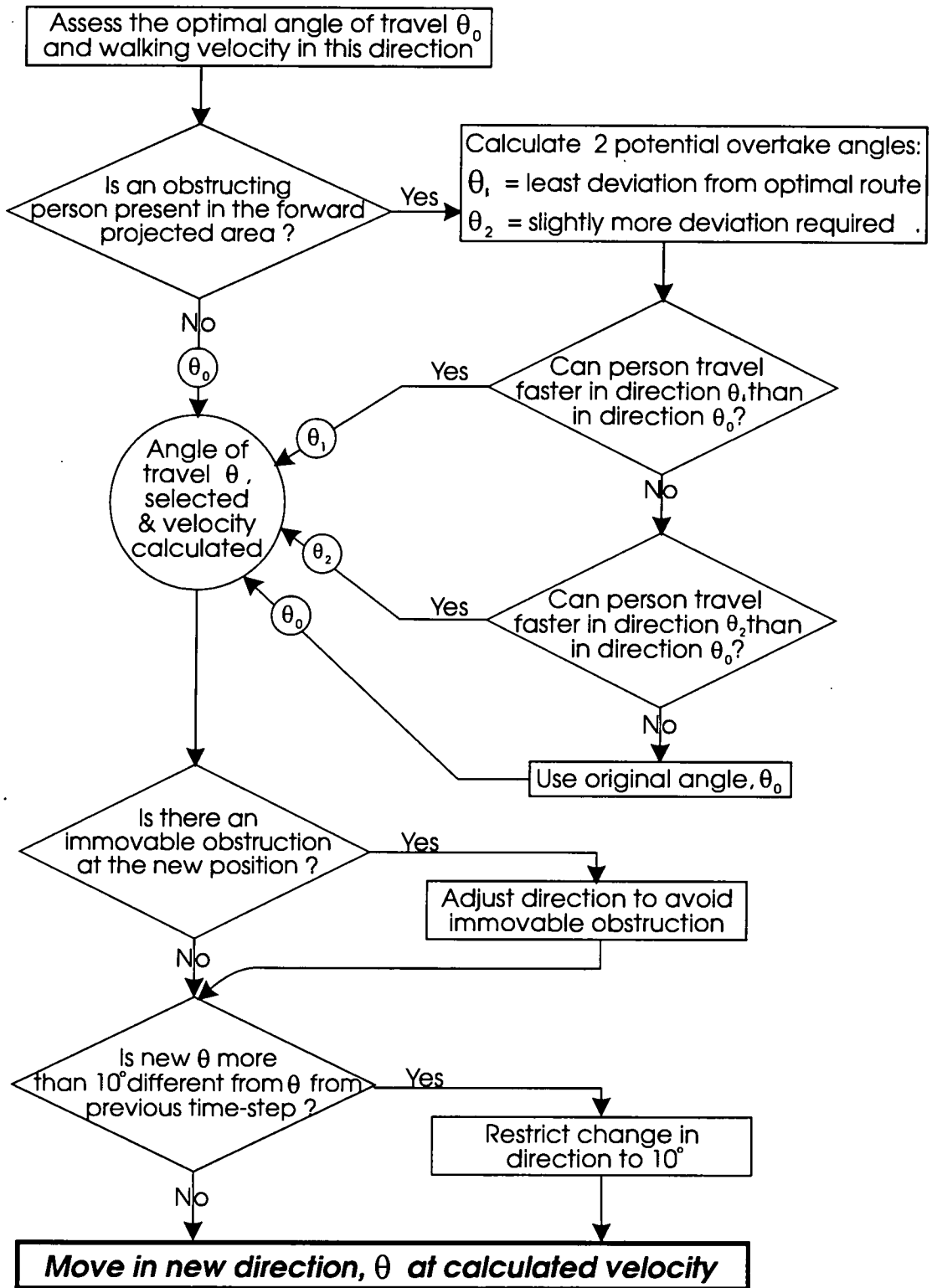


Figure 11.2. Summary of the Decision Process for Each Individual at each 0.1 sec.

The decision process for each individual involves the assessment of many different calculations. Firstly the co-ordinate position of the individual is retrieved from the 'position' data stack. The route assessment algorithms are then invoked to assess the optimal direction to exit from that position.

The person then 'looks forward' by scanning the forward projected area for the presence of another individual. If the way forward is clear, then the optimal direction to exit θ_0 , is adopted as the desired route but if another person presents a potential obstruction to movement in the forward projected area, then the decisions for overtaking are invoked. Two potential deviation angles, θ_1 and θ_2 , that facilitate movement around the 'obstructing person' are calculated. One angle will be a deviation to the left, and one will be a deviation to the right. Because it is rare for an 'obstructing person' to be directly in line with the centre of the 'assessing person', one overtaking angle will cause significantly more deviation from the optimal route than the other. This is illustrated below in Figure 11.3.

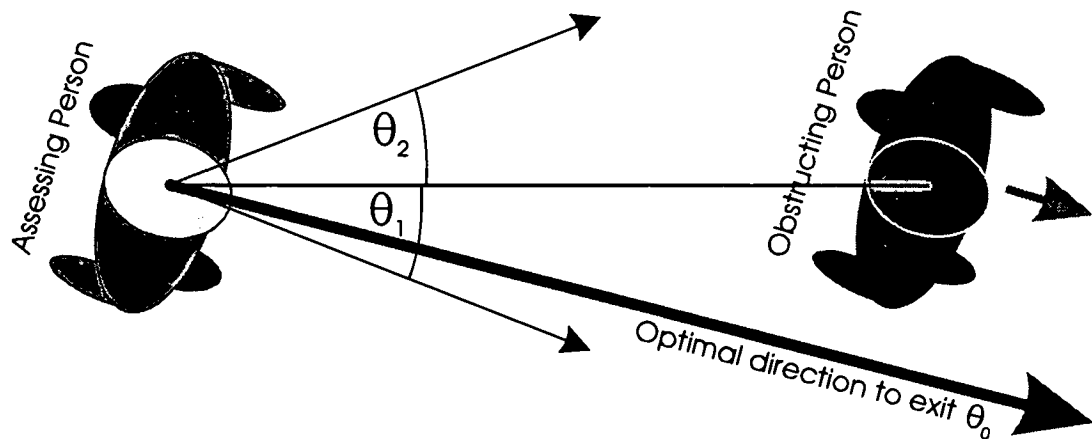


Figure 11.3. The Relationship between Overtaking Angles and the Optimal Direction to Exit

In the example above, the 'obstructing person' is to the left of the optimal direction to exit, so the overtaking angle that causes the 'assessing person' to move to the right is preferable, and is therefore assessed first. Therefore, if θ_1 allows unobstructed movement, θ_2 does not need to be assessed. If all angles θ_0 , θ_1 , and θ_2 are assessed,

then the direction that yields the least obstructed route (and potentially the fastest) is adopted.

A new, projected position is calculated, based on the calculated angle of travel and the velocity calculated for that direction using the method described in Chapter 8. This projected position is then checked for the presence of immovable objects, such as shelving or walls. If such objects are present, the necessary directional and positional adjustments (described in Chapter 9) are calculated. The new angle of travel is then compared to the orientation of the body from the previous time-step. If there is a large difference, the angle of orientation of the body is changed by only 10 degrees towards the desired angle of travel, in one time-step, to prevent excessive body twist. This angle of body orientation becomes the new angle of travel and the velocity in this direction is recalculated to obtain the new body position. This new position is the final position that is drawn on screen and is stored in computer memory for this time-step.

The whole evacuation simulation consists of a series of repeated analytical loops. At each time-step, the position and attributes of each individual are retrieved, and the decision process in Figure 11.2 is executed for that person. The new position, angle of orientation, and distance to exit are then calculated and stored in computer memory. The processing for the whole population occurs sequentially in the order of the person nearest to exit first, to the person furthest from exit, last. When all individuals have been assessed for one time-step, the order of data storage is reassessed to ensure that all data stacks conform to the specified order in terms of the distance to exit of each occupant. When the data stacks have been reassessed, all occupants possessing a distance to exit of zero are removed from the stacks, erased from the screen display, and are deemed to have left the building. The "Number of Occupants" display reflects this change in the number of building occupants. The next time-step is then processed in the same way. This analytical loop of ;

execute decision & movement process for all occupants
reassess order of data storage
remove all occupants with an exit distance of zero
update the time & number of occupants
----- repeat whole process -----

is repeated until the number of occupants in the building is exactly equal to zero.

Thus, the entire evacuation of the building is modelled by SIMULEX by combining many individual processing algorithms. Most of these algorithms concentrate on the physical aspects of escape movement, but further developments will incorporate algorithms to emulate some of the complexities of human psychological response and the mutual interaction of individuals.

The computer processing time required for the complete decision making procedure, movement data assessment system and graphic display for each individual, at each time-step is approximately 0.009* seconds. Therefore, the whole system produces real-time animation of the evacuation process when 11 people are present in the building. Larger populations take longer to process and therefore appear to move much more slowly on the screen. A building population of 1100 requires a processing time of about two hours for a simulated evacuation of one minute. However, in a few years the same evacuation will only take a matter of minutes to process on a standard PC, if computer technology continues to advance at the current rate. The computer processing time will also be reduced when SIMULEX is rewritten to operate in the Windows environment because the speed of access to upper memory areas will be increased.

** Data obtained using a 486 DX2-66 Quad PC with the motherboard running at 33MHz. Processing takes significantly longer on lower performance computers such as a 386 PC. Faster processing can be achieved if a Pentium based PC is used.*

11.2 TESTING THE 'VALIDITY' OF SIMULEX RESULTS

It is crucial that any computer model that produces results which will be used to assess life safety, produces consistently realistic results. Predictions by SIMULEX for the time taken to evacuate individual areas of a building can be used in conjunction with fire growth calculations and toxicity models to assess the potential danger to life. If the onset of hazardous conditions are predicted before the evacuation of that area is complete, then a significant risk to life safety will occur which may ultimately result in the death of a number of the building occupants. The quantitative accuracy of SIMULEX is therefore of paramount importance.

Design guides, such as ADB1, consistently regard the most important aspect of crowd movement to be the relationship between the width of an exit passageway and the maximum sustainable flow rate through that passageway in terms of the number of persons per second. This relationship is regarded as linear for passage widths greater than 1.1m. Therefore, the standard form of evaluating flow rate is by using a figure that expresses flow rate in terms of number of people per unit width per unit time. The usual units are metres and seconds respectively, although some design guides express the unit width as a multiple of a standard body breadth (0.5-0.6 m). Values of the flow rate per unit width, from different sources, were presented in Table 3.4. Very little data is available for passages that are less than 1.1m wide. The publication 'Post War Building Studies' (1952) describes a series of tests by the Paris Fire Brigade where groups of firemen moved through different width exits under controlled conditions. These tests suggested that there was no real significant difference in flow rate per unit width between a 1m and a 1.1m wide exit, although the validity of the results should be viewed with scepticism due to the 'unreal' nature of the experiments. ADB1 suggests a rapid reduction in flow rate per unit exit width when exits are less than 1.1m wide. There appears to be no real evidence for this effect, other than the knowledge and judgement of the original engineers who devised the flow rate table.

It is imperative that SIMULEX produces realistic maximum sustainable flow rates over a range of different exit widths because unrealistic flow rates will produce unreliable results when calculating the total evacuation times of different buildings. A set of tests were therefore carried out to investigate the overall performance of SIMULEX by simulating the evacuation of a specific number of individuals over a wide range of exit widths in order to assess the maximum sustainable flow rate of the group through different passageways. The form of testing was useful because the movement of the individuals, moving in close proximity through a restricted opening invoked all of the decision and movement algorithms involved in 'The Decision Process' (Figure 11.2). The tests therefore presented an overall measure of the performance of the individual calculations within SIMULEX and the way in which each of the calculation processes interacted.

The evacuation simulation program was used to test flow rates through exit widths ranging from 0.7 to 3.0 metres, in increments of 0.1 metres. The physical geometry of the space that the tests were carried out in, is illustrated in Figure 11.4 overleaf. The section of corridor that the exit leads into is 5 metres long, and 5 metres

internal width. The centre of the exit is aligned with the centre of the corridor. The initial test conditions consisted of a group of 100 individuals that possessed random initial angles of orientation and an initial population density of 4 persons/m². The conditions were intended to simulate a fairly concentrated, non-panicking crowd.

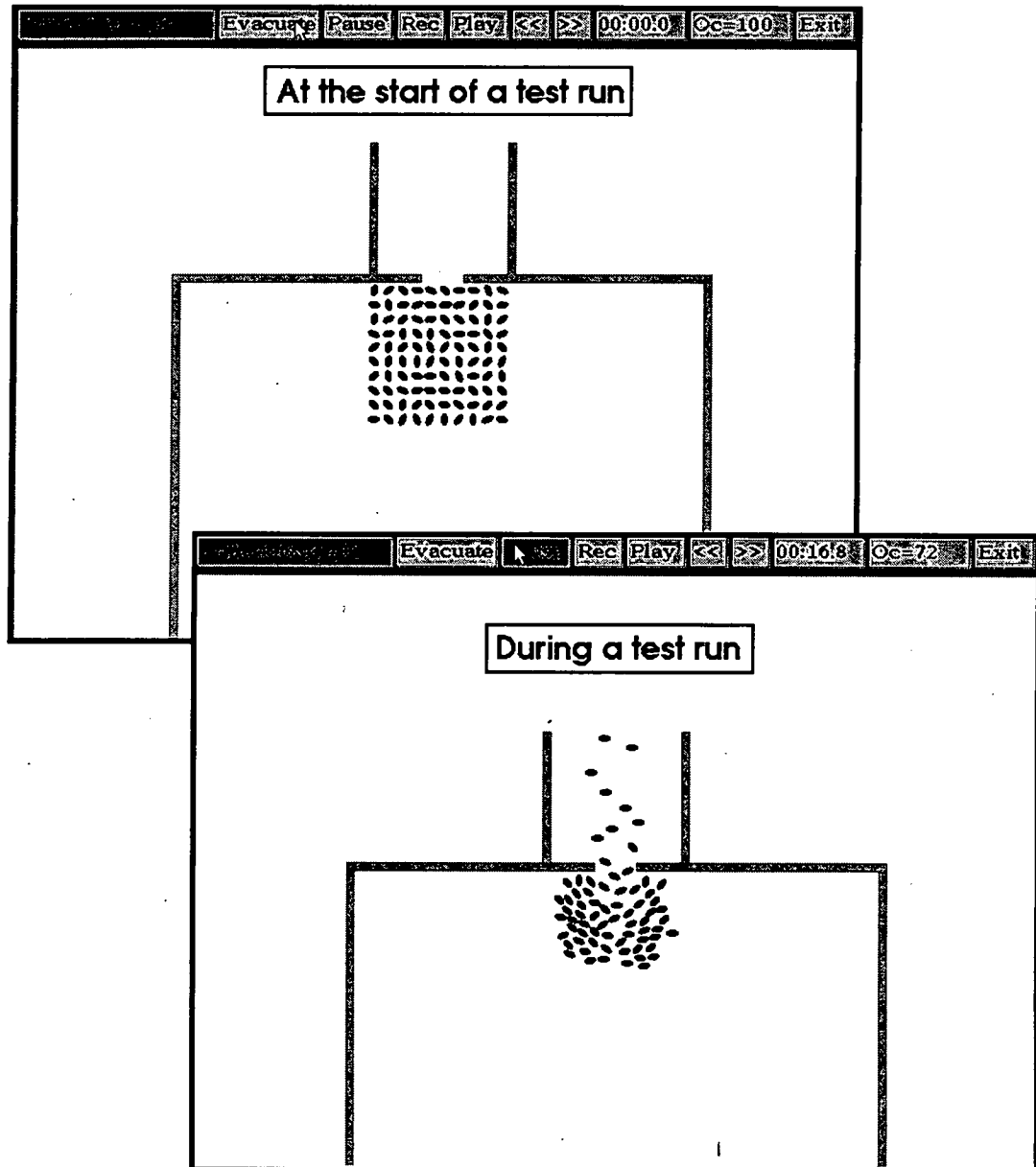


Figure 11.4. Screen Displays illustrating the testing of SIMULEX for a group of people moving through a specific width of doorway.

The section of corridor was placed on the other side of the exit so that the motion of the people as they passed through the exit opening and spread out into the wider passageway could be observed. It was necessary to model the movement of the occupants as they emerged from the 'test' exit because their movement could affect the motion of individuals behind them, who were in the process of moving into or through the opening. Occupants were removed from the evacuation process when they reached the end of the 5 metre section of corridor.

For each test on an exit greater than one metre wide, exactly the same group of 'people' were used, in terms of initial position, orientation, and normal unimpeded walking speed. The only difference in initial conditions for each test was the lateral width of the exit. The test conditions were changed for exits less than 1.1 metres wide because when narrow exits were tested with the highly concentrated group initially placed at the mouth of the exit, a permanent 'jam' of bodies occurred within the first 10-15 seconds of movement. The front two rows of people were removed in order that more space would be available for movement in the initial stages of evacuation. Therefore, in the narrow exit tests, the foremost members of the group (now reduced from 100 to 80 persons) started 2m back from the face of the exit opening.

Each test was initiated by clicking onto the "Evacuate" icon on the SIMULEX screen display. When the evacuation started, the individuals in the group began to orientate themselves towards the exit by turning at the rate of 10 degrees per time-step, and then started to walk towards the opening. The time taken for the first 10 occupants to pass through the 'test' exit was noted as T_{10} . When the evacuation proceeded, the time at which 10 people remained behind the exit (that is, the time taken for a total of 90 occupants to pass through the exit) was then noted as T_{90} . The exit was deemed to be functioning at its maximum sustainable flow rate for the duration between T_{10} and T_{90} . In the case of the narrower exits, T_{10} and T_{90} were replaced with T_5 and T_{70} to accommodate the lower number of occupants, and the fact that the maximum flow rate was achieved after only a few individuals had passed through the exit. The figures were then used to calculate the maximum sustainable flow rate in each case.

The results of the 'exit width' tests are presented in Table 11.2 on the two pages overleaf. The formulae and notation used are given at the head and foot of the table respectively.

D_w (m)	T_{10} (sec)	T_{90} (sec)	$Q = \frac{80}{(T_{90} - T_{10})}$ (Persons/m/s)	$q = \frac{Q}{D_w}$ (Persons/m/s)	Notes 80 people starting at doorway
3.0	3.0	22.2	4.167	1.39	Regular Flow
2.9	2.9	22.4	4.103	1.41	" "
2.8	3.1	22.6	4.103	1.47	" "
2.7	3.2	23.5	3.941	1.46	" "
2.6	3.2	24.4	3.774	1.45	" "
2.5	2.8	24.9	3.620	1.45	" "
2.4	3.0	28.1	3.187	1.33	" "
2.3	3.2	28.4	3.162	1.37	" "
2.2	3.2	28.4	3.162	1.44	" "
2.1	3.7	32.2	2.807	1.34	" "
2.0	4.0	33.7	2.694	1.35	" "
1.9	4.0	34.3	2.640	1.39	" "
1.8	3.9	34.5	2.614	1.45	" "
1.7	4.4	37.4	2.424	1.43	" "
1.6	5.1	38.5	2.395	1.49	" "
1.5	5.4	43.1	2.122	1.41	" "
1.4	5.7	48.9	1.852	1.32	" "
1.3	5.8	49.5	1.831	1.41	" "
1.2	6.0	53.9	1.670	1.39	Slightly irregular
1.1	8.8	65.9	1.401	1.27	Primarily single file, irregular flow. High density system jams for widths below 1.1m

Table continued overleaf.....

D_w (m)	T_5 (sec)	T_{70} (sec)	$Q = \frac{55}{(T_{90}-T_{10})}$ (Persons/m/s)	$q = \frac{Q}{D_w}$ (Persons/m/s)	70 people, starting 2 m from door. Initial density 4m ² /person
1.1	5.8	45.5	1.385	1.26	Flow is usually single file and irregular
1.0	6.2	48.7	1.294	1.29	
0.9	6.0	50.3	1.242	1.38	
0.8	6.8	67.8	1.078	1.35	
0.75	6.3	65.5	0.929	1.24	Severe shuffling
0.70	6.3	-----	-----	-----	Permanent jam after 30 seconds.

D_w = Door/passage width (metres).

T_5 = Time at which 5 people have moved through door.

T_{10} = Time at which 10 people have moved through door.

T_{60} = Time at which 60 people have moved through door

T_{90} = Time at which 90 people have moved through door.

Q = Flow rate through doorway (persons, P / second).

q = Flow rate per metre width of doorway (P/m/sec)

Technical specification for tests :

Time-step = 0.1 sec.

Maximum twist for all occupants = 10 degrees per time-step

Threshold distance for all occupants = 1.6 metres

Normal, unimpeded walking speeds are randomly assigned between 0.8 and 1.7 m/s.

Table 11.2. Testing SIMULEX for different passage widths.

The times quoted in Table 11.2 are accurate to one tenth of a second. It was sometimes difficult to ascertain the exact time when a specific number of people had passed through the exit because it was fairly common for two people to walk through at the same time, side by side. For example, the 10th and 11th occupant might leave the exit simultaneously, leading to the possibility that only 79 people, instead of 80 would pass through the exit between T_{10} and T_{90} . It was therefore inevitable that some experimental error would be encountered. Some variation in flow rates was also expected because the different attributes of individuals would create different patterns of movement when the group moved through different exits. The actual variation in flow rates was not regarded as excessive. The flow rate achieved for each width of exit was plotted on the graph presented in Figure 11.5 below, and compared to the values quoted by Hankin and Wright (1958) and ADB1.

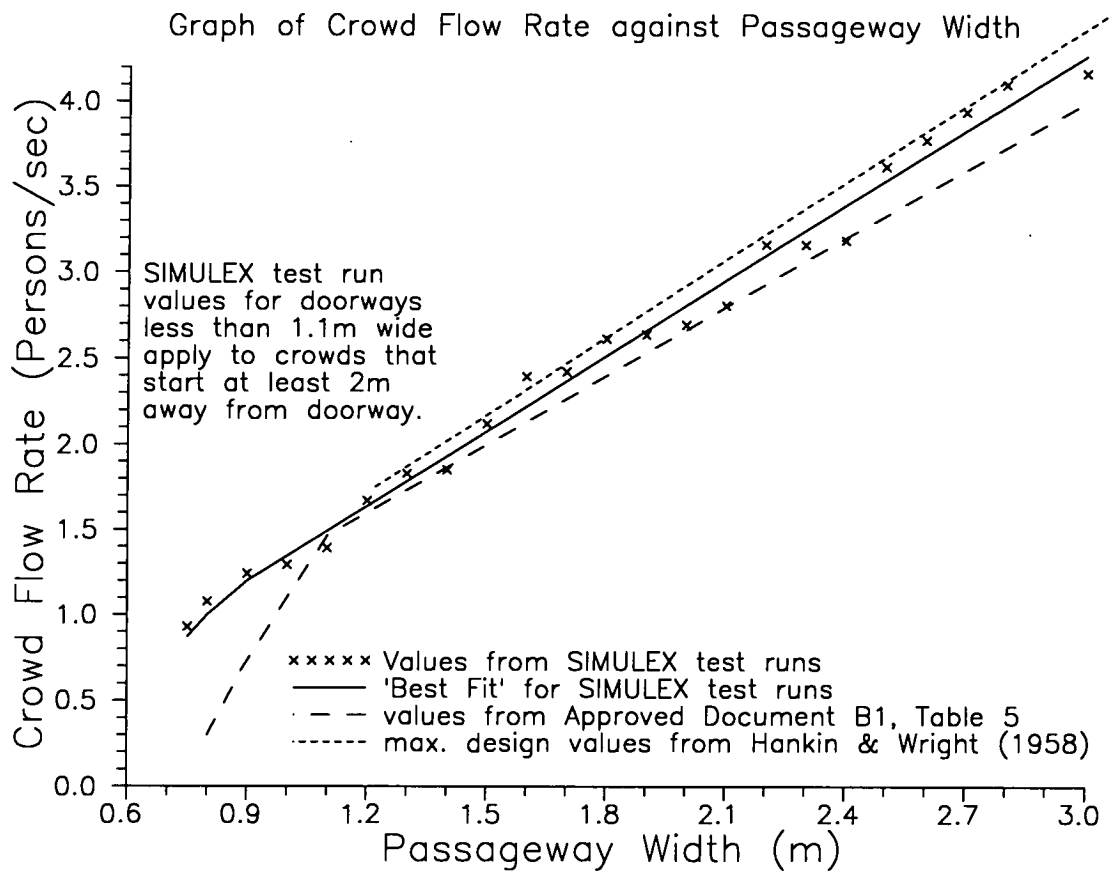


Figure 11.5. Graph of Crowd Flow Rate against Passageway Width.

- comparing SIMULEX results with other data.

The linear relationship between flow rate and exit width was observed in the SIMULEX test runs for widths greater than or equal to 1.1 metres, at the average sustainable rate of 1.40 persons / metre width / sec. This value compares well with those quoted from various sources in Table 3.4, and lies between the data points plotted from Hankin & Wright (1958) and ADB1.

The difference in values between the SIMULEX tests and ADB1 for exit widths less than 1.1 metres, is significant. It should be remembered that there appears to be no experimental evidence for the ADB1 figures for exit widths of less than 1.1 metres, so they may not represent realistic flow rates. The ADB1 figures are intended as a design guide, and as such are very useful because their use severely limits the number of occupants served by narrow exits. This ensures that a high density build-up of people at the face of the exit is avoided, and therefore a 'jam' or stagnation of the crowd flow should not occur. SIMULEX produced complete stagnation of movement for high density groups attempting to move through narrow exits, when the foremost members of the group were initially positioned at the face of the exit. Sustained flow was only possible by ensuring that the group began movement at a distance of two metres back from the exit. By effectively moving the initial position of the group of people away from the face of the exit, the density at which the occupants entered the exit was reduced slightly. This initially reduced density enabled the maintenance of movement through the opening that allowed test results to be obtained, although the flow was somewhat irregular, and the 'pulsing' flow observed by Peschl (1971) sometimes occurred. Continuous movement could not be achieved for exits less than 0.75 metres wide as the bodies of different individuals became 'entwined' with each other and jammed against the edges of the exit opening.

The movement of individuals emerging from the exit into the wider corridor proved to be important because it did, as expected, affect the movement of the occupants who were entering, or already in, the exit opening. As individuals emerged from the exit, they resumed the expected patterns of overtaking and twisting. This produced the effect of the emerging group 'spreading out' laterally across the 5 metre section of corridor and produced group formations similar to the 'circular packing' configurations observed by Fruin (1971).

The results from these tests are encouraging, because they indicate that the parameters for movement that were used in the program were realistic for the simulation of a normal, non-panicking crowd. The most important parameters that affect the transition of people through an opening are the rate of body twist and the threshold distance. If the rate at which the bodies of individuals can turn is not restricted, then the overall flow rate of a group of people generally increases by approximately 10%. If the threshold distance is reduced, then the flow rate increases dramatically. The threshold distance derived from Ando et al, in Figure 8.3, is 1.1 metres. When SIMULEX uses a threshold distance of 1.1 metres instead of 1.6 metres, the maximum sustainable flow rate increases to 1.7 persons/m/s. This value corresponds well to the average 'maximum' flow rate of 1.65-1.75 persons/m/s calculated from the data produced by Ando et al over the range of 1.5-5.0 persons/m² (see Figure 8.7). The threshold distance may be regarded as the limit of 'personal space' in front of a moving person. This indicates that SIMULEX may be able to model cultural and/or psychological differences between different groups of people by changing the threshold distance of individuals, which hence, effects the overall flow rate through a passageway. A group of people who are in a hurry and therefore possess a higher 'anxiety level' are likely to accept more of an invasion of personal space than in normal, comfortable conditions. This could be modelled by decreasing the threshold distance and would result in an increase in overall flow rate.

One area that has not yet been fully explored is the difference in body size of the occupants. SIMULEX currently assigns the average body dimensions to each person. It is certain that if all members of a group of people possess significantly larger body sizes than normal, then the overall flow rate will decrease as a result. For example, a test run was executed by SIMULEX for a group of uniformly sized individuals with body dimensions that were double the average (1.0 × 0.6 metres). The exit tested was 3.0 metres wide, and the threshold distance was kept at 1.6 metres. The maximum sustainable flow rate was reduced to 0.9 persons/m/s (approximately 2/3 of that for normal body dimensions) as a result of the increase in body sizes. Unfortunately, no data is currently available to compare the effect of differences in body size upon the overall flow rate achieved by a group of people moving through a passageway of specific width.

11.3 THE APPLICATION OF SIMULEX TO ACTUAL BUILDING DESIGNS

SIMULEX is intended for eventual use as a design tool, to be used by fire safety engineers, architects and building engineers when devising the geometric layout of buildings in the design stages. This section describes the application of the computer modelling system to the design of a branch of a well known superstore. This building will subsequently be referred to as The Superstore.

The Superstore was chosen as a case study because it was still in the design stages, and certain aspects of the design had not been finalised. One important aspect was that design population density had not been finalised, and it was uncertain whether the population density of 7.0 m²/person or 4.0 m²/person was applicable to the design. The reason for the use of two different population densities was that The Superstore was to sell primarily D.I.Y. goods. The figure quoted by ADB1 for the occupant density of supermarkets and department stores is 2.0 m²/person, but this concentration of people is not normally encountered in DIY stores and was not deemed suitable. The occupant density quoted by the same guide for shops that sell primarily furniture, floor coverings, cycles, prams, large domestic appliances or other bulky goods is 7.0 m²/person. The classification of D.I.Y. stores may sometimes lie between these two categories, so a figure of 4.0m²/person is often used instead of 7.0 m²/person. The designers therefore wished to assess the capacity of the building plan for evacuation for the two different initial population conditions.

The single-storey plan of The Superstore was input using DRAWPLAN, which took approximately 4 hours. Walls, stacks, racking and other immovable obstructions were defined with the use of 'wall units'. At two points, small 'wall units' were drawn 3 metres from the boundary of the plan so that subsequent programs using the building plan would consider not only the building plan, but a 3 metre wide space, surrounding the perimeter of the building. The plan was saved as a file onto the computer hard disk. The execution of GRIDFORM then loaded the building plan file, segmented the space into a mesh of 0.25×0.25m spatial blocks, assigned the perimeter of the 3 metre boundary space with an exit distance of zero, and formed the distance map. The formation of the distance map required approximately 10 minutes computer processing time, and was saved as a file onto the hard disk when the formation process was complete.

The building plan and distance map were downloaded by SIMULEX for processing. The "Analyse Travel Distances" screen informed the user that the maximum travel distance was 44.7 metres. The perimeter space width of 3.0 metres was deducted from 44.7 to yield a maximum travel distance within the building of 41.7 metres. The travel distance of 41.7 metres was just within the limit of 45 metres specified by ADB1.

The perimeter of the occupied area of the building was defined in the "Specify Population" screen. The occupied sales area was found to be 7676.4 m². The densities of 7.0 m²/person and 4.0 m²/person were entered for the two evacuations. The number of occupants calculated by SIMULEX were 1097 and 1919 persons, respectively. The two evacuations were executed in the "Simulate Evacuation" screen, and the flow rate results stored for later analysis. An example of one of the simulated evacuations is illustrated in Figure 11.6, below.

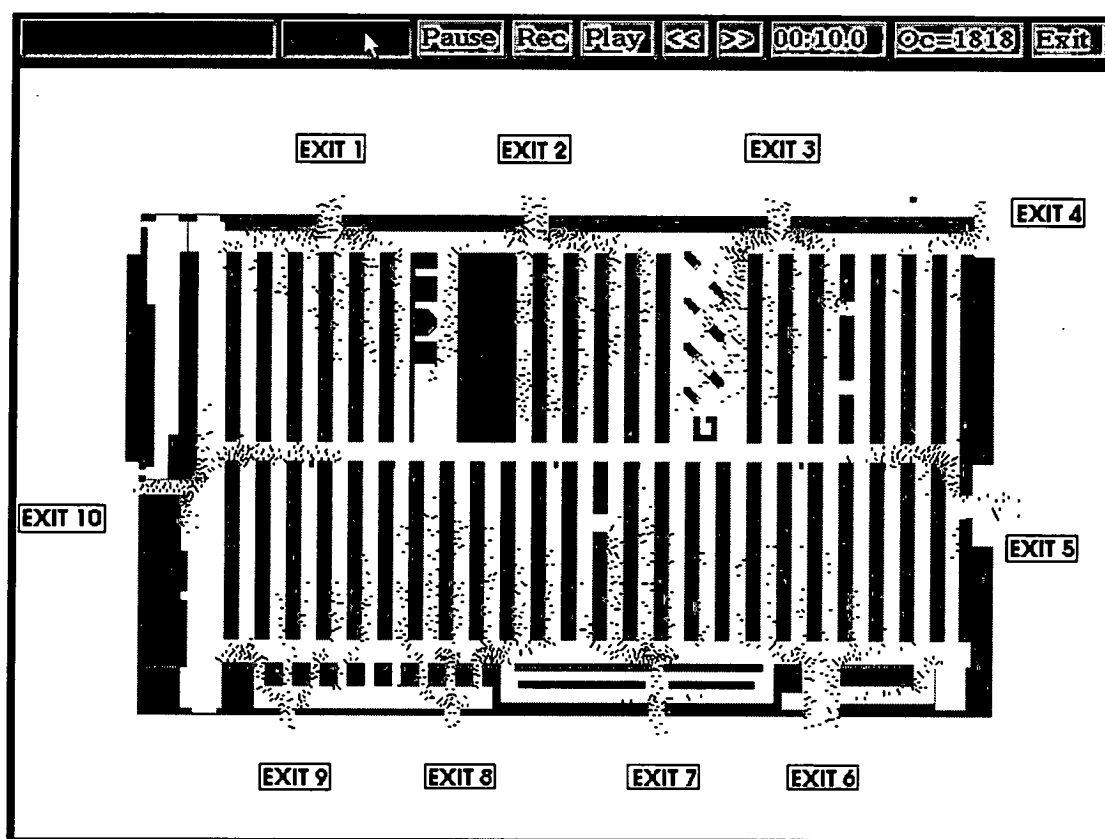


Figure 11.6. The simulated evacuation of The Superstore, after 10 seconds.
Initial density = 4m²/person.

The simulation of the two evacuations illustrated the general patterns of movement and queuing that occurred during the entire escape process. The distance map had been formed in such a way that all occupants moved towards the nearest exit. In both evacuations, Exits 1,2,3,8,9 and 10 were the only exits that approached or achieved the maximum flow rate and caused queues to form behind the face of the exit opening. The rate of flow throughput at Exit 7 was hampered by the constrictions within the escape route before the exit. The aisle which served most of the occupants using Exit 5, was actually narrower than the width of the exit doorway. Exit 5 therefore never approached its maximum potential flow rate. Exit 4 was oversized for the number of occupants that it served.

Exits 1,2,3,6,7,8,9 and 10 all experienced the convergence of different flows of occupants as they emerged from different aisles and moved towards the exits. The convergence of different flows at Exit 3 is illustrated in Figure 11.7, below. Note that on the right hand side, a number of slower people create a form of obstruction.

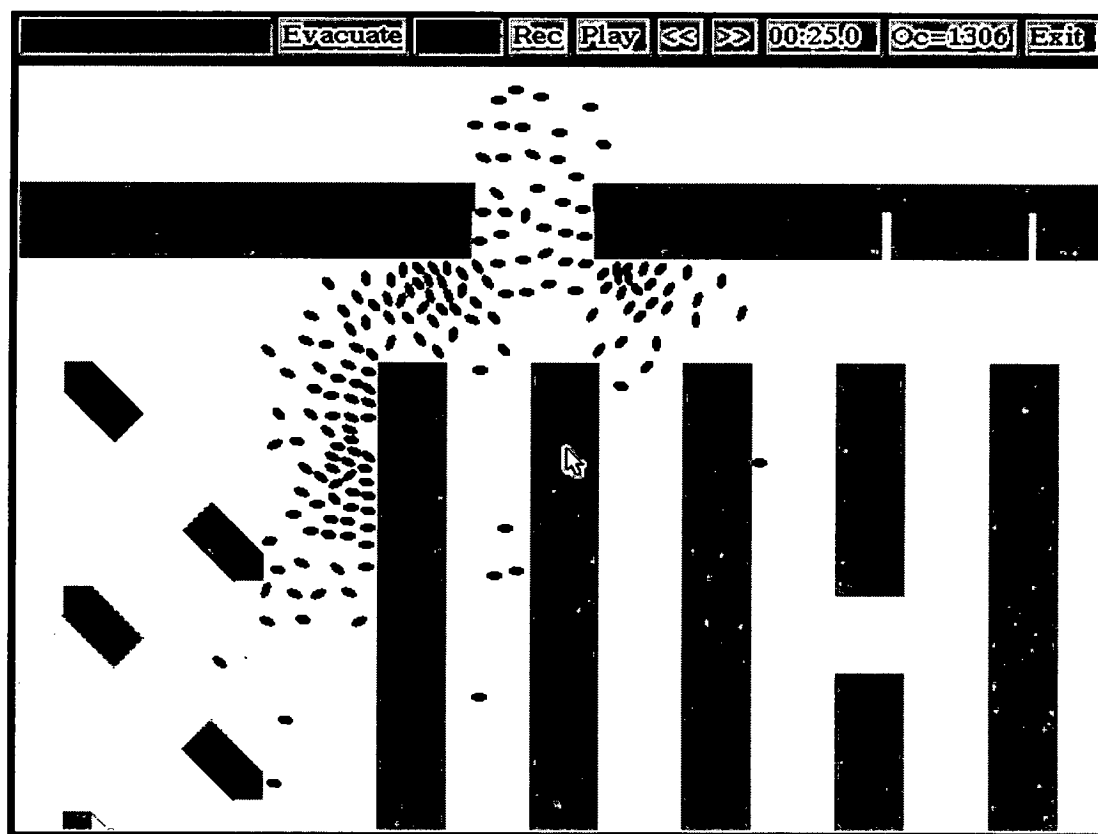


Figure 11.7. Exit 3 of The Superstore simulated evacuation, after 25.0 secs.

The total simulated evacuation times were 58.1 seconds for the 7.0 m²/person occupancy loading, and 105.1 seconds for the 4.0 m²/person occupancy loading. Significantly more queuing, and some stagnation of movement, occurred for the evacuation with the initial occupancy loading of 4.0 m²/person. Both evacuations were therefore predicted to take significantly less time than the maximum of 150 seconds stated by ADB1.

It is possible to apply the approximate calculation given in Equation 11.1 to The Superstore, and compare the values obtained to the results of the simulated evacuations carried out by SIMULEX. The exit widths are presented in Table 11.3, and the subsequent calculations are detailed in Equations 11.4-11.6.

Exit No.	1	2	3	4	5	6	7	8	9	10	$\sum w$
Width (m)	3.5	3.6	3.5	3.4	3.6	5.2	2.4	2.4	2.4	1.8	31.8

Table 11.3. Width of Exits for The Superstore.

$$Q_{\max} = q_{\max} \times \sum w = 1.26 \times 31.8 = 40.1 \text{ persons / sec} \quad \dots\dots\dots (11.4)$$

$$T_7 = \frac{D}{v} + \frac{N_{\text{occ}}}{Q_{\max}} = \frac{41.7}{0.5} + \frac{1097}{40.1} = 110.8 \text{ sec.} \quad \dots\dots\dots (11.5)$$

$$T_4 = \frac{D}{v} + \frac{N_{\text{occ}}}{Q_{\max}} = \frac{41.7}{0.5} + \frac{1919}{40.1} = 131.3 \text{ sec.} \quad \dots\dots\dots (11.6)$$

where: Q_{\max} = Total combined flow capacity of all exits (persons/s)

q_{\max} = flow rate per unit exit width = 1.26 (persons/m/s)

w = exit width (m)

T_7 = Total evacuation time for occupancy loading of 7.0 m²/person (sec.)

T_4 = Total evacuation time for occupancy loading of 4.0 m²/person (sec.)

D = Maximum travel distance (m)

v = individual walking speed = 0.5 (m/s)

N_{occ} = Total number of building occupants

The values used for q_{\max} and 'v' represent the conservative values that might be used by a consulting fire safety engineer to predict evacuation times for this type of building, with moderate occupancy loadings. The calculations yield conservative predictions for the building evacuation times, compared to the times predicted by SIMULEX, but they tell us nothing of the characteristics of the evacuation. The conservative calculation predicts that there is a 19% increase in evacuation time when the initial occupancy loading becomes more concentrated, from 7 m²/person to 4 m²/person. However, SIMULEX predicted an 81% increase in evacuation time because the increase in occupant numbers produced significantly more queuing, and all of the building exits never achieved maximum flow throughput simultaneously. In fact, some of the exits never achieved more than 50% of their maximum flow capacity. The graph representing overall building performance is illustrated below.

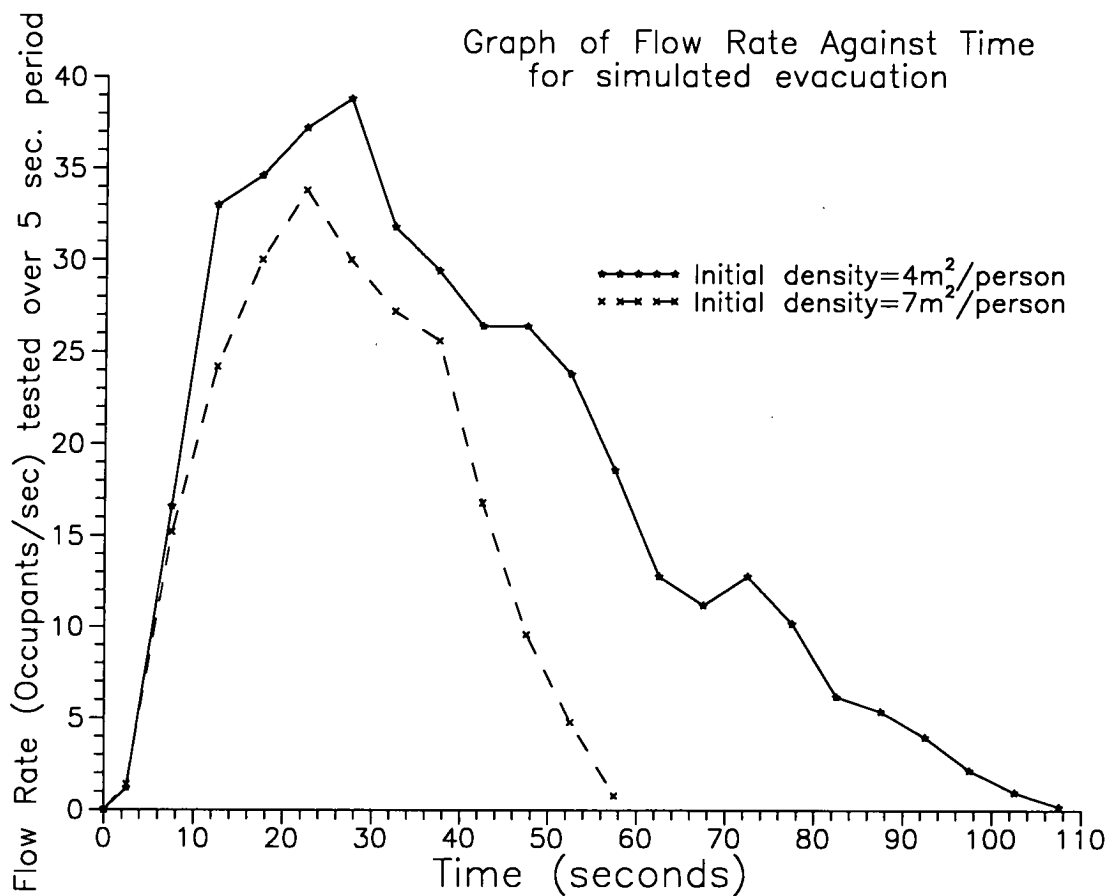


Figure 11.8. Graph of total Flow Rate against Time for two simulated evacuations of The Superstore.

In both evacuations, the rate at which occupants leave the building increases rapidly in the first 10 seconds, and climbs to a peak between 20 to 30 seconds. The total flow rate then 'tails off' as some exits are completely emptied, while others are either still serving queues of people or groups of slower individuals that have taken significantly longer to arrive at the exit openings. The larger number of occupants in the 4 m²/person evacuation produced slightly higher flow rates because exits that did not achieve their individual maximum flow capacities served more occupants than in the 7 m²/person evacuation. The fact that these exits were more fully utilised when more occupants were present, meant that they contributed more to the total flow rate from the building at the peak flow times.

The peak flow rate achieved for the whole building was 38.7 persons/sec at 25-30 seconds for an initial occupancy loading of 4 m²/person. If all exits operated simultaneously at the maximum sustainable flow rate produced by the SIMULEX 'exit width' tests, the building could potentially evacuate 44.5 persons/sec, but this potential flow rate was never achieved because of the lack of usage of some exits. The flow throughput of each exit during the period in which the peak total evacuation flow was observed and estimated numerically by the user as a fraction of the maximum possible flow rate for that exit. These exit usage values are presented in Table 11.4.

Exit Number	1	2	3	4	5	6	7	8	9	10
Usage as a fraction of maximum possible flow for each exit	max 1	max 1	max 1	emptied 0	part 1/3	part 1/2	part 3/4	max 1	max 1	max 1

Table 11.4. Exit usage at peak flow in The Superstore evacuation for an initial occupancy loading of 4.0 m²/person.

The table above demonstrates that even at the peak flow rate of numbers of occupants leaving the building, only six of the exits operate at, or near, the maximum sustainable flow rate. These 'partially used' exits could either be repositioned to serve a larger percentage of the population or reduced to a size more suitable to the number

of occupants that they serve, with no detriment to the overall evacuation time. For example, Exit 5 could be moved upwards (on the plan) to be located directly at the end of the main aisle that spans left to right across the shop floor area, which would increase the number of people that it served; would directly align it with a wider passageway, and it would therefore operate at a higher flow rate efficiency. It would also be clearly visible to the occupants in that central aisle. However, no design changes are strictly necessary because the evacuation times predicted are significantly less than the maximum stated by ADB1.

The application of SIMULEX to building designs is useful because it is capable of highlighting areas where queues form, stagnation of movement may occur, and also where exits are significantly oversized. The data for the changes of total flow rate with time can be used to realise the overall performance of the building to accommodate the evacuation process. In the example given, the overall flow rate peaked over a 10-20 second period, but if the flow rate had reached a peak and maintained that maximum level for a sustained period, it would have indicated that a significant amount of queuing had occurred at a number of exits. In such a case, the existing exits might be widened, repositioned or the number of exits increased.

CHAPTER 12

CONCLUSION

A general summary of the achievements of the project are presented in this chapter. The merits of the various modelling techniques are discussed briefly, and the success and limitations of SIMULEX are debated.

12.0 NEW MODELLING TECHNIQUES

A range of new techniques for accurately modelling the escape movement of individual occupants from a building were developed during the course of this study. The initial exploration of fluid modelling methods produced some interesting, and encouraging results but the fluid techniques would require a number of years of development to discover whether or not they might become a useful tool for research and design. As a result, it was decided in the early stages of this project to devote all subsequent efforts towards the development of computer modelling systems (see Section 1.3) and the collection of 'real-life' data.

The 'distance-mapping' technique is very useful for assessing travel distances throughout a building space. It represents the first computerised method for the accurate calculation of travel distance and is particularly effective for the assessment of maximum travel distances in large, geometrically complex buildings. The graphic representation of a distance map as a series of shaded contours, allows the user to realise the initial plan area from which occupants will travel to a particular exit. This facility would allow the designer to make an 'informed' change to an exit position in order to increase or decrease the number of people that would escape through it, and hence maximise the efficiency of exit usage.

The algorithms that control the assessment of escape routes and the deviation from such routes (in the form of overtaking) are precise, but allow the direction of travel for an individual to be reassessed when the physical presence of another person presents a potential obstruction to movement. The complexity of a total escape route has no effect on the processing time required for the calculation of the route, because only the immediate direction of travel is calculated at each time-step. The calculation of individual routes requires far less user-input than for any other contemporary program, and is also more geometrically accurate.

The size and shape of the body of each person is defined by using a combination of circles. This method of physical representation allows the calculation of the contact between the body of a person and a solid object to be executed quickly and precisely. The direction of travel of a person is therefore adjusted if such contact is predicted, and the resulting 'corrected' direction realistically models the 'avoiding' behaviour of a person who would walk around a solid object. However, not all of the aspects of the physical definition of each person's body have been investigated. For

example, the difference in body size and shape that is synonymous with age, gender and disability needs to be explored further.

The 'invasion of personal space' was identified at an early stage in this project as being of crucial importance to the accurate simulation of personal decision-making and movement. The subsequent analysis of individual motion revealed the previously uninvestigated relationship between inter-person distance and walking velocity. This relationship illustrates the way in which the movement of one person is affected by the position of another individual who presents a potential obstruction to forward motion. The form of the graphical curve that represents this relationship has a significant effect on the flow rate of a group of individuals who pass through an exit of specific width. This aspect of individual motion represents the fundamental mechanism involved in the creation of interactive 'crowd movement'.

The rate at which an individual can physically twist, and turn towards another direction was proved to be an important parameter when considering the actions of a person who is walking through a building space. A realistic maximum 'twisting rate' was ascertained and used successfully in the simulation program.

12.1 THE OVERALL PERFORMANCE OF SIMULEX

The general approach towards maintaining the 'validity' of SIMULEX was to ensure that individual algorithms, such as the assessment of individual velocity and rate of body twist, were based on the data collected from real-life analyses. This approach was verified by the early 'validation' tests that were carried out. The simulation package was used to model the evacuation of a group of 75-100 people through the exit doorway from a simple, rectangular room into a wide corridor. When the simulated evacuation was repeated for a wide range of different door widths, the flow rates achieved by the group bore a close correlation to the data obtained by Hankin & Wright(1958). This correlation is very encouraging, and illustrates that SIMULEX addresses the primary mechanisms of individual movement that are required for the realistic simulation of the movement of a group of people, during the evacuation of a building.

12.2 THE COLLECTION OF 'REAL-LIFE' DATA

Recent advancements in computing power, the image capture package Media Pro HiRes, standard video equipment and software written by the author all combined to achieve the collection of new data relating to the movement of individual people. The data that was obtained was used to verify the relationship between inter-person distance and walking velocity and allowed the maximum twisting rate achieved by each building occupant during the process of evacuation, to be ascertained. The method of data collection and analysis was fairly laborious, but the results were required before the output of SIMULEX could be used with any real degree of confidence, for the purpose of realistic simulation.

The methods that were devised for the collection of the data are fairly advanced, in terms of image analysis and motion assessment. These methods will be used in the Civil Engineering Department at Edinburgh University to collect data in other areas of scientific analysis where the quantification of physical and thermal movement would not otherwise be possible.

12.3 CONCLUDING COMMENTS

The most significant development in this thesis, in terms of real-life data, was the derivation and testing of the relationship between individual walking velocity and inter-person distance. This is the first time that such a relationship has been investigated, and is the main reason that SIMULEX produced such encouraging results in the exit width/flow rate tests. Other simulation programs, such as VEGAS (Still-1993) that do not use the concept of 'inter person distance' do not reproduce realistic crowd flow rates for different widths of exit. In short, this is the first study to analyse 'inter-person distance', which is a fundamental concept when considering the interaction that occurs between individual people in crowded situations.

The distance-mapping techniques, physical parameters for individual movement, wayfinding algorithms and overtaking routines have all been incorporated into SIMULEX to produce a unique research and design tool. The package is by no means perfect, and requires a significant amount of development in certain areas but a solid, reliable, basis for future development has been created.

CHAPTER 13

FUTURE DEVELOPMENT OF SIMULEX

The future development of the program written for the simulation of building evacuation is discussed, and areas for improvement are highlighted. The future application of the program is discussed both in terms of scientific research and its potential for use as a design tool.

13.0. DEVELOPMENT OF THE MODEL FOR MULTI-LEVEL BUILDINGS.

At present, SIMULEX can model the movement of thousands of individual people through a building plan. Each person is assigned individual characteristics such as age and normal walking speed, and movement is re-assessed every tenth of a second. The program accommodates buildings with complex plan geometries and is capable of simulating the movement of individuals through building spaces as large as 1km².

The next step in the development process is to write additional algorithms for SIMULEX to accommodate multi-level buildings. Each building floor plan would be stored separately in memory, with stairwells modelled as links between different levels. The model would still use the complex 'distance mapping' techniques for route-finding on a given floor, but it is possible that stairs could be treated slightly differently due to the comparably simple geometry of staircases. Routines based upon the 'Effective width model' (Pauls - 1980) could be used for vertical pedestrian movement through the building. An alternative way of modelling vertical movement through the building would be to define a staircase as a series of inclined planes (stair flights) and horizontal planes (landings) through which each simulated person could walk, guided by a three-dimensional distance map.

When staircases can be modelled, SIMULEX will become an extremely useful design tool, allowing the user to test a variety of escape geometries for a proposed multi-level building. The merits of certain staircase geometries and corridor layouts might be assessed to maximise both the available floor space and the efficiency of use of emergency exits. The commercial advantages of increasing the usable floor space of a shop or office, while maintaining safe evacuation routes, could be considerable.

13.1 DIFFERENT OPERATING ENVIRONMENTS

SIMULEX should be developed for use in an operating environment other than standard DOS, to radically change the way in which the simulation program uses computer memory. At present, all data has to be segmented into separate, discrete blocks of not more than 65 Kb because of the way in which memory access occurs through DOS. This produces a very cumbersome method of access to distance

maps which can be larger than 1Mb in size, and need to be segmented into hundreds of different memory blocks. A memory management program, "386MAX", is currently used to facilitate access to most of the upper memory areas of the PC, by the use of a system known as 'virtual memory'. Therefore, in order to gain access to any block of upper memory, SIMULEX has to 'page-in' the block by transferring it to a lower area of 'dynamic memory', accessing the relevant numbers, and returning the block to its original location in upper memory. This whole process drastically reduces the speed at which SIMULEX can extract a section of the distance map for route assessment, because four blocks of memory have to be 'paged-in' every time that the optimal angle of travel is assessed for each person.

If SIMULEX was rewritten to run under the Windows95 environment (not yet available) or the Pharlapp Memory Extender, the distance map would not need to be segmented into different blocks, and the process of 'paging-in' sections would not require the transfer of data blocks from one area of memory to another. The facility of SIMULEX to record a simulated evacuation onto hard disk, and to 'play-back' the recording for future viewing is also severely restricted by memory access under DOS. This facility could be fully utilised by accessing memory through a 32 bit access system (Windows95 or the Pharlapp Extender).

Some algorithms in SIMULEX would, however, run more slowly when operating under Windows. This is because the Windows environment maintains the function of certain additional systems in the 'background' while running a specific program, such as SIMULEX.

The future development of SIMULEX for use under a 32 bit access operating system, such as Windows 95 or the Pharlapp Memory Extender is essential. Such development would allow much more efficient use of memory, and make SIMULEX more commercially viable, by decreasing the processing time required to simulate an evacuation. The resultant full use of the 'record' and playback' functions would become an invaluable feature for use in the office of a building design practice because the simulation of the evacuation of thousands of individuals requires approximately three to six hours of computer processing time. Such a simulation could be executed, and 'recorded' onto hard disk, outside office hours to be 'played-back' for viewing by the user at a more convenient time.

13.2. DATA COLLECTION TO VERIFY AND IMPROVE THE MODEL

The movement algorithms in SIMULEX are based on a combination of the data that is currently available, and the information collected from the analysis of video recordings, described in Chapter 10. Specific areas that need to be investigated in more depth are the effects of different individual body sizes on overall crowd movement; the presence and effect of disabled persons amongst normal, able-bodied people; and specific, individual parameters of movement for disabled individuals in wheelchairs, on crutches, or with support from walking aids. SIMULEX also needs to be used to simulate evacuations from existing buildings, and the results of such simulations compared to the actual 'real-life' evacuations of people from the selected building environments. It is very important that a computer model such as this should be based upon extensive, well-researched data because it is intended for use as a tool to assess life safety.

Further psychological data needs to be collected. Parameters such as the response time to alarm, reaction to an alarm and group interaction need to be assessed. The data that is available at present is not extensive enough for use in a computer model, but it does suggest that the response time to alarm can vary from 5 seconds to 15 minutes. Parameters such as these are therefore extremely important, and can occupy the majority of an evacuation time in certain circumstances.

13.3 THE ADVANTAGES OF FUTURE DEVELOPMENT

With these developments and improvements, SIMULEX has the potential to become an extremely useful tool for the assessment of life safety in buildings. Its ability to constantly display the movement of people through an entire building plan yields an important graphical insight into crowd movements and allows the user to observe where bottlenecks and areas of danger can occur. The building plan can be tested, adjusted, and re-tested until crowd movement is optimised and the design is deemed to be safe. This facility is important when dealing with large, modern buildings which are becoming increasingly complex in design. It is intended that, in the future, an additional software option will be added to allow the user to define the building space by using a Computer Aided Design package, rather than DRAWPLAN. The main reason for this is to increase the commercial viability of the simulation tool, by allowing architects and engineers to use computer files that may

have already been generated during the course of the design process, rather than requiring them to 're-draw' the building with DRAWPLAN.

SIMULEX is reasonably user-friendly and is intended for use as a tool to design and test the evacuation performance and safety of a given building. It can also be used as a research tool to analyse the effect that the geometry of an exit has on the flow rate and the patterns of crowd movement. It has received an encouraging response from members of the Fire Research Station and various Fire Services in Britain, who are willing to be involved in further testing of the model.

13.4 COLLABORATION AND IMMEDIATE DEVELOPMENT

SIMULEX is to be developed by the author of this thesis, at Edinburgh University Department of Civil Engineering and Building Science, in conjunction with members of the Department of Fire Safety Engineering at Lund University (in Sweden) from the 1st of October 1994. The initial funding for this collaborative project is supplied by The Swedish Fire Research Board. The three primary areas of development are: (i) the simulation of pedestrian movement on staircases; (ii) the use of SIMULEX under a different operating system in order that features such as the 'record' and 'playback' facilities can be fully utilised for the simulation of large populations; and (iii) more detailed simulation of psychological characteristics for each individual.

Research staff at Lund University will investigate the creation of psychological profiles for individuals and the time taken by occupants to react positively to an emergency alarm. Additional data will be collected in Sweden by filming evacuations from a superstore, and a night club with four floor levels. The footage will then be analysed by research staff at Lund, by using the image analysis techniques discussed in Chapter 10.

The final goal of the collaborative project is to produce a comprehensive evacuation model that accurately simulates the escape movement of large populations through multi-level buildings. The psychological profiling methods developed at Lund University will become an integral part of the simulation package. The final software package is intended to become a commercially viable tool for the purposes of both research and design.

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APPENDICES

APPENDIX 1

*Publications produced during
the course of this project*

This appendix contains the six papers written by the author during the course of this research project. Supervision and co-authorship were provided by Eric Marchant on all six papers, with additional assistance from Robin Wardlaw for the paper in Appendix 1.2, "Hydraulic Modelling of Crowd Flow".

APPENDIX 1.0

"MODELLING TECHNIQUES FOR EVACUATION"

This paper was presented at the international conference "Engineering for Crowd Safety", 17-18 March 1993, held at the Institute of Civil Engineering, London, and was subsequently published in the book "Engineering for Crowd Safety", R.A. Smith & J.F. Dickie (eds), 1993, Elsevier (Pub.), Amsterdam, The Netherlands.

MODELLING TECHNIQUES FOR EVACUATION

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Abstract

The assessment of the effectiveness of evacuation routes for complex spaces such as: stadia, places of assembly, shopping malls and leisure facilities can present very real problems. Often the geometry of the spaces, combined with high occupancy loadings can reduce the effectiveness of applying standard building regulations which were essentially designed for fairly simple room/corridor/exit layouts. These problems have given rise to the development and application of various crowd simulation models. Computer programs with their potential for accuracy and flexibility, have been developed in recent years and have achieved varying degrees of success. The analogy of crowd movement to fluid flow has been used frequently over the years but, so far, this analogy has not been proved experimentally. This paper outlines the investigation of two modelling methods by the concurrent development of both fluid simulation techniques and a new computer model.

1. CURRENT COMPUTER MODELS

Various computer models for evacuation have been developed to date, but only a few are capable of handling large numbers of people while still processing the movements of each person individually. An outline description of some of the more recent models is given in the following paragraph.

1.1 EXIT 89 [1]

EXIT 89 was the first program to achieve the processing of large numbers of individual people and incorporates some modelling of the effect of smoke spread upon the occupants. The program treats a building as a room network / node system of linked rectangles. Within each rectangular space all occupants are given the same walking speed, unless impeded by smoke. This model has been incorporated into the HAZARD1 package, in an attempt to combine the simulation of fire growth, smoke spread, fire detection, and evacuation. Some correlation with the real life evacuation of a multi-storey building has been achieved. The program is still under development.

1.2 EGRESS [2]

In an attempt to bring some probabilistic modelling and artificial intelligence to the field, this program applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagon may be 'occupied' or 'empty'. An occupied hexagon represents the volume space of one person. Each person steps from one position to the next depending on certain rules. Each person's speed is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real life experiments be carried out soon.

1.3 VEGAS [3]

The VEGAS system has arisen from the recent developments in virtual reality techniques. What is striking about the system is the complexity and detail of the 3-D graphics that illustrate fire growth, smoke spread, and occupant behaviour using real-time animation. The psychological aspects modelled are: group behaviour, alarm awareness and the effects of smoke. Each person chooses a direction by assessing pre-set target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived. Unlike EGRESS and EXIT 89 this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic and the problems of the complex geometry of the escaping persons, their mutual obstruction and pressure increases at crowded doorways.

None of the computer programs have yet undergone the extensive validation procedures required for use as a quantitative assessment tool, but their application provides some interesting qualitative insights.

2. FLUID MODELLING OF ESCAPE MOVEMENT

When people are densely packed into a group, individual movement is prevented, as observed by Fruin [4] in his "no touch zone" configuration. Individuals are carried along by the crowd as a whole and their movements are dictated by the group flow. This movement is normally in one direction in a passageway, and certain characteristics (such as pressure increase) have been observed to be "fluid" in behaviour. The possibility of fluid modelling has been under discussion for more than twenty five years. Peschl [5] suggested that the flow properties of gases, liquids, and plastically viscous materials have been investigated exhaustively and it has not, so far, been possible to establish a law that governs the passage of large numbers of people through doors and narrow passages. The first "Green Guide" [6] made the positive recommendation that the escape flow paths in stadia should be designed as pipe network systems. Riddel & Barr [7] attempted to model the flow of people around crush barriers in a sports stadium by using coloured water flowing over a tilted table which contained model obstructing walls. From close analysis of known data, it is evident that the fluid models described by Peschl and Riddel & Barr cannot combine the complex speed / flow / density relationships, arching characteristics, and flow interactions observed in real life [5-6].

3. TWO PHASE FLUID MODELLING

A crowd flow can be seen as a collection of particles whose mass and movement interact mutually. Looking at the problem logically, it would be incredibly difficult to create masses in a fluid model that control their own movement individually, unless each mass contained a complex "thinking computer" and its own motive system. However, in order to recreate high density system blockages at openings, as observed by Peschl [5] and Predtechenskii & Milinskii [8], some form of mass representation must be incorporated into a physical model. A moving fluid is the obvious choice to provide both the potential for pressure fluctuations and a universal motive force for the crowd particles. Early tests using a combination of rolling masses in fluid [9] appeared to bear some correlation to real life observations.

3.1 EARLY TWO PHASE TESTS

The first tests using the 2 phase modelling system used 24 mm diameter plastic balls rolling in a shallow water flow. The balls were of the same mass density as water to maximise the ball / fluid interaction. The system was tested on a horizontal varnished plywood table, with plywood vertical walls to model corridors. The balls were dropped into the moving water over a 900mm length. The time taken for the last ball to travel the full 900mm was timed and recorded. Changing the number of balls initially introduced over the 900mm length changed the effective density of the modelled crowd flow. The units of density used were m^2 (occupied space) per m^2 (free space) because the maximum packing density of circles is $0.91 m^2 / m^2$ which is similar to the maximum packing density of crowds ($0.92 m^2 / m^2$) observed by Predtechenskii & Milinskii [8]. The experimental results are summarised in Figure (1).

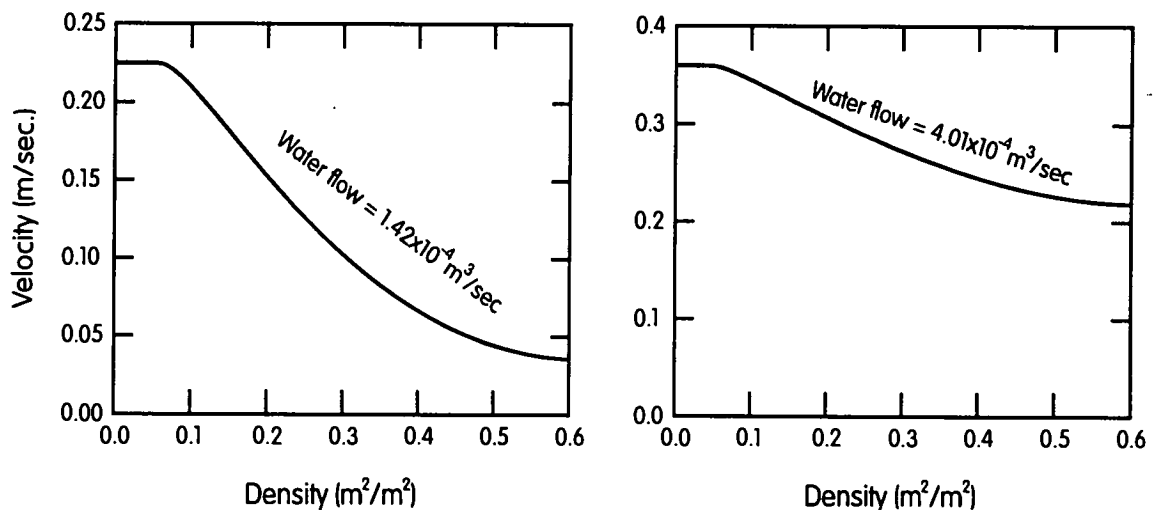


Figure 1a. Experimental speed characteristics for 35mm (scale 0.74m) corridor.

1b. Experimental speed characteristics for 64mm (scale 1.4m) corridor.

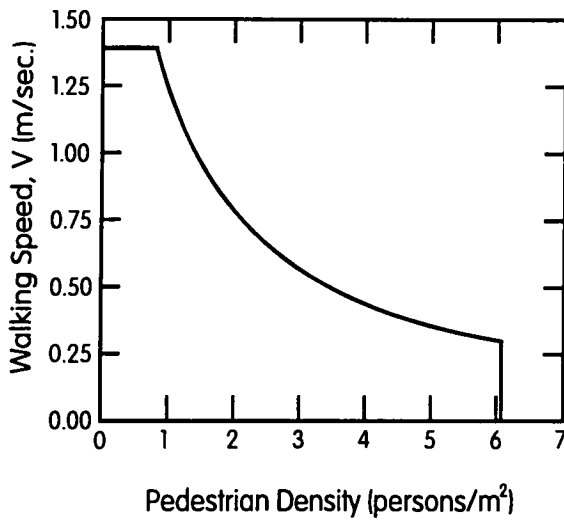
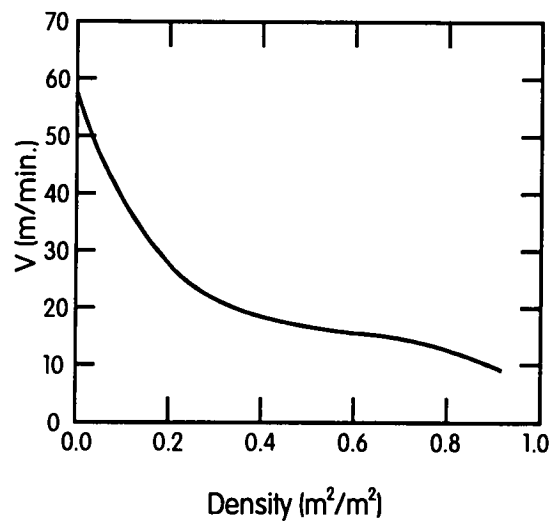


Figure 2a. Real life speed curve for corridors above 1.1m width, adapted from Ando *et al.* [10]



2b. Real life speed curve for corridors above 1.1m width, adapted from Predtechenskii & Milinskii [8]

A comparison of the results from Figures (1) and (2) reveals an encouraging similarity in the experimental and real life speed/density curve shapes. The commonly referenced flow/density curves shown in Figure (3) can be seen as derivations of the speed/density curves and a comparison of these curves reveals more about the mechanism of the model. Although this is not a quantitative comparison, there is a reasonable similarity between graphs of the experimental results and real life measurements.

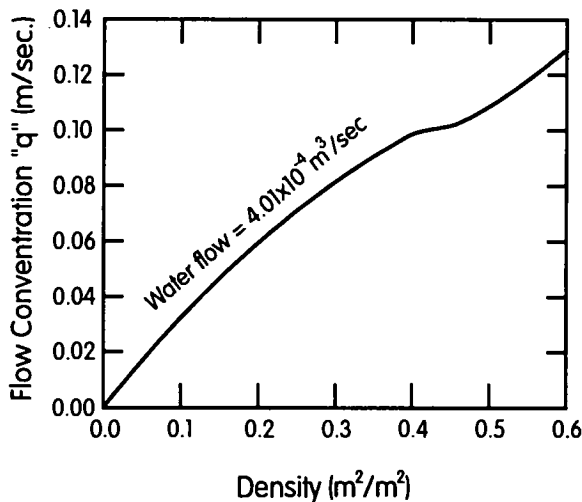
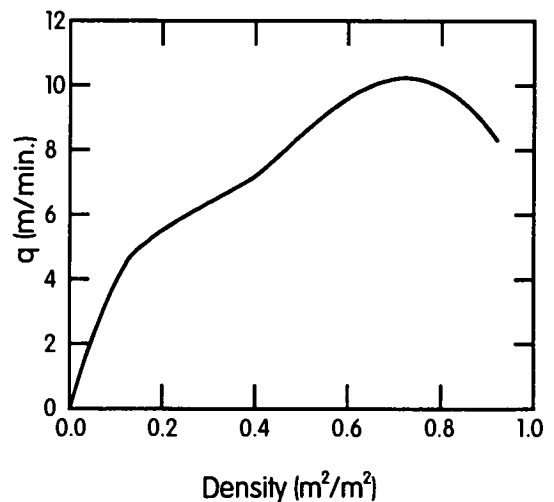


Figure 3a. Experimental flow curve for 64mm (scale 1.4m) width corridor



3b. Real life flow curve for corridors above 1.1m width, adapted from Predtechenskii & Milinskii [8]

Figure (3) shows that the curve shape obtained experimentally is similar to that observed for real life readings up to $0.6 \text{ m}^2/\text{m}^2$. Above this value, results could not be obtained due to friction in the apparatus and premature jamming which occurred below the maximum packing density value. For corridors less than 1.1 metres wide, data is scarce, but BS5588 [11] suggests a rapid restriction of flow as corridors decrease in width below 1.1 m. The preliminary two phase tests support this view.

3.2 The Mechanism Of The Model

It is postulated that the fluid pressure in the open channel represents psychological pressure (*i.e.* the invasion of personal space). As ball (or model person) density increases, water height increases resulting in an increase in fluid pressure and a decrease in overall system speed.

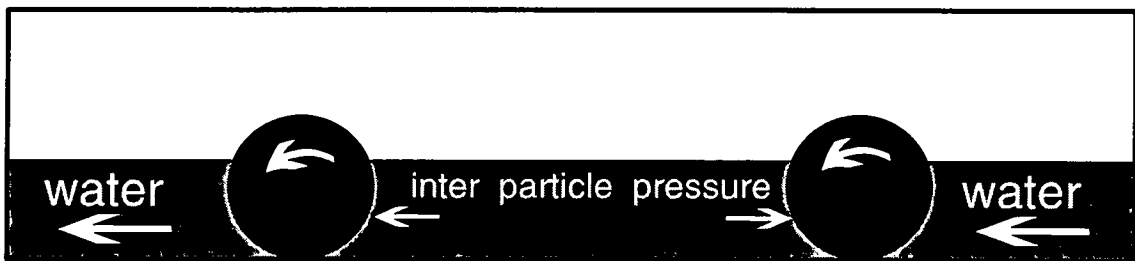


Figure 4. The mechanism of two phase flow

3.3 CURRENT DEVELOPMENT OF THE MODEL

The first apparatus using fluid flow to motivate lines of initially stationary balls yielded some encouraging results. It was possible, however, that the total travel time for each ball was significantly effected by the time taken for the water to accelerate all of the balls to their flow velocity. In order to consolidate the results, some form of constant circulation/steady state apparatus was required. This new apparatus has been developed and consists of a pulse generator that controls solenoid pistons which feed the balls into the fluid flow at a controlled rate. The balls roll in the water flow and once they leave the fluids table they are propelled by compressed air through a pipe and are recycled to the piston feed system.

The new system produces a continuous, variable flow of balls and fluid. These continuous flows have generated a 2-phase system in which the properties of either flow can be measured easily. The results from the new apparatus have shown that the velocity changes with people (ball) density changes are similar to the results generated in the original apparatus.

A large number of tests using small scale corridors of real size 0.7 - 2 m are to be executed. There is a possibility of testing complex geometries by dropping balls in over large areas via a grid network and assessing the fluid/mass escape behaviour of the system.

4. THE NEED TO DEVELOP NEW COMPUTER MODELS

Existing computer models either make significant assumptions about the speed and direction of travel of each person, or accommodate each person's position by use of a grid cell network where each cell is the size of one person. The one exception is the VEGAS package which processes each person's precise co-ordinates. The VEGAS package contains many psychological factors and physical shape characteristics but the direction finding capabilities are dependent on user-specified target points dictating the direction of his/her chosen exit route. There remains a need for a program that treats each person individually, with individual characteristics (including age, disability and eagerness to escape) that can cope with infinite geometrical possibilities, whilst automatically assessing the entire escape route for each person, and reassessing the route (both locally and globally) at each time step of motion. There is also a need for overtaking, queuing, and other behaviour modelling. Each position should be precise and the crowd should be continuously displayed on the computer screen. The VEGAS package does achieve all of these factors, except for the automatic assessment of individual routes through an infinitely complex geometry. When applied to the building types for which it is designed, it yields a useful graphical insight into the whole escape process. As with all egress computer models, the prime need is for validation with real - life behaviour and crowd flow characteristics.

5. SIMULEX

In an attempt to achieve egress simulation through any building geometry a program was embarked upon that automatically defines an escape route map, using distance contouring.

5.1 ASSESSING ROUTE TO EXIT BY DISTANCE CONTOURING

Firstly, the building plan is drawn on the screen using the mouse to drive a simple drawing package designed for this program. This plan is then passed to a program which processes it and automatically sets up a high definition integer distance grid with all space occupied by walls / objects possessing high (solid) values, and exit (empty) values set to zero. Within this grid it sets up a contour map (see Figure 5) of distance from the nearest exit through the whole building space. This map is set up so that the optimum direction to nearest exit is accurate to within 2 degrees, while computer processing time remains short. The routine can also be used to assess minimum travel distance alone.

5.2 ASSESSING SPEED

Each person's speed is assessed individually at each time step. Each person is given a random unimpeded walking speed of between 0.8 m / second (i.e. an elderly woman) and 1.7 m / second (an able-bodied adult male). Reduced speed due to the proximity of others is calculated using an approximation of the speed/density curve presented by Ando *et al.* [10]. Unfortunately, the curve assesses speed in relation to crowd density over a given area, so some data manipulation is required to yield a

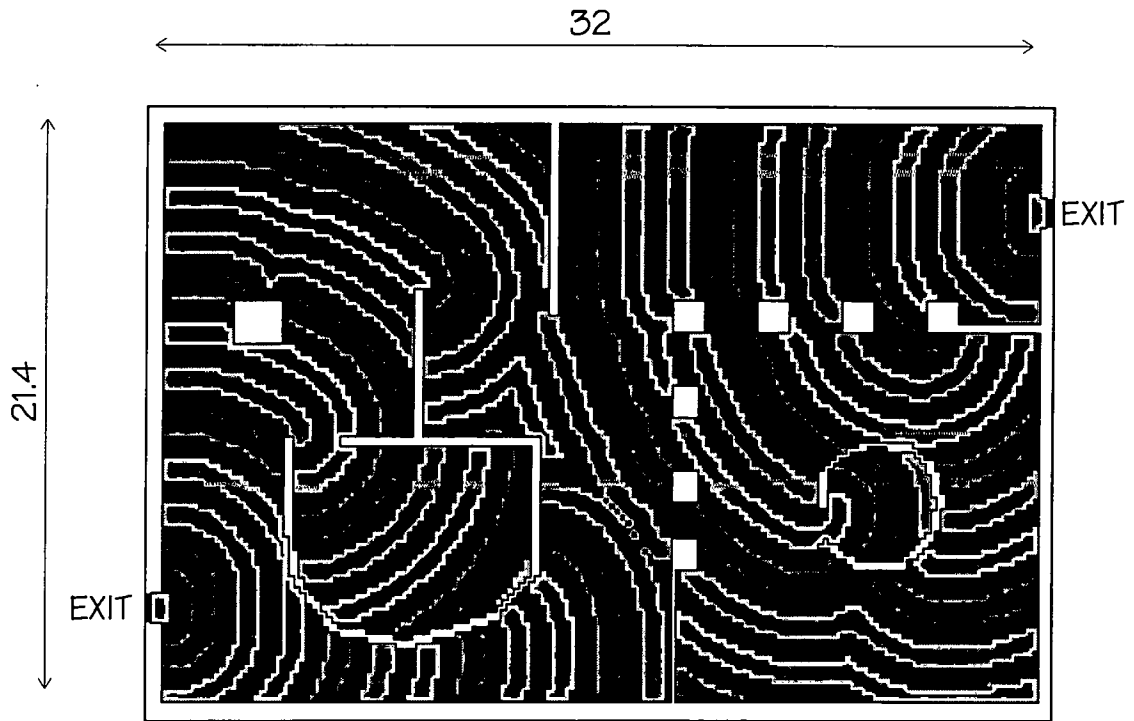


Figure 5. A Distance Contour Map, (dims. m.) (Walls / obstructions in white with black outline. 1 Contour Width = 0.8m)

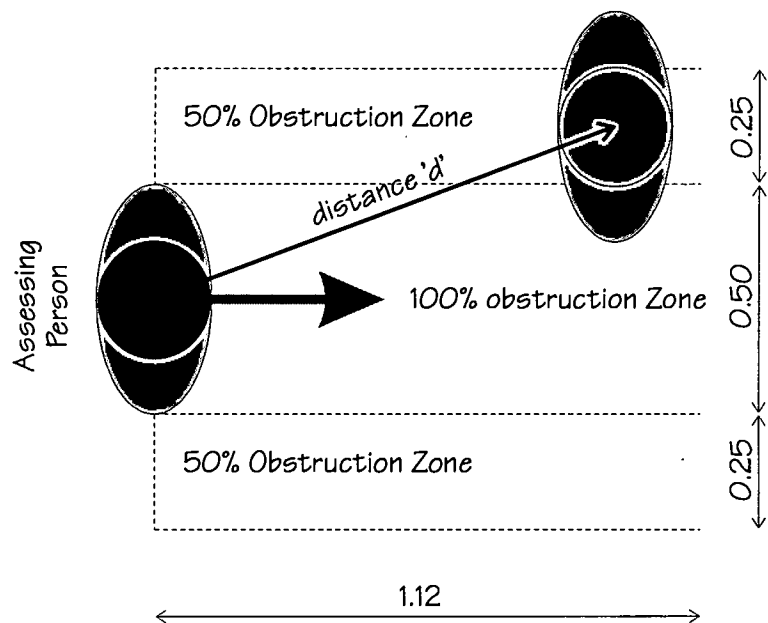


Figure 6. Obstruction Zones For Speed Assessment, (dims. m.)

method of assessing speed reduction caused by the proximity of other individuals. For the purposes of the program, an individual's velocity is related to the distance d between centre co-ordinates of the person in question and others in the obstruction zones. From the relationship

$$\text{density} = 1/d^2 \quad (\text{for a single obstructing person}) \quad (1)$$

the following formula for speed reduction was derived.

$$\text{speed reduction ms}^{-1} = (\text{unimpeded speed} / 1.4) \{1.4 - [0.25 + ((d - 0.4) / 0.6309)]\} \quad (2)$$

where 0.6309 is a time factor (sec) and also if $d < 0.4$, absolute speed = 0.1ms^{-1}

The speed reduction effect is fully implemented in the 100% zone (Figure 6) but only $1/2$ of the speed reduction factor is implemented in the 50% obstruction zones. Only the bodies nearest to the assessing person in each zone are considered. If both 50% zones contain bodies closer than any in the 100% zone, the 100% zone is ignored.

5.3 OVERTAKING & QUEUING

If a person's speed is reduced, the program scans each side of the direction of travel; if a significant improvement in speed is obtained, then the direction of travel changes to the new deviated angle. Overtaking and localised deviation of route is observed frequently, and the deviation routine produces a degree of jostling in the higher density crowds.

The program, by its nature, inherently models queuing. The speed calculations never yield a zero value, but each person is only allowed to move into unoccupied space and will therefore become stationary if standing exactly behind another person, with no room to move sideways. As yet, no pushing or pressure build up is modelled.

5.4 TEST RUNS

The program has been tried on various plan layouts. At this stage, staircases have not yet been modelled because validation on a single storey, flat plane is first required.

Test runs start by the user specifying a density of persons per unit area distributed evenly over the building plan. The program sets up each person's co-ordinates and unimpeded walking speed, and then begins to move them immediately. No delay has yet been programmed in for reaction time and different types of alarm; this will be implemented in later versions. These psychological factors are far too important to ignore in a final version.

In order to assess the maximum flow capacity of a doorway width, the test shown in Figure 7a was executed to simulate a high density, non-panicking crowd at a doorway. In this test the flow rate q was found to be 1.8 persons/(m width)/s. When slight changes are made to the overtaking/jostling algorithm and the order in which speed assessment occurs, then q can vary from 1.5 to 2 persons/(m width)/s. Real life

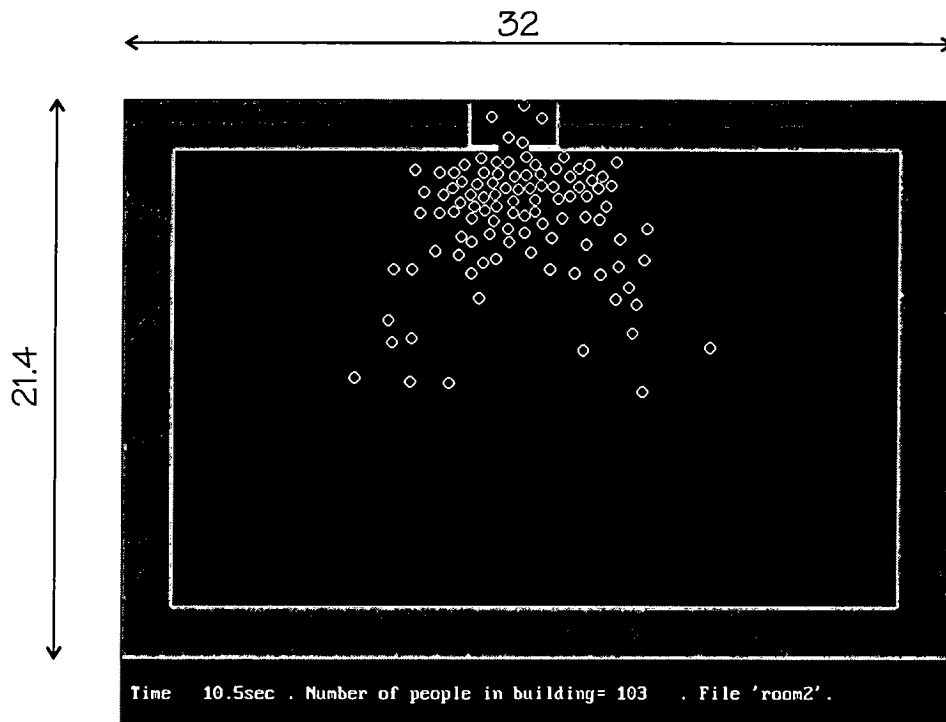


Figure 7a. Screen display from SIMULEX test run on simple room (dims. m.)

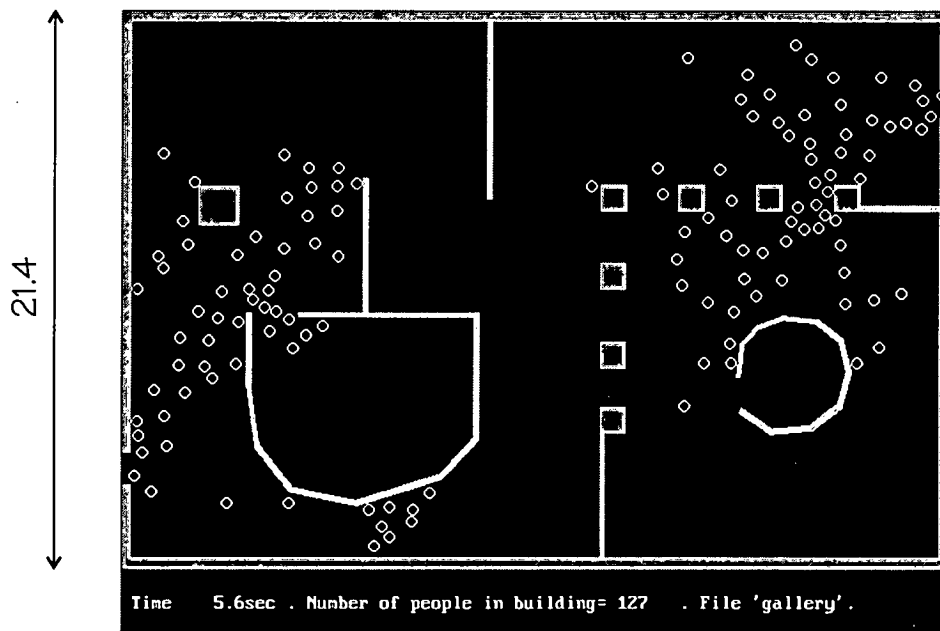


Figure 7b. Screen display from SIMULEX test run on complex area (dims. m.)

observations of q include 1.5 ('Fire & Buildings' [12]) and 1.8 persons/(m width)/s (Melinek [13]). This correlation of simulated value to real life is very encouraging, especially in view of some of the assumptions made in the speed assessment routine.

Figure 7b demonstrates the ability of the program to cope with complex geometries and obstructions of any size. It became clear from watching the progress of various simulations that putting a narrow obstruction in the centre of a 1.8m opening significantly reduced its flow capacity, even though the total combined opening width was only be reduced by 0.1m.

6. CONCLUSIONS

The two phase model has proved effective in simulating some of the characteristics of simple crowd flow. The continued development of the model using steady state rolling experiments is expected to yield more valuable and complete data. More thorough validation over a wide range of corridors is required, and then the model may be applied to test different door opening geometries, as well as unusual corridor/room layouts. SIMULEX was not used to simulate the specific fluid experiments because in this early version of the program, friction factors in narrow corridors have not yet been applied.

To date, one of the most notable results from the computer model test runs is the correlation between test results and real life values of crowd flow rate per unit exit width, but more large scale validation is required. The route finding methods adopted, automatically reassess exit routes at each time step, the only input required being the building plan itself. All exits in the building are recognised automatically and any geometry of obstruction can be accommodated. The program is currently restricted to small areas but is being converted to a more powerful language assembly tool in order to model areas the size of large stadia.

The investigations described have provided an insight into the fluid flow analogy and the potential for strong correlation now exists for specific crowd flow conditions. The computer methods adopted in SIMULEX show promise because of their flexibility in handling infinite spatial variations combined with the routines for automatic route assessment. The program is written to easily incorporate disability, aggressiveness and variation in body size and shape. In order that a choice of exit other than the nearest one be assessed (for each person) contour maps for different exits could be overlaid in computer memory, and familiarity weightings could be applied by increasing the initial contour value at an exit before the complete contour map is created. Smoke spread could be simulated by the progressive addition of weighting factors to the contour maps, over increasing areas.

In the future, further validated results from the fluid experiments could be incorporated into the computer program, especially with regard to the speed assessment routines. This investigation has produced the first encouraging results from the crowd/fluid flow analogy and a new type of route finding technique has been developed for the computer model. Both models, however, contain restrictions and future work will attempt to improve the flexibility and validity of both systems.

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APPENDIX 1.1

"MODELLING AND MEASUREMENT OF ESCAPE MOVEMENT"

This paper was presented at the international conference "Engineering Fire Safety in the Process of Building Design" (CIBW14 - Seminar/Workshop), 14-16 September 1993, held at the University of Ulster, Jordanstown, Co. Antrim, Northern Ireland. The paper will be included in the conference proceedings, which have not yet been published.

MODELLING AND MEASUREMENT OF ESCAPE MOVEMENT

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Abstract

Modern research into 'escape movement' has been primarily concerned with analysing the general movement of crowds as a whole. These observations have been used as the basis for approximate rules that attempt to simulate crowd speeds and flow rates in fairly simple geometries.

The 'general rule' approach has come under increasing scrutiny in recent years, and the sophistication of modern computer modelling techniques demands that the data available should be of a more specific and quantitative nature. The accuracy of any computer model is wholly dependant upon the exactness and nature of the data that is available to it. The effects of people's reaction to alarm has been observed by Proulx [1], and other researchers both in the U.K. and the U.S.A.. The dependency of an individual's unimpeded walking speed upon age and gender [2] and disability [3] has been collated, and there have been many observations of overall crowd speeds and flow rates by Predtechenskii & Milinskii [4], Pauls [5], and Hankin & Wright [6], but there has been little research into the 'mechanics' of crowd movement. It is understood that crowd speeds decrease when the concentration of people increases, but there is a lack of knowledge about the interactive dynamics that cause this behaviour. Laws for the velocity and directional behaviour of a crowd's individual constituent members need to be developed if simulation models are to become more sophisticated and more accurate. This paper details some of the ongoing research into the nature of crowd flow and escape movement.

1. FLUID MODELLING OF ESCAPE MOVEMENT

Crowd movement has been frequently compared to fluid flow, and the possibility of fluid modelling has been under discussion for more than twenty five years. Stahl [7] has stated that " the early meetings of the Committee on Safety to Life appear to have formally adopted a physical-science approach to building egress in which building occupants, like water, gas particles or ball-bearings, were assumed to respond immediately, and to be affected only by spatial configuration and density". The first "Green Guide" [8] made the positive recommendation that the escape flow paths in stadia should be designed as pipe network systems.

Fruin [9] observed that in his "no touch zone" configuration, when people are densely packed into a group, individual movement is prevented. People are carried along by the crowd as a whole and their movements are dictated by the group flow. This movement is normally in one

direction in a passageway, and certain characteristics (such as pressure build-up) have been noted as being 'fluid' in behaviour. Peschl [10] suggested that the flow properties of gases, liquids, and plastically viscous materials have been investigated exhaustively but that it had not been possible to establish a law that governs the passage of large numbers of people through doorways and narrow passages. Riddell & Barr [11] attempted to model the flow of people around crush barriers in a sports stadium by using coloured water flowing over a tilted table, around model obstructing walls. On close analysis of known data for crowd behaviour, it is evident that the fluid models described by Peschl [10] and Riddell & Barr [11] cannot combine the arching characteristics, flow interactions and complex speed / flow / density relationships observed in real life.

There will always be some inherent limitations in any fluid model, however successful, because of the physical nature of fluid flow. Stahl [7] described some of the pre-requisite assumptions for a hydraulic model as being; "...1. building occupants are alert, able bodied and ambulatory; 2. fire safety depends on the 'safe end' of the evacuation system....", and "... 3. there is high density building occupancy which, during a fire emergency, limits the reasonable options for evacuation that are available to building occupants". A successful fluid model must be appreciated in context. Complex psychological scenarios such as; reaction to alarm, family group interactions, occupant familiarity to the building and reaction to hazardous conditions will not be simulated. The success of a fluid model should be gauged by how well it describes some of the basic parameters of crowd flow, including the reduction of speed with increased crowd concentration and pressure fluctuations or 'surges' within the crowd.

2. THE BASIC PARAMETERS OF CROWD FLOW

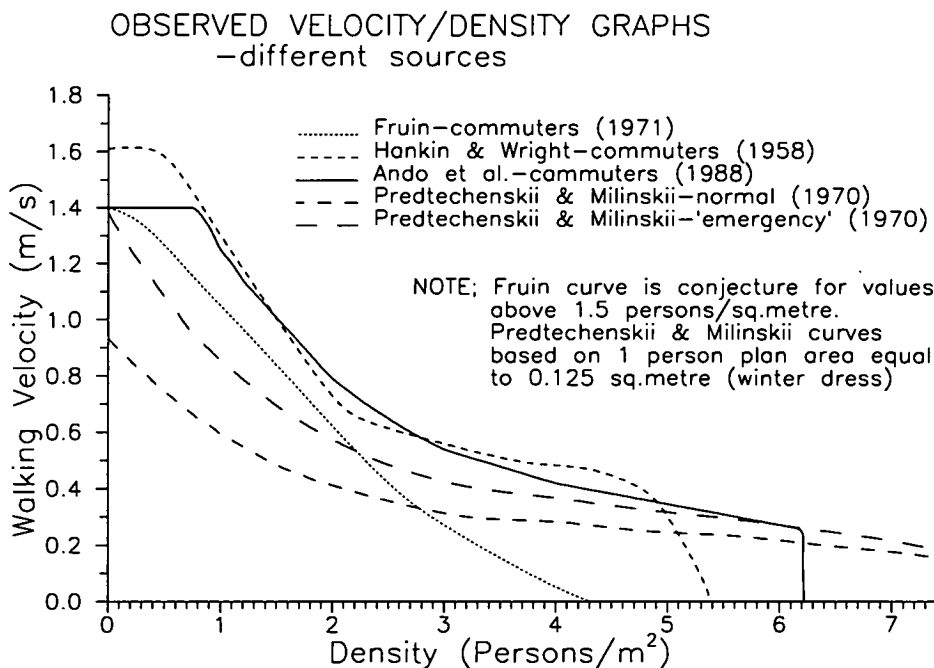


Figure 1. A comparison of available data on the crowd velocity / density relationship

The essence of simple crowd flow is the relationship between the proximity of individuals and their walking speed. As the distance between people in a crowd is reduced, the crowd density increases and the overall speed of forward motion in the group decreases. When the proximity increases to such a degree that bodily contact is incurred, then 'shuffling' and further irregular speed reduction occurs. At very high crowd concentrations 'body arching' or jamming can cause major speed reductions, and halt the forward motion of the crowd. This pattern of behaviour has been observed and collated by many researchers, some of whose results are summarised in Figure 1. Note that the units are those used by Ando *et al* [2], and that all other data has been converted from different unit values; notably Predtechenskii & Milinskii [4] who originally used density units of square metres (occupied space) per square metre (free space). For comparison purposes, 1 person/sq. metre = 0.125 m²/m².

3. '2-PHASE' FLUID MODELLING - Mass Particles in Fluid

It is evident from standard hydraulic equations [12], that simple, uninterrupted fluid flow cannot describe the basic parameters of crowd flow. The crowd density cannot be assimilated and it is known that the speed reduction effects cannot be observed. For example, reducing the width of a channel in uninterrupted open channel flow actually leads to an increase in the fluid velocity.

Individuals in a large, moving group of people may travel at a speed that is different from the average velocity of the group. The movements and actions of individuals cause changes in the psychological and physical pressures within the group. For such pressure fluctuations to be observed, some form of representing the mass of individuals within the 'crowd' is required. It would be incredibly difficult to create masses in a fluid model that control their own movement individually, unless each mass possessed artificial intelligence and it's own motive system. In order to recreate high density system blockages at openings, as observed by Peschl [10] and Predtechenskii & Milinskii [4], a physical model must contain masses that interact, and possess frictional properties. A moving fluid is the obvious choice to provide both the motive force for the crowd particles and the means for particle-particle interaction by wave propagation and pressure fluctuations.

Early tests using a combination of rolling masses in fluid [13] appeared to bear some correlation to real-life observations, and these tests have been developed further into 'steady state' rolling ball experiments.

4. EARLY '2-PHASE' TESTS - Balls initially static

The first tests using the 2 phase modelling system used 24 mm diameter plastic balls rolling in a shallow water flow. The balls were of the same mass density as water to maximise the mass / fluid interaction. The system was tested on a horizontal varnished plywood table, with plywood vertical walls to model corridor walls. The balls were dropped into the moving water over a test section of 0.9m length, and the time taken for the last ball to travel the full length was timed and logged. The mean velocity was obtained by dividing 0.9m by the total travel time. Changing the number of balls initially introduced over the section changed the effective density of the modelled flow of people. The units of density used were m² (occupied

space) per m^2 (free space). These units were used because the maximum packing density of circles is $0.91 m^2 / m^2$ which is similar to the maximum packing density of crowds ($0.92 m^2 / m^2$) observed by Predtechenskii & Milinskii [4]. Some of the experimental results are summarised in Figure 2.

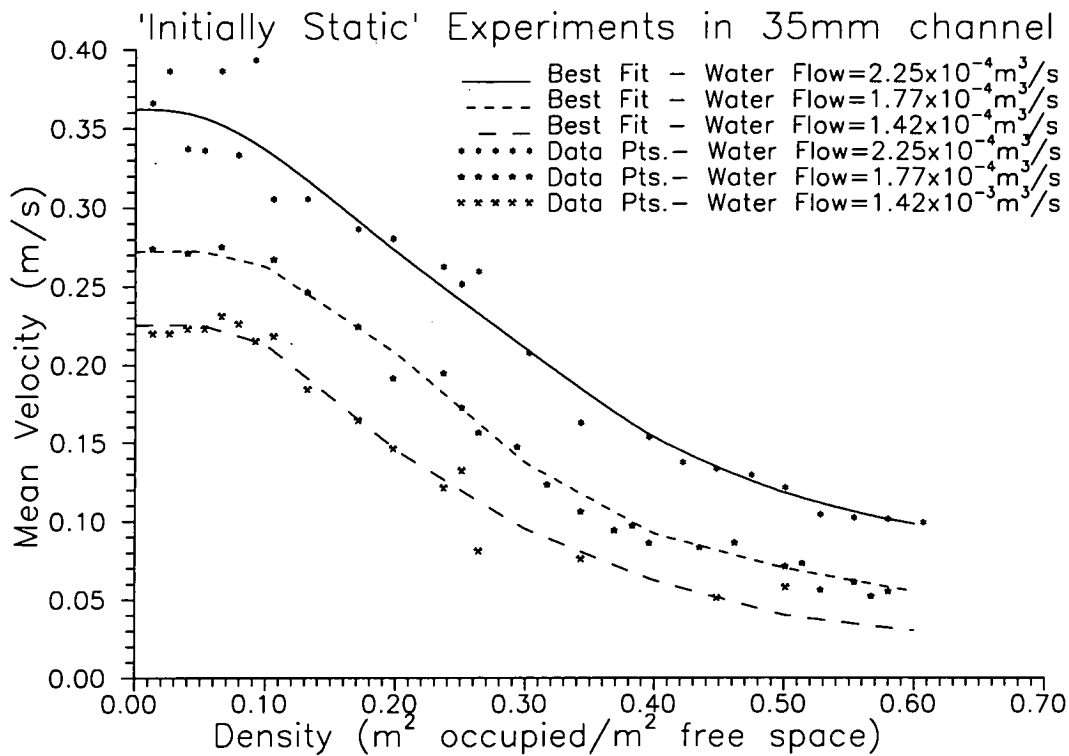


Figure 2. Speed characteristics for 35mm (scale 0.74m) corridor - 'static' tests

It can be seen from the results illustrated in Figure 1 and Figure 2 that the curve shape obtained by experiment is similar to that observed, for densities up to $0.6 m^2/m^2$. Above $0.6 m^2/m^2$, results could not be obtained due to the large amount of friction in the apparatus and the occurrence of jamming premature to achieving the maximum packing density value. For corridors less than 1.1 metres wide, data is scarce, but BS5588 [14] suggests a rapid restriction of flow as corridors decrease in width below 1.1 m, and the early 2-phase tests support this view. Although this is not a quantitative comparison, there is a reasonable similarity between the experimental results and the readings from observational measurements.

5.0 'STEADY-STATE' ROLLING EXPERIMENTS

A more advanced type of apparatus was developed, as illustrated in Figure 3. One possibility for the formation of the speed / density curve shape in the early apparatus was that the time to exit was dependent upon the time taken for the moving water to accelerate the balls from zero velocity up to flow velocity. As a result, some form of a 'steady state' apparatus was required. The new apparatus was designed and constructed. Balls are fed into the fluid flow by a

regulated solenoid piston. Once the balls leave the fluids table they enter a pipe and are recycled to the piston feed system, propelled by compressed air. This new system produces continuous, variable flows of balls and fluid. These continuous flows have generated a 2-phase system in which the properties of either the ball or fluid flow can be measured easily. After the 'steady state' has been achieved for a specific density, each test is video-taped and the results obtained by analysing the images on a monitor.

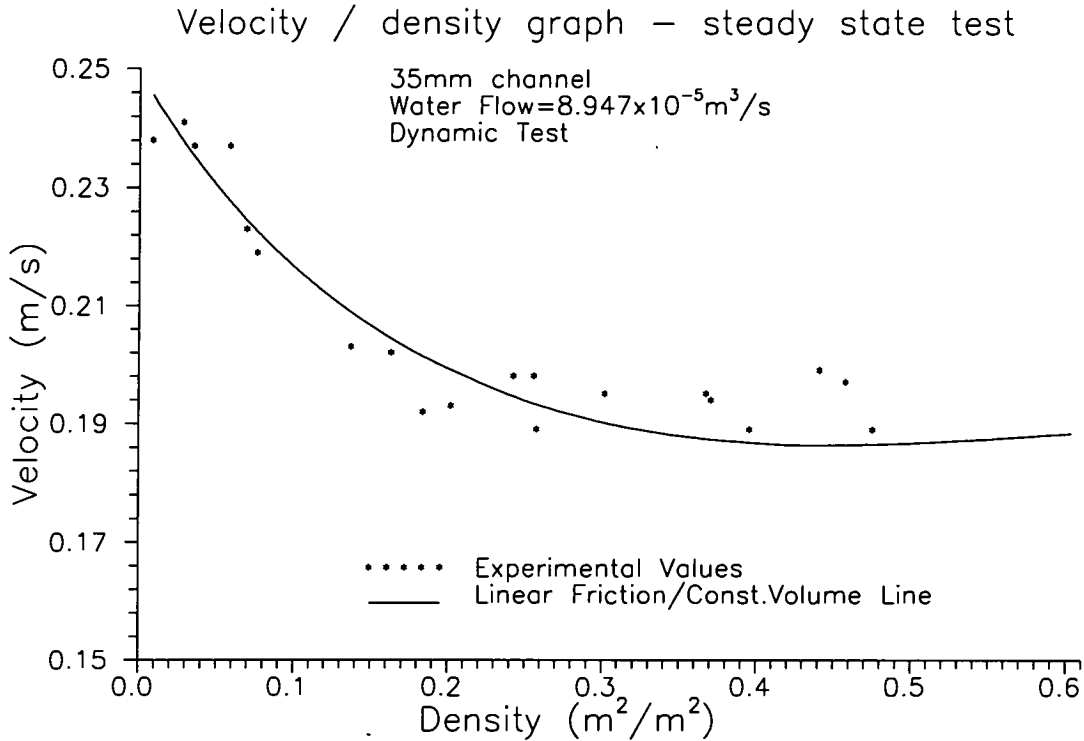


Figure 4. Early results from the Steady State apparatus.

The results presented in Figure 4, show that the velocity/density relationship in the 'steady state' apparatus displays a trend that is similar to the behaviour observed in the earlier 'initially static' tests shown in Figure 2. The trend is encouraging, but the absolute value of velocity is not sufficiently reduced at high densities for direct correlation. Further tests are in progress and the available range of variables will be examined in the search for a good correlation. A large number of tests using small scale corridors of equivalent sizes 0.7 - 2 metres wide are to be executed. There is a possibility of testing complex geometries by dropping a grid balls into the surface of a tray of water, representing large areas, and assessing the fluid / mass escape behaviour of the system.

5.2 MECHANISM AND MATHEMATICS OF THE MODEL

In this physical crowd flow simulation, fluid pressure in the open channel is analogous to psychological pressure (the invasion of personal space). As ball (or 'model person') density increases, water height increases resulting in increased fluid pressures and a decrease in the overall system speed and flow rate.

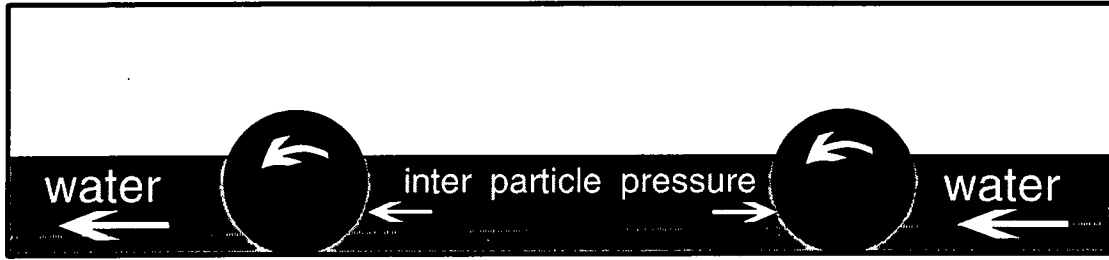


Figure 5. The mechanism of '2-phase' flow

The 'Linear Friction/Const. Volume Line' displayed in Figure 4 is calculated using an adaptation of Mannings Equation for open channel flow. The graphical curve obtained describes a 'best fit line' through the experimental data, and therefore the equation models the flow of semi-submerged particles fairly well. In this adapted form of open channel flow, Mannings Equation takes the form;

$$V = \frac{\left(\frac{A}{P}\right)^{\frac{2}{3}} \sqrt{i}}{(\eta + NF)} \quad \dots (1)$$

where:- - V is velocity (m/s)

- A is the average cross-sectional area of water (m²)
- P is the wetted perimeter (m) calculated by dividing the total wetted surface area over the test section, by 1.5m (the test section length)
- i is the hydraulic gradient (assumed to be the apparatus bed slope)
- η is Mannings skin friction factor for the channel surface
- F is the friction factor for each ball
- N is the number of balls in the test section

This equation assumes that total friction in the system is proportional to N, and that there is a constant volume of water flowing through the test section.

5.3 APPLICATION OF THE HYDRAULIC MODEL

The '2-phase' hydraulic model is to date, the only physical fluid model to demonstrate any of the characteristics of crowd flow, and should be useful for certain predictive aspects of modelling crowd movement. It is envisaged that, under conditions where the crowd movement is uni-directional, the effect of exit shapes and fluctuating corridor widths be assessed, and compared to some of the real-life observations of Peschl [10], Predtechenskii & Milinskii [4] and Hankin & Wright [6].

6.0 COMPUTER MODELLING TECHNIQUES

Various computer models for evacuation have been developed to date, but only a few are capable of handling large numbers of people, while still processing the movements of each person individually. An outline description of some of the more recent models is given in the following paragraph.

6.1 EXIT 89 [15]

EXIT 89 was the first program to achieve the processing of large numbers of individual people and incorporates some modelling of the effect of smoke spread upon the occupants. The program treats a building as a room network-node system of linked rectangles. Within each rectangular space all occupants are assigned the same walking speed, unless impeded by smoke. This model has been incorporated into the HAZARD1 package, in an attempt to combine the simulation of fire growth, smoke spread, fire detection, and evacuation. Some degree of correlation with a real-life evacuation of a multi-storey building has been achieved. The program is still under development.

6.2 EGRESS [16]

In an attempt to bring some probabilistic modelling and artificial intelligence to the field, this program applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagon may be 'occupied' or 'empty'. An occupied hexagon represents the volume space of one person. Each person steps from one position to the next depending on certain rules, and speed is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real-life experiments will be carried out later in 1993.

6.3 EXODUS [17]

The movement model in EXODUS bears some resemblance to that incorporated in EGRESS, in that movement is accommodated by a person stepping from one 'cell' or node to the next. The program is primarily intended for use on mass transport vehicles and the environment space is represented by a network of nodes, connected by arcs that define the available path of movement from one position to the next. Each node is the size of one person, and is regarded as either occupied or empty. Many character traits are described, and input from a fire & smoke spread program can be received and used to affect the behaviour of the occupants. An early validation exercise was executed by comparing EXODUS output to some aircraft evacuation tests and the experimental trends were simulated. Some of the simulated evacuation times were similar to the real-life tests, but not consistently so. This was possibly due to the lack of specific data for the traits of each person in each evacuation.

6.4 VEGAS [18]

The VEGAS system has arisen from the recent developments in virtual reality techniques. The system illustrates fire growth, smoke spread, and occupant behaviour using real-time

animation. The psychological aspects modelled are: group behaviour, alarm awareness and the effects of smoke. Each person chooses a direction by assessing pre-set target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived. Unlike EGRESS and EXIT 89 this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic, the mutual obstruction of escaping people and forces acting on their bodies at crowded doorways.

None of the computer programs outlined above have yet undergone the extensive validation procedures required before they could be used a quantitative assessment tool, but their application does provide some interesting qualitative insights.

7.0 THE NEED TO DEVELOP NEW COMPUTER MODELS

Existing computer models either make large assumptions about the speed and direction of travel of each person, or accommodate each person's position by use of a grid cell network where each cell is the size of one person. The one exception is the VEGAS package which processes each person's precise co-ordinates. The VEGAS package contains many psychological factors and physical shape characteristics but the direction finding capabilities are dependent on user-specified target points dictating the exit route. There remains a need for a program that treats each person individually, assigning individual characteristics (including age, disability, eagerness to escape) that can cope with infinite geometrical possibilities for escape. It should automatically assesses the entire escape route for each person, whilst re-assessing the route (both locally and globally) at each time step of motion. There is also a need to model overtaking, queuing, and other behaviour characteristics. The VEGAS package does achieve many of these factors, except for complex overtaking routines and the automatic assessment of the direction of individual routes through an infinite geometry. When applied to the building types for which it is designed, it does yield a useful graphical insight into the whole escape process. All 'egress' and 'escape' computer models require validation with real-life behaviour tests and crowd flow characteristics, but the adoption of more realistic movement parameters and methods should ensure that the comparison to real-life observations becomes more rewarding.

8.0 SIMULEX - developing some new techniques

The SIMULEX program is being developed in order that individual movement can be modelled more realistically, through any geometry of building plan. This is made possible by the use of distance contouring. Other parameters that are built into the program include; walking speeds, overtaking, body twisting, and queuing.

8.1 ASSESSING ROUTE TO EXIT

Firstly, the building plan is drawn on the screen using the mouse and a simple drawing package designed for this program. This plan is then processed and automatically converted to a high definition integer distance grid where all walls / solid objects are assigned the maximum value, and exit values are set to zero. Within this grid the program sets up a contour map of distance from the nearest exit which emanates through all of the open space available

to people. The contour map shown in Figure 6 is set up so that the optimum direction to the nearest exit is accurate to within 2 degrees, while computer processing time remains relatively short. The routine can also be used to assess minimum travel distance from the most remote point of the building, as required by the building regulations.

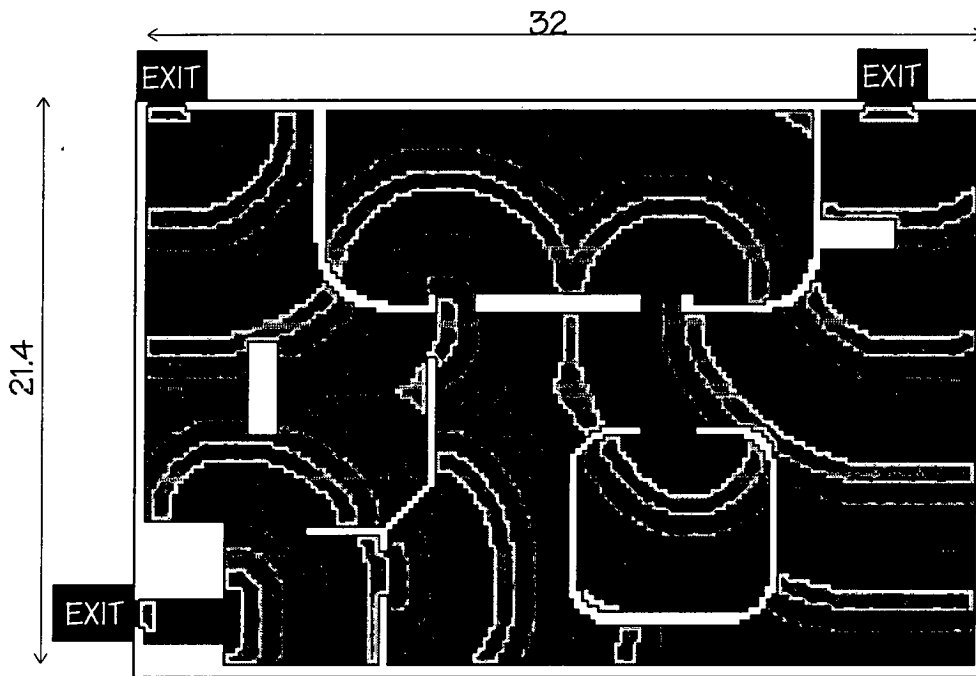


Figure 6. Distance Contour Map for a Complex Office Space

8.2 WALKING SPEED

Each person's speed is assessed individually at each time step (0.1 sec.). Each person is assigned a random unimpeded walking speed of between 0.8 m/s (an elderly woman) and 1.7 m/s (an eager, young man of 20 years). Speed reductions due to the proximity of others is calculated using an approximation of the speed / density curve presented by Ando *et al* [2]. Unfortunately, the curve assesses speed in relation to crowd density over a given area, so some data manipulation is required to yield a method of assessing speed reduction caused by the proximity of other individuals.

For the purposes of the program, the speed is related to the inter-person distance 'd' between centre co-ordinates of the assessing and obstructing persons, as illustrated in Figure 7. Equation (2) assumes that in a crowd of evenly spaced people, the area per person is equal to the square of the inter-person distance. Using this spatial assumption, the velocity/density relationship described by Ando *et al* [2], is approximated in terms of inter-person distance by Equation 3. The original data plotted by Ando *et al* is plotted in Figure 1, and a graph of the derived data is shown in Figure 6.

$$d = \sqrt{\frac{1}{D}} \quad \dots(2)$$

$$\text{speed.reduction} = \left(\frac{V}{1.4} \right) \left\{ 1.4 - \left(0.25 + \left(\frac{d - 0.4}{0.6309} \right) \right) \right\} \quad \dots(3)$$

Note: d is inter-person distance (m), D is density (Number of persons/m²), V is unimpeded walking speed (m/s), 0.6309 is a time factor (sec). If $d < 1.12$ then speed reduction = 0.

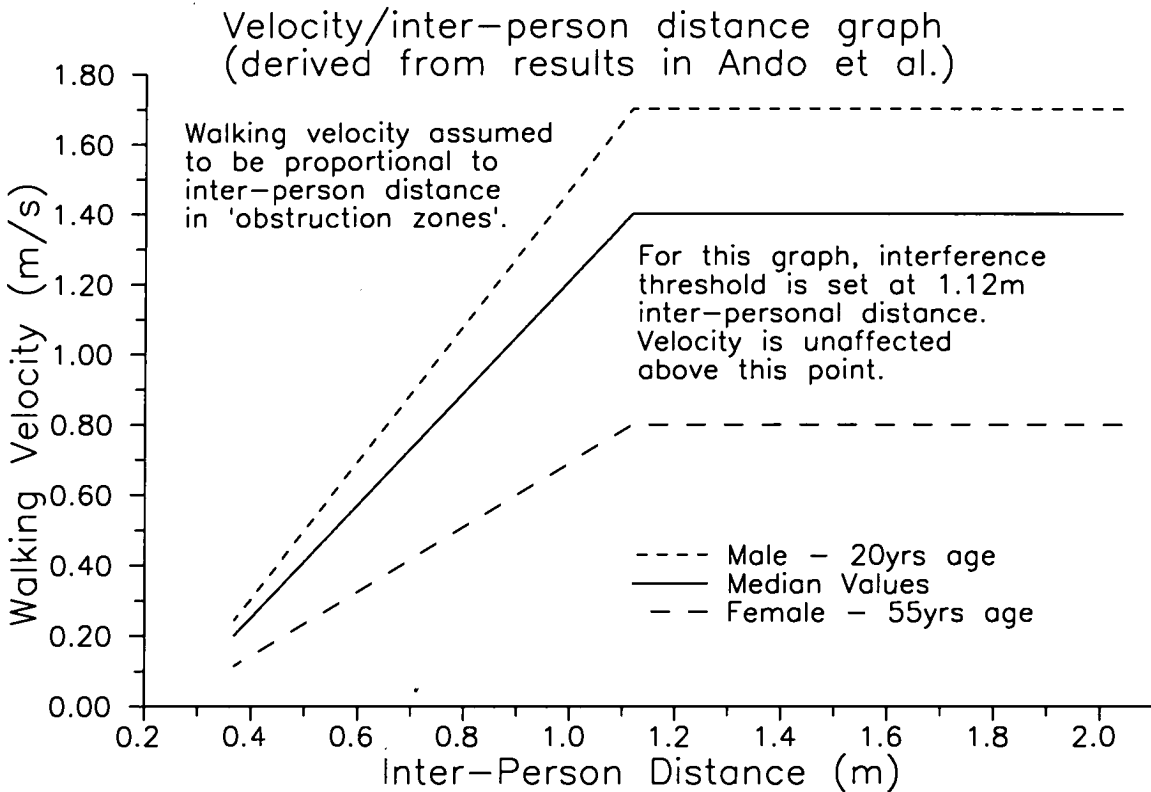


Figure 6. The Velocity / Distance data used by SIMULEX

The formula is fully applied when the nearest obstructing person is within the 100% zone (Figure 7). If the nearest obstructing person is within a 50% zone, the speed reduction is multiplied by 0.5, and a second 'nearest person' in either of the other two zones will also incur only half of the speed reduction effect.

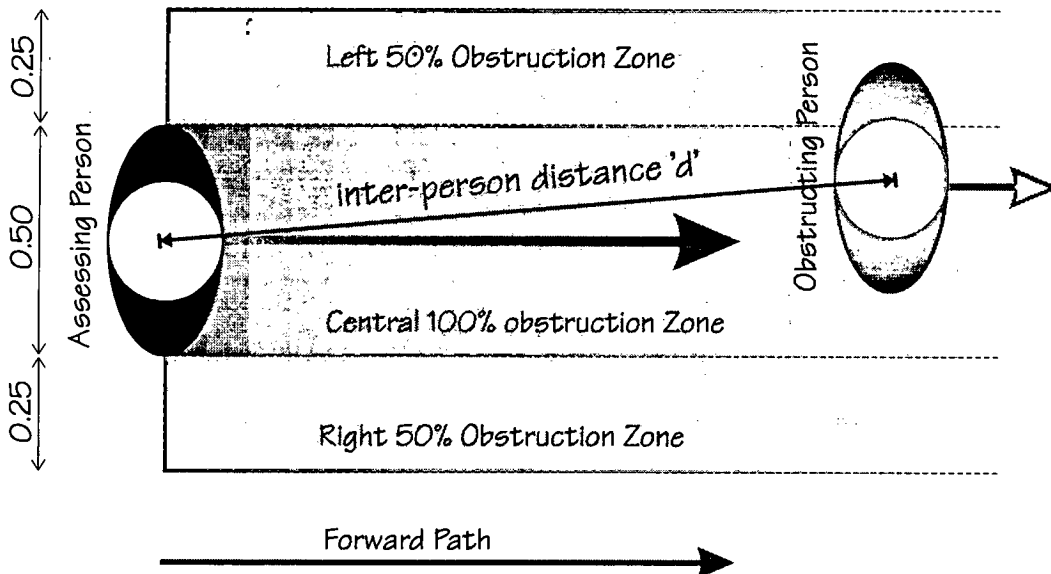


Figure 7. Obstruction Zones For Speed Assessment

8.3 MOVEMENT CHARACTERISTICS

If the walking speed of an individual is impaired by the proximity of one or more obstructing persons, then the overtaking routines are invoked. The program scans either side of the direction of travel, and if a significant improvement in speed is obtained, then the direction of travel changes to the new deviated angle. The angle of deviation, or overtake angle, increases as an obstructing person becomes closer. Overtaking and localised deviation of route is observed frequently, and the deviation routine produces a degree of jostling in the higher density crowds.

The program, by its nature, models queuing inherently. The speed calculations never yield a zero value, but each person is only allowed to move into unoccupied space and will therefore become stationary if exactly behind another person. Twisting movements of the body are restricted by an 'available twist factor' which is currently set at 0.01 seconds/degree. This twist factor is to be checked and updated, depending on the results of forthcoming observational research. As yet, no pushing or pressure build-up is modelled.

8.4 EARLY SIMULATION RUNS

Simulation runs begin with the user specifying a uniform density of persons per unit area evenly over the building plan. The program also asks if movement traces are to be shown. These movement traces map out the path that each individual has followed during the course of an evacuation, describing where overtaking, and other manoeuvres have taken place. The program then creates each person's co-ordinates, unimpeded walking speed (dictated by age and gender), and initial angle of orientation of the body. A delay can be programmed in for reaction time to alarm, delaying the initial movement of individuals depending on their awareness and eagerness to move. More complex psychological factors such as the familiarity

of routes and aggressiveness will be incorporated in a later version. The program has been tried on many plan layouts. At this stage, staircases have not yet been modelled because validation on a single storey, flat plane is required first.

In order to assess the maximum flow capacity of a doorway width, the program was used to model a single, large room that possessed one narrow doorway, and a large number of people. The simulation was intended to recreate a high density, non-panicking crowd at a doorway. In this test q (flow rate, persons/(metre width)/second) was found to be 1.8. With slight changes of the overtaking/jostling algorithm and the order in which speed assessment occurs (scanning from [most remotely positioned person] first, to [person at exit] last, or visa versa) then q can vary from 1.5 to 2 persons/m/s. Real-life observations of q include 1.5 ('Fire & Buildings' [19]) and 1.8 (Melinek [20]) persons/m/sec. This correlation of simulated value to real life observation is encouraging, especially in view of some of the assumptions made in the speed assessment routine.

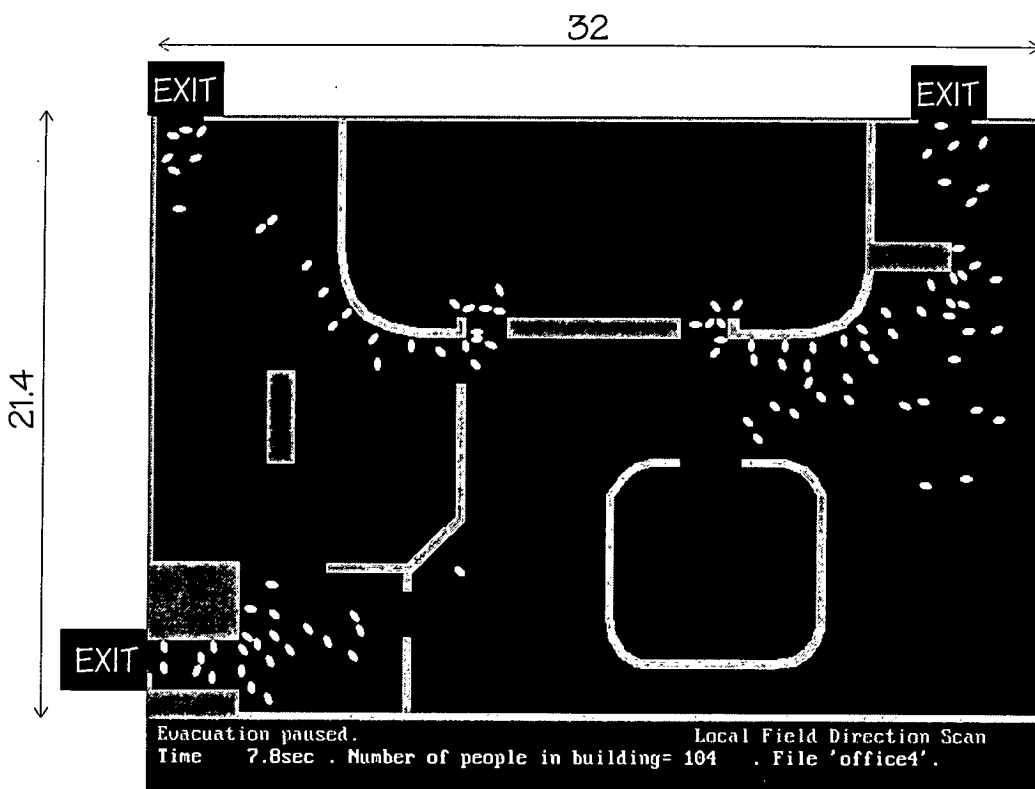


Figure 8. Sample Screen Display for a Complex Office Space Evacuation . Note dims.(m).

Figure 8 demonstrates the ability of the program to cope with complex geometries and obstructions of any size. In the example shown, immediate reaction to alarm was assumed. It became clear from watching the progress of various simulations that the presence of a narrow obstruction in the centre of a 1.8 metre wide opening significantly reduced flow capacity, even though the total combined opening width was only reduced by 0.1m.

9. CONCLUSIONS AND DEVELOPMENT

This investigation has produced the first encouraging results from the crowd / fluid flow analogy and the potential for real correlation now exists. New route finding techniques, overtaking methods and behaviour patterns have been developed for the computer model. Both models, however, contain restrictions and future work will attempt to improve the flexibility and validity of both systems.

The further development of the '2-phase' hydraulic model, using steady-state experiments is expected to yield more valuable and complete data. More thorough testing over a range of channel widths and water flow rates is required. The model will then be applied to test different door opening geometries, as well as unusual corridor/room layouts. The immediate programme of development for the fluid model consists of producing a selection of graphs for different water flow rates in a single channel width. This set of results will enable the formulation of friction factor equations for a full mathematical prediction of the hydraulic model behaviour in uniform width channels.

The computer program was not used to simulate the specific fluid experiments because in this early version friction factors in narrow corridors have not yet been applied to the movement algorithms. To date, one of the most notable results from the computer model is the correlation between test results and real-life values of crowd flow rate per unit exit width, but more large scale validation is required. The route finding algorithms automatically reassess exit routes at each time step, and the only input required is the building plan itself. All exits in the building are recognised automatically and any geometry of obstruction can be accommodated. The program is restricted to fairly small areas at present but is currently being adjusted for large memory usage in order to model areas the size of large sports stadia.

The computer methods adopted in SIMULEX show promise because of their flexibility in handling infinite spatial variations combined with the automatic exit route assessment routines. The program is written to incorporate aspects of disability, aggressiveness and different body shapes as part of the future development. A choice of exit could be achieved by overlaying various distance contour maps based on different available final exits, and the effects of smoke spread could be simulated by the progressive addition of weighting factors to the contour maps, over increasing areas. It is envisaged that additional parameters will be incorporated into the speed assessment routines of SIMULEX.

Observational tests on evacuating people are to be carried out in order that the accuracy of the computer methods can be determined. Results such as overtaking behaviour, twisting ability, and general route deviation will be logged and incorporated into the model algorithms.

10. ACKNOWLEDGEMENTS

Thanks to Les Russell for building the 'steady state' apparatus, and for having a large input into the design. Thanks also to Robert Wardlaw for his help and ideas in formulating the adapted form of Mannings equation.

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APPENDIX 1.2

"HYDRAULIC MODELLING OF CROWD FLOW"

This paper is presented in draft form, and is to be revised by Robin Wardlaw. It is intended that the paper be submitted for publication in the Fire Safety Journal.

HYDRAULIC MODELLING OF CROWD FLOW

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ABSTRACT

The analysis of crowd movement has been a topic of research for more than eighty years. Studies of crowd transit have been both diverse and distinct. Early analyses, produced in the 1930's, included the publication of initial U.S. guidelines [1], and the Manual of Safety requirements in Theatres [2] which instigated the adoption of the British Standard 2¹/₂ minutes building evacuation time.

Since these early investigations, researchers have observed crowd motion and attempted to derive general rules to describe the evacuation movement of groups of people. These rules have been used to simulate building evacuations, with varying degrees of success. Such rules are empirical, and little is known of the mechanism of crowd movement. Velocities and pressures fluctuate; bottlenecks and 'jams' can occur in crowd transit, and individual crowd members interact to produce an overall pattern of movement. The creation of 'crowd flows' by the interaction of a large number of individuals has not been scientifically analysed, and requires further research if the assessment of certain irregularities in crowd transit is to be fully realised.

A common analogy to crowd flow is that of fluid flow. The comparison of the escape movement of large groups of occupants from a building structure to the 'outflowing' of a fluid from a containing vessel has been discussed many times in the past. Subsequently, the modelling of crowd movement by the use of fluid flows has been attempted by a number of researchers, but such attempts have never yielded realistic results.

This paper describes the basis and development of a new type of fluid model and presents the analysis of some of the results obtained by experiment. The model is used to recreate specific aspects of crowd motion, such as the variation of speed produced by a change in crowd concentration. The effects of fluid pressure in this type of simulated crowd movement are discussed, and the results are analysed mathematically by the use of an adapted form of Mannings equation. A realistic fluid model, in conjunction with an accurate method of analysis, might become an invaluable design tool for the assessment of the safety of certain areas of a complex escape route geometry.

1. THE BASIC PARAMETERS OF CROWD MOVEMENT

The most extensively researched aspects of crowd movement are group concentrations, speeds, and flow rates. Observations of these values form the basis for design guides, with regard to corridors, door widths, and plan layouts. They provide rules that are used to approximate the maximum flow rate for a given width of passageway. For more accurate analysis, it should be noted that crowds move at varying speeds and with different flow rates. Equation (1) was derived by Predtechenskii & Millinskii [3] and explains that flow rate is the product of velocity and density. Velocity is not, however, independent of density and this study therefore concentrates primarily on the relationship between velocity and density alone.

$$q = Dv \quad \dots (1)$$

Units; q ='intensity of movement', or flow rate per metre width (m/s)

D =density (m² occupied space/m² total space)

v =velocity (m/s)

The relationship between crowd velocity and density has been observed by Fruin [4], Hankin & Wright [5], Ando *et al* [6], and Predtechenskii & Milinskii [3]. Their observations are summarised in Figure 1.

OBSERVED VELOCITY/DENSITY GRAPHS -different sources

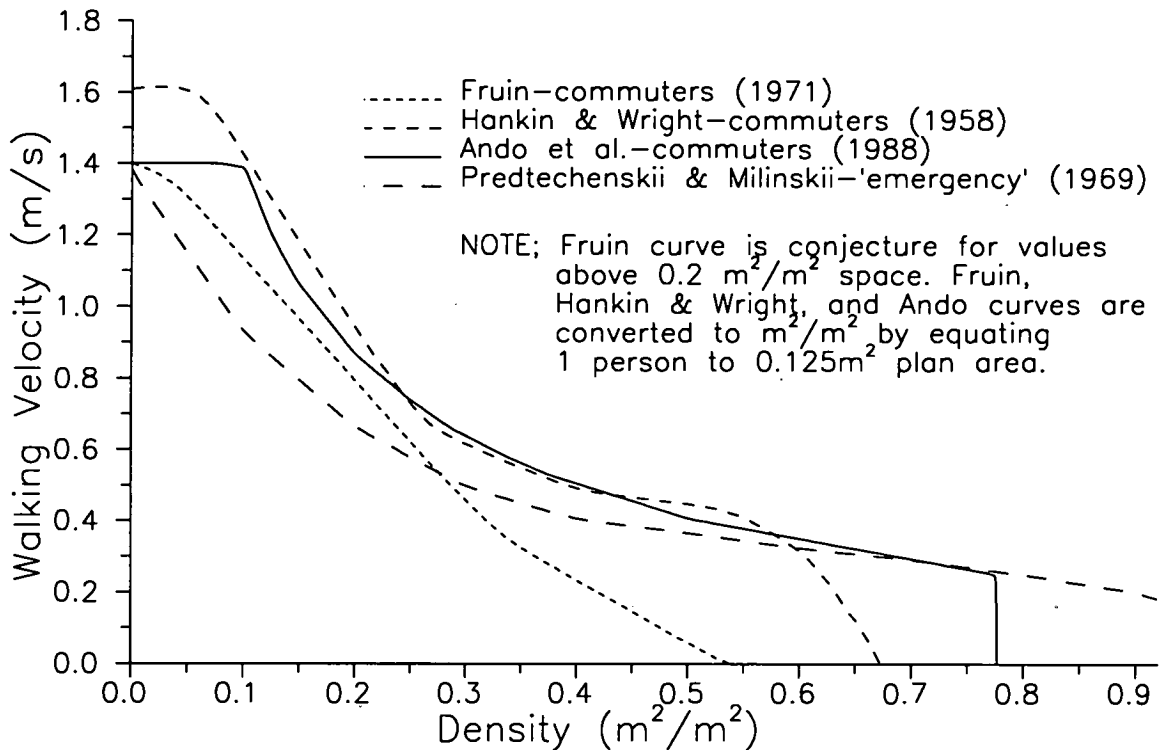


Figure 1. The relationship between crowd velocity and density.

The units of crowd density in Figure 1, are those used by Predtechenskii & Milinskii [3] and all other data has been converted to these. Crowd density is expressed in terms of the plan area occupied by the crowd per square metre. This approach accommodates crowds whose members possess differing body sizes, caused by age, build, gender and type of clothing. It should be noted that for comparative purposes, $1 \text{ person/m}^2 = 0.125 \text{ m}^2/\text{m}^2$ (winter dress). Dividing the density values in Figure 1 by 0.125 will therefore yield the number of people per square metre, assuming that they are wearing winter clothes.

As the crowd density increases, the overall speed of forward motion in the group decreases. When the proximity of individuals increases to such a degree that bodily contact is imminent, then 'shuffling' and further irregular speed reduction occurs. At very high crowd concentrations 'body arching' or jamming can cause major speed reductions, and halt the forward motion of the crowd. The reduced speed of crowds at low densities, where there is little or no bodily contact, is of particular importance when analysing the cause of speed fluctuations.

2. THE FLUID FLOW ANALOGY - A BRIEF SUMMARY

The first "Green Guide" [7] made the positive recommendation that the escape flow paths in stadia should be designed as pipe network systems. It is not the only advisory document to adopt this form of approach. Stahl [8] suggested that "... the early meetings of the Committee on Safety to Life appear to have formally adopted a physical-science approach to building egress in which building occupants, like water, gas particles or ball-bearings, were assumed to respond immediately, and to be affected only by spatial configuration and density".

Research groups and individuals have compared certain characteristics of crowd movement to fluid flow, and some have attempted real physical models to justify these comparisons. Fruin [4] observed that in his "no touch zone" configuration, when people are densely packed into a group, individual movement is prevented. People are carried along by the crowd as a whole and their movements are dictated by the group flow. This movement is normally in one direction in a passageway, and certain characteristics (such as pressure build-up) have been noted as being 'fluid' in behaviour. Peschl [9] suggested that the flow properties of gases, liquids, and plastically viscous materials had been investigated exhaustively and that it had not been possible to establish a law that governs the passage of large numbers of people through doors and narrow passages. Riddell & Barr [10] attempted to model the flow of people around crush barriers in a sports stadium by using coloured water flowing over a tilted table, around model obstructing walls. On close analysis of known data for crowd behaviour, however, it is evident that the fluid models described by Peschl [9] and Riddell & Barr [10] cannot combine the arching characteristics, flow interactions and complex speed / flow / density relationships observed in real life.

There will always be some inherent limitations in any fluid model, however successful, because of the physical nature of fluid flow. Stahl [8] described some of the pre-requisite assumptions for a hydraulic model as being;

1. building occupants are alert, able bodied and ambulatory
2. fire safety depends on the 'safe end' of the evacuation system
3. there is high density building occupancy which, during a fire emergency, limits the reasonable options for evacuation that are available to building occupants

Complex psychological scenarios such as; reaction to alarm, family group interactions, occupant familiarity to the building, and reaction to hazardous conditions are not considered here. These factors must be taken into account if a more complete evaluation of escape movement is to be considered.

A fluid model must be appreciated in context; it's success should be gauged by how well it describes some of the basic parameters of crowd flow, including the reduction of speed with increased crowd concentration and the resultant pressure fluctuations or 'surges' within the crowd. The potential for any form of fluid simulation lies in its ability to predict how well the geometry of a building accommodates the escape movement of its occupants, and the impact of the building shape upon individuals and the crowd motion as a whole.

3. THE DEVELOPMENT OF A NEW TYPE OF FLUID MODEL

It is evident from the previous analyses described above, that simple, uninterrupted fluid flow cannot describe the basic parameters of crowd movement. The crowd density cannot be assimilated and it is known that the speed reduction effects cannot be observed. For example, reducing the width of a channel in uninterrupted open channel flow leads to an increase in the fluid velocity; the inverse occurs in 'real-life' crowd flow.

Individuals in a large, moving group of people may travel at a speed that is different from the average velocity of the group. The movements and actions of individuals cause changes in the psychological and physical pressures within the group. For such pressure fluctuations to be observed, some form of representation for the mass of individuals within the 'crowd' is required. In order to recreate high density system blockages at openings, as observed by Peschl [9] and Predtechenskii & Milinskii [3], a physical model must contain masses that interact, and possess frictional properties. A moving fluid is the obvious choice to provide both the motive force for the crowd particles and the means for particle-particle interaction by wave propagation and pressure fluctuations. Individual crowd members can be represented by spheres, and transported by the moving fluid.

The model developed uses plastic balls to represent the mass of individuals within a crowd. Each ball is solid, 24mm in diameter and has the same mass density as water. This size of ball was chosen because each ball is large enough to be easily

observed and photographed, while the scale of the apparatus retains manageable proportions. The width of a ball is intended to model the body width of an average person in winter street dress (0.5m), but each single ball does not represent one person. The plan area of a person is roughly elliptical, unlike the circular plan of a ball. Fruin [4] noted that the packing arrangements of people were usually regular, with each person possessing a circular 'body buffer zone' that defined 'personal space'. Figure 2 illustrates that the maximum packing density of circles is $0.91\text{m}^2/\text{m}^2$, and Predtechenskii & Milinskii [3] observed that the maximum packing density of a crowd whose member's are not deformed by pressure is $0.92\text{ m}^2/\text{m}^2$. This similarity means that the spheres can be used, on plan, to represent the density of a crowd, in terms of 'occupied plan area' per unit of 'available plan area'.

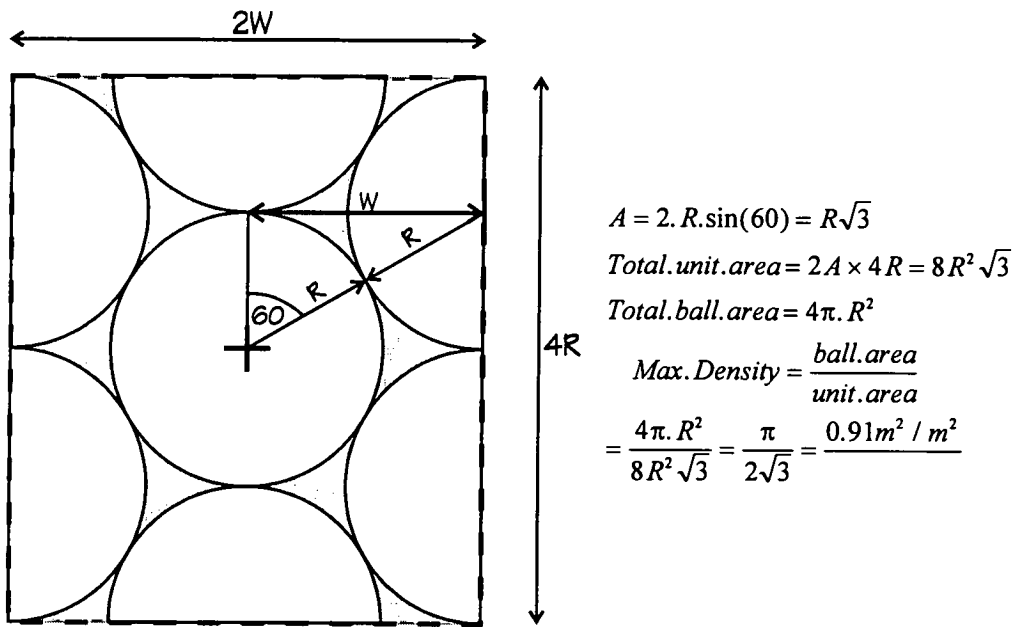


Figure 2. The maximum packing density of circles

4.0 EARLY EXPERIMENTS - BALLS INITIALLY STATIC

The balls described in Section 3.0 were introduced into a constant flow of water, in a narrow channel. The water flow in the channel was adjusted, prior to the introduction of the balls, so that the fluid depth was not more than 12mm. It was important that the water depth never exceeded the diameter of the balls because this would lead to the production of a uniform fluid pressure over a given length of the open channel. The fact that different pressures heads could be created between individual balls was an important aspect of the modelling system. This created a complex system of individual, moving particles where each particle had an effect upon others in close proximity. The system was tested on a horizontal varnished plywood table, with unvarnished plywood channel walls.

The main objective of these early experiments was to assess whether this type of modelling system could reproduce the relationship between crowd velocity and density, illustrated in Figure 1. Therefore, a number of tests were carried out where different concentrations of balls were introduced into a moving fluid, where the balls became an integral part of the fluid flow. The resulting speed of motion of the balls, as they rolled along the channel in the moving fluid, was quantified so that a graphical relationship between concentration (density) and velocity might be derived.

Each test was executed as follows;

1. A ball 'rack' was loaded with the specified number of balls N_b , at regular spacings adjacent to a 0.9m long section of channel. The ball at the rear end of the rack was designated the 'test ball'
2. The rack was tilted by hand, so that the balls dropped simultaneously into the water, as illustrated in Figure 3 .
3. Timing commenced when the 'test ball' made contact with the plywood base. All of the balls were then taken up by the water flow and propelled through the channel.
4. Timing was stopped, when the 'test ball' passed a mark at the end of the 0.9m test section. The time reading T_b for the 'test ball' to travel the full 0.9m length was noted and logged.
5. The mean velocity v_b was obtained by dividing 0.9m by T_b .

Each test was repeated 3 times and the average value of v_b used for the calculations and graphs.

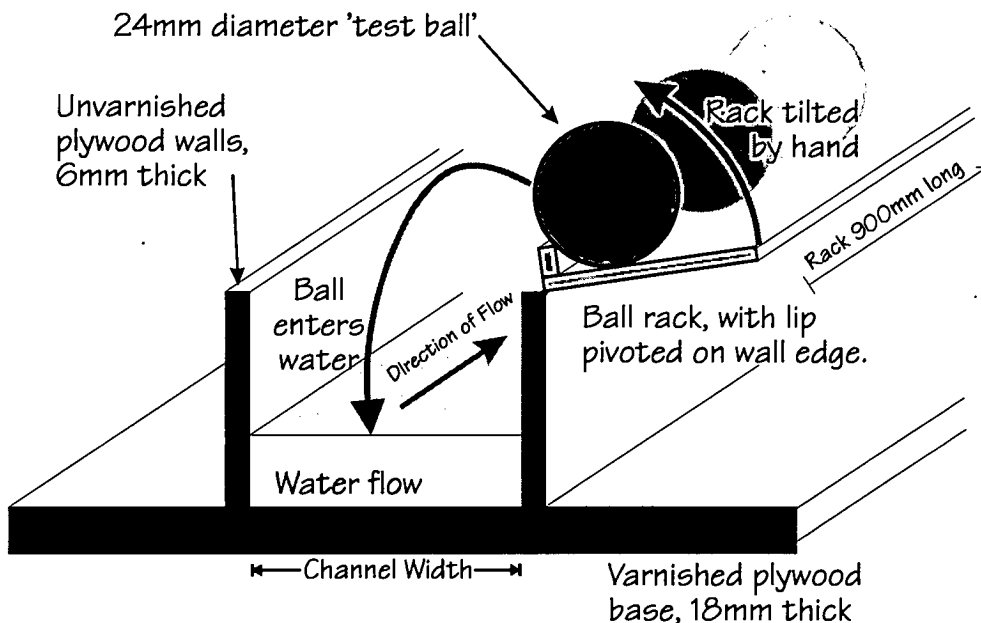


Figure 3. Sketch, illustrating the introduction of balls into the shallow water flow. Two basic equations were used for these early results.

$$v_b = \frac{l}{T_b} \quad \dots(2)$$

where: l = travel distance of balls over test section length (0.9m)
 v_b = mean ball velocity over test section (m/s)
 T_b = total travel time of ball (s), defined in section 5.

$$D = \frac{N_b \cdot \pi \cdot r^2}{l \times w} \quad \dots(3)$$

where: D = plan density(concentration) of balls (m^2/m^2)
 N_b = number of balls over test section length l
 r = ball radius (m)
 l = test section length (m)
 w = channel width (m), illustrated in Figure 3.

4.1 RESULTS FROM 'INITIALLY STATIC' EXPERIMENTS

The results of these experiments are presented in Figure 4. The shape of the graphical curve obtained by experiment is similar to that for the observed crowd flow data in Figure 1, for densities up to $0.6 m^2/m^2$. It should be noted that for a corridor of this width, the maximum packing density is only $0.61 m^2/m^2$. At this point the balls would 'jam' in the channel, as one might expect an extremely concentrated crowd to jam and stop moving completely. At the lowest water flow rate, results became more difficult to obtain, due to the dominance of friction in the apparatus and the occurrence of jamming premature to achieving the maximum packing density value. This was due to the slower flow providing less motive force for the balls, providing the balls with less power to overcome friction. What is encouraging is that this form of erratic system jamming could be observed at high concentrations, similar to real-life observations of densely packed crowds.

For corridors less than 1.1 metres wide, data is scarce, but BS5588 (14) suggests a rapid restriction of flow as corridors decrease in width below 1.1 m, and the early 2-phase tests support this view. Although this is not a quantitative comparison, there is a reasonable similarity between the experimental results and the readings from observational measurements.

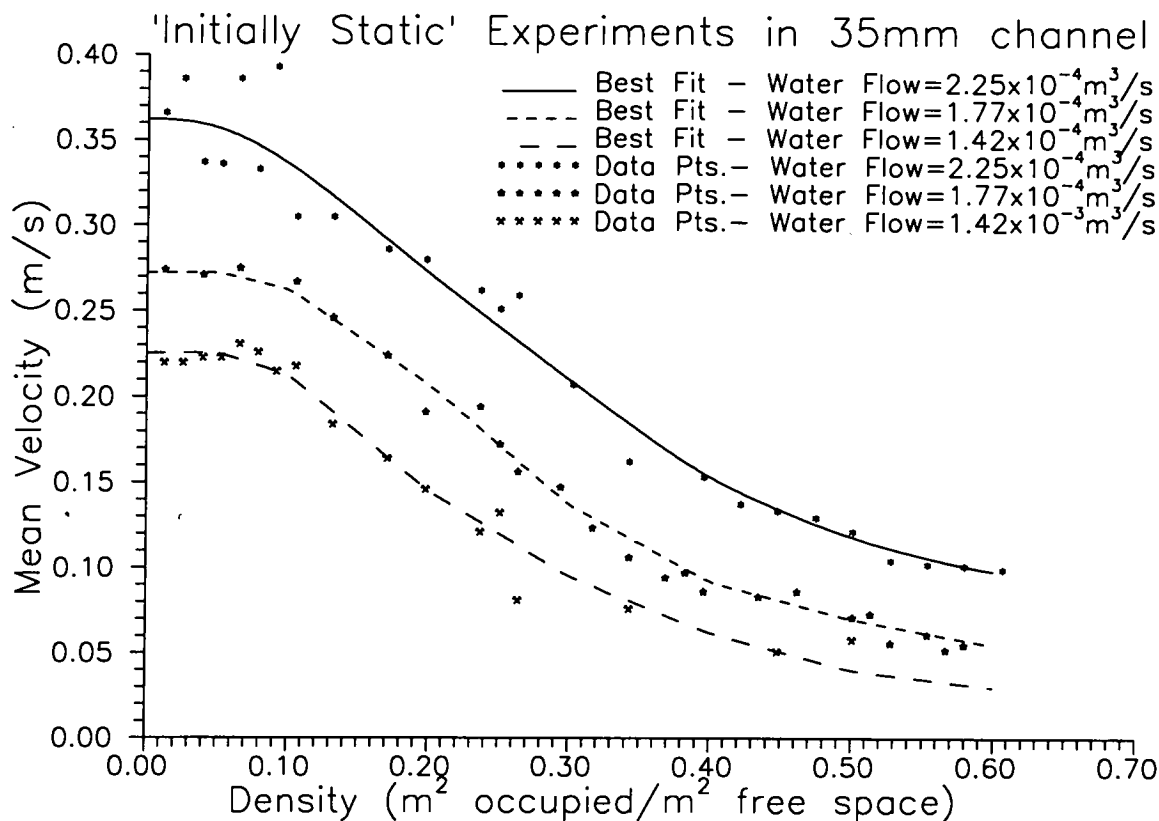


Figure 4. Results from 'Initially static experiments' in 35mm wide channel (scale width 0.74m)

5.0 'STEADY-STATE' ROLLING EXPERIMENTS

The preliminary results were encouraging but a slight error existed in the experimental methods for the assessment of the mean velocity of the balls. In the early experiments, all of the balls in the rack entered the fluid simultaneously and came to rest on the bed of the channel. The balls were not immediately propelled forward, but instead temporarily interrupted the fluid flow. The water level rose around the balls, and a pressure head built up that forced the balls forward; accelerating them from a state of rest to a steady velocity, at the same rate of forward motion as the surrounding fluid. The time required for this acceleration process was negligible when only a few balls were introduced into the fluid flow, but increased to more than one second when 20-30 balls were used. In order to eradicate this 'ball acceleration time' from the calculation of the mean ball velocity, a form of a 'steady-state' apparatus was developed. This apparatus is illustrated in Figure 5.

The new equipment was designed to reduce the initial effect that the inertial mass of a group of balls had on the moving fluid. In the apparatus illustrated in figure 5, individual balls are fed into the fluid flow by a regulated solenoid piston; roll along the channel; leave the fluids table and are returned to the 'ball stack' by a pipe filled with compressed air.

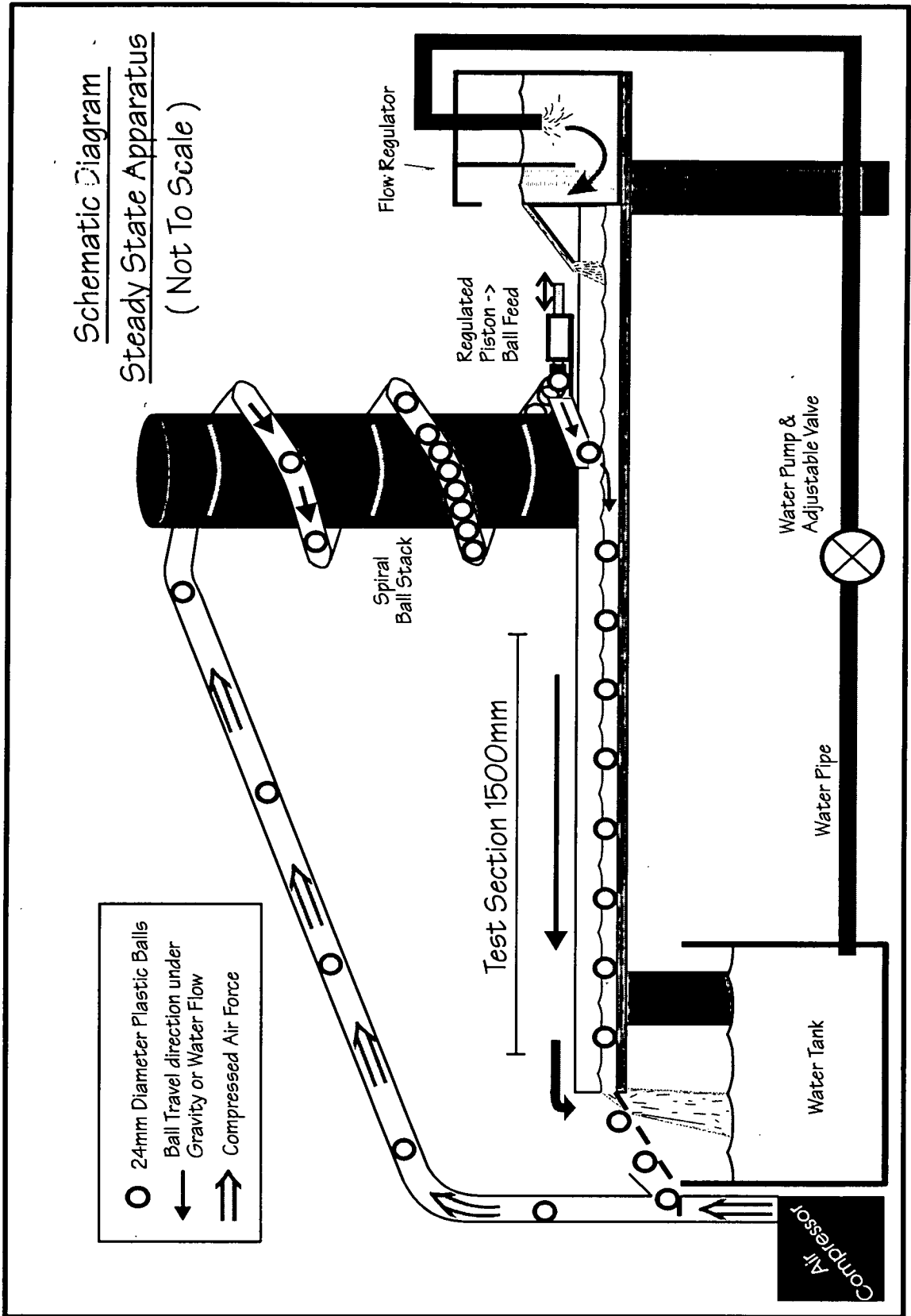


Figure 5. Schematic Diagram of 'Steady State' Apparatus

The use of the 'steady-state' apparatus produced a continuous mixture of balls and fluid where the flow rates of either could be adjusted by the user. The first tests used a channel width of 35mm channel and a constant water flow rate. These tests were video-taped and the rates of motion of individual balls were assessed by analysing the images on a television monitor. The velocity and density values for each reading were calculated using equations similar to those described in Section 4.0.

5.1 RESULTS FROM 'STEADY-STATE' EXPERIMENTS

The results presented in Figure 6, show that the velocity/density relationship in the 'steady state' apparatus displays a trend that is similar to the behaviour observed in the earlier 'initially static' tests shown in Figure 4. The trend is encouraging, but the absolute value of velocity is not sufficiently reduced at high densities for direct correlation to the 'real-life' results shown in Figure 1.

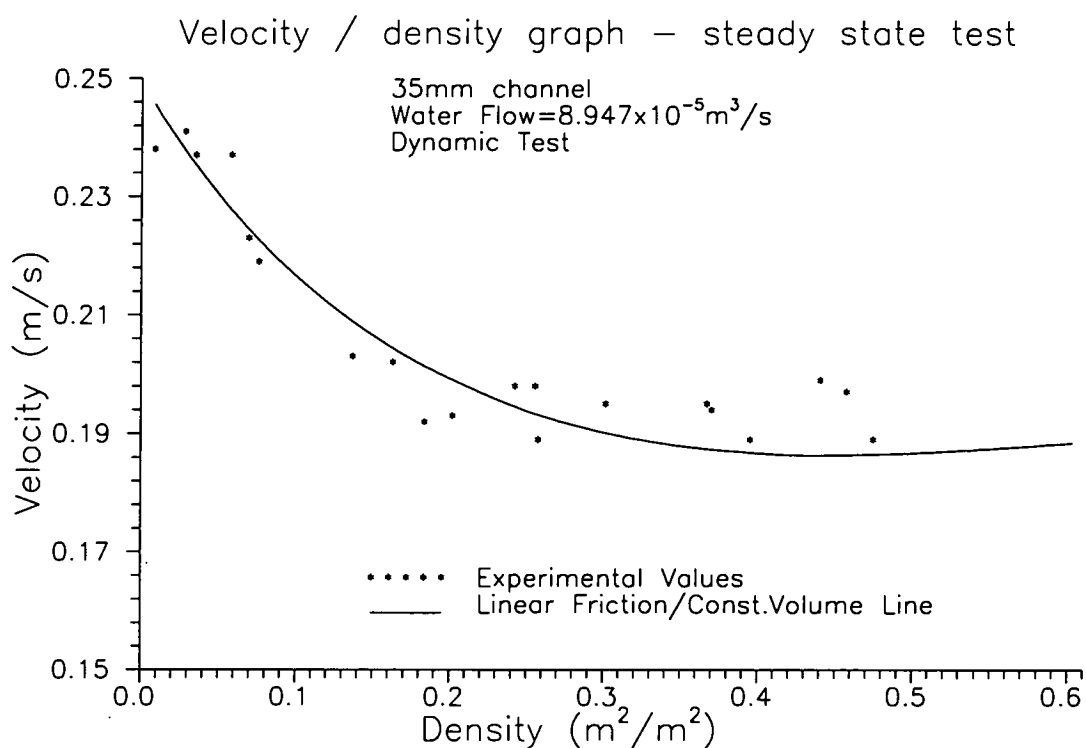


Figure 6. Early results from the Steady State apparatus.

The 'Linear Friction/Const. volume line' represents a form of best-fit line, based on standard hydraulic equations. The alteration, and application of standard hydraulic equations to this form of rolling mass/fluid flow is explained in the following Section 6.0.

6.0 MATHEMATICAL MODELLING OF THE 'STEADY-STATE' TESTS

Mannings Equation for open channel fluid flow takes the form described below, in Equation 4. In the case of the 'steady-state apparatus, this equation requires some adjustment because the presence of the rolling balls in the water causes an increase in friction against the fluid flow. The 'Linear Friction/Const. Volume Line' displayed in Figure 6 is calculated using Equation 5, and represents an attempt at a physical description of the way in which the presence of the balls creates greater frictional resistance and affects the flow velocity of the water.

$$v = \frac{\left(\frac{A}{P}\right)^{\frac{2}{3}} \sqrt{i}}{\eta} \quad \text{(standard form of Mannings Equation)} \quad \dots (4)$$

$$v = \frac{\left(\frac{A}{P}\right)^{\frac{2}{3}} \sqrt{i}}{(\eta + N_b F)} \quad \text{(adapted form of Mannings Equation)} \quad \dots (5)$$

where:

- v = mean fluid velocity (ms^{-1})
- A = average cross-sectional area of water (m^2)
- P = the wetted perimeter (m) calculated by dividing the total wetted surface area over the test section, by 1.5m (the test section length)
- i = hydraulic gradient (assumed to be the apparatus bed slope)
- η = Mannings roughness factor for the channel surface
- F = Roughness Factor for each ball
- N_b = number of balls in the test section
- $(\eta + N_b F)$ = the Total Roughness Factor for the channel and balls

Equation 5 assumes that total friction in the system is proportional to N , and that there is a constant volume of water flowing through the test section. The mean ball velocity was found by experiment to be consistently within 5% of the fluid velocity. Therefore, the wetted perimeter was not adjusted to take account of the surface of the balls, because the balls possessed a forward velocity which was similar to that of the water. On observation, the effect of surface tension between the balls did not appear to be significant, but such an effect would increase linearly with an increase in the number of balls and should be accommodated by the use of the Total Roughness Factor.

The water flow in the channel was assumed to be generally turbulent, which is important because Mannings Equation applies only to turbulent flows. This assumption was verified by calculating Reynolds number for the water flow, without considering the presence of any balls. This calculation is described below, in

Equation 6. The result of $R=2621$ suggests that the uninterrupted fluid flow is in the early transition phase from laminar to turbulent flow. When balls are added to the system, the currents in the fluid flow will become less uniform, and hence can be regarded as more turbulent in nature.

$$R = \frac{v \cdot l}{\nu} = \frac{0.24 \times 0.011}{1.007 \times 10^{-6}} = 2621 \quad \dots(6)$$

where: v =mean fluid velocity over test section (ms^{-1})
 l =characteristic length, taken as the average flow depth (m)
 ν =kinematic viscosity of water at 20°C ($\text{m}^2 \text{s}^{-1}$)

6.1 APPLICATION OF THE THEORETICAL FORMULAE

A sketch of a cross section through the combined ball/fluid flow is presented in Figure 7. The sketch shows a only a short length 'L' of the test section for the purposes of clarity. In this type of combined flow, the calculation of water depth becomes quite complex but is imperative if factors such as the average cross-sectional area of fluid are to be calculated.

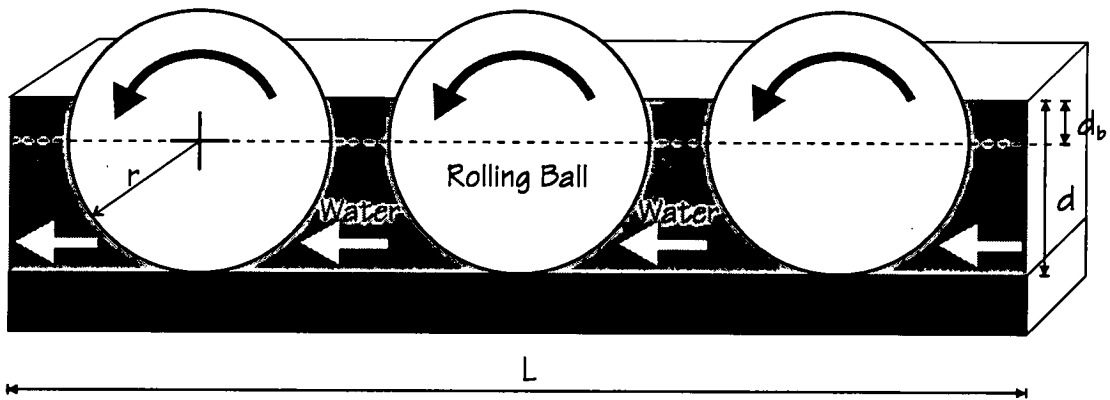


Figure 7. Sketch of combined ball/fluid flow.

The calculation of water depth for a specific number of balls becomes an iterative process, because of the way in which the volume of water displaced by the balls affects the water depth 'd'. In the sketch in Figure 7, the water depth is d_0 , prior to the introduction of 3 balls. When the balls are introduced into the fluid, the total submerged volume (of balls and water) becomes V_0 . However, the presence of the balls in the fluid displaces a percentage of the water volume, which leads to an increase in the water depth from d_0 to d_1 . This increased depth means that a larger portion of each ball becomes immersed and displaces a greater volume of water than in the initial calculation. Hence, the total submerged volume (of balls and water) increases from V_0 to V_1 . Once more, the increase in fluid depth immerses even more

of the mass of the balls, which displaces more water and leads to a further rise in water depth from d_1 to d_2 . This cyclical (iterative) calculation continues by recalculating the total submerged volume (of balls and water) V_n and the water depth d_n until the change in depth is regarded as negligible (0.1mm). The formulae used for this iterative calculation of water depth are given below in Equations 6-8.

$$d_b = d - r \quad \dots(6)$$

$$V_s = \pi \left[r^2 d_b - \frac{d_b^3}{3} + \frac{2r^3}{3} \right] \quad \dots(7)$$

$$d = \left(\frac{V_w + NV_s}{w \cdot L} \right) \quad \dots(8)$$

where:

- d_b = water depth relative to centre of ball, -ve below, +ve above (m)
- d = absolute water depth, measured from base surface of channel (m)
- V_s = water volume displaced by one semi-submerged ball (m^3)
- V_w = water volume in test section, constant value (m^3)
- r = radius of ball (m)
- N = number of balls in the test section
- L = test section length (m)
- w = channel width (m)

Figure 8 illustrates the relationship between the density of the balls in the channel (calculated using Equation 3) and the absolute water depth. The 'Linear Friction/Const. Volume Line' (calculated by the iterative method described above) assumes a constant water volume in the test section, which enables the prediction of the change in water height due to the volume of water displaced by a given number of balls.

The cross-sectional area of fluid in the test section of channel can be calculated by using the principle that cross-sectional area is equal to 'volume' divided by 'length'. This principle is used in Equation 9. The average volume of water per unit length is equal to the total submerged volume of balls and water, minus the submerged volume of the balls alone. The 'theoretical' values in Figure 9 were calculated by using this equation to plot the Linear Friction/Const. Volume Line. The experimental and 'theoretical' values of 'A' were based on the values of 'd' obtained by experiment, and those calculated by the method of iteration respectively.

$$A = \frac{\text{total submerged volume} - \text{submerged volume of balls}}{\text{length}} = \frac{(w \cdot l \cdot d) - (N \cdot V_s)}{l} \quad \dots(9)$$

Notation; A = total wetted surface area in test section (m^2)
 w, l, d, N, V_s as before

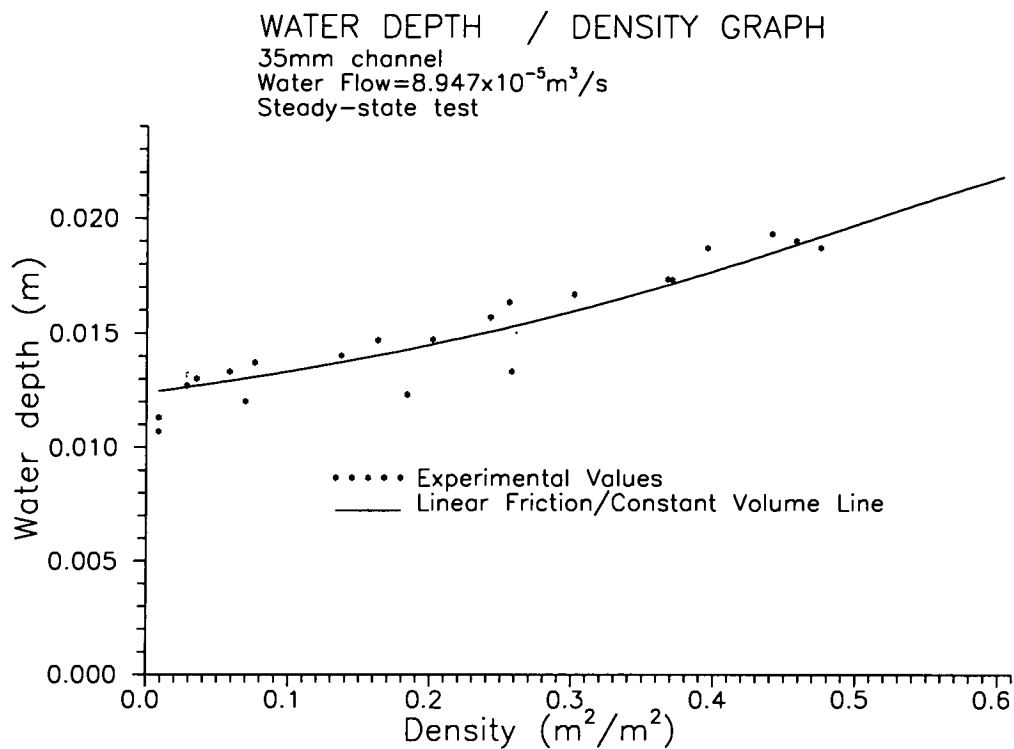


Figure 8. Graph of water depth against ball density (concentration).

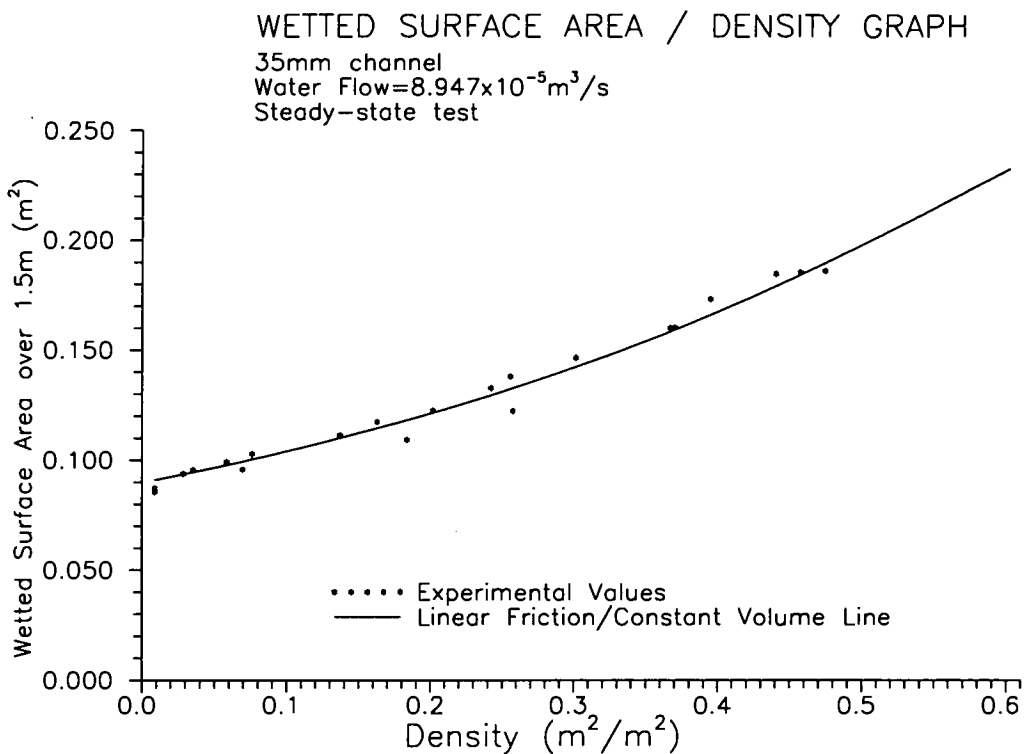


Figure 9. Graph of wetted surface area against ball concentration (density).

The values of Combined Coefficient of Roughness, defined in Equation 4, were calculated from the values of depth, wetted surface area and velocity obtained by experiment. These values are plotted in Figure 10, and illustrate a definite experimental trend.

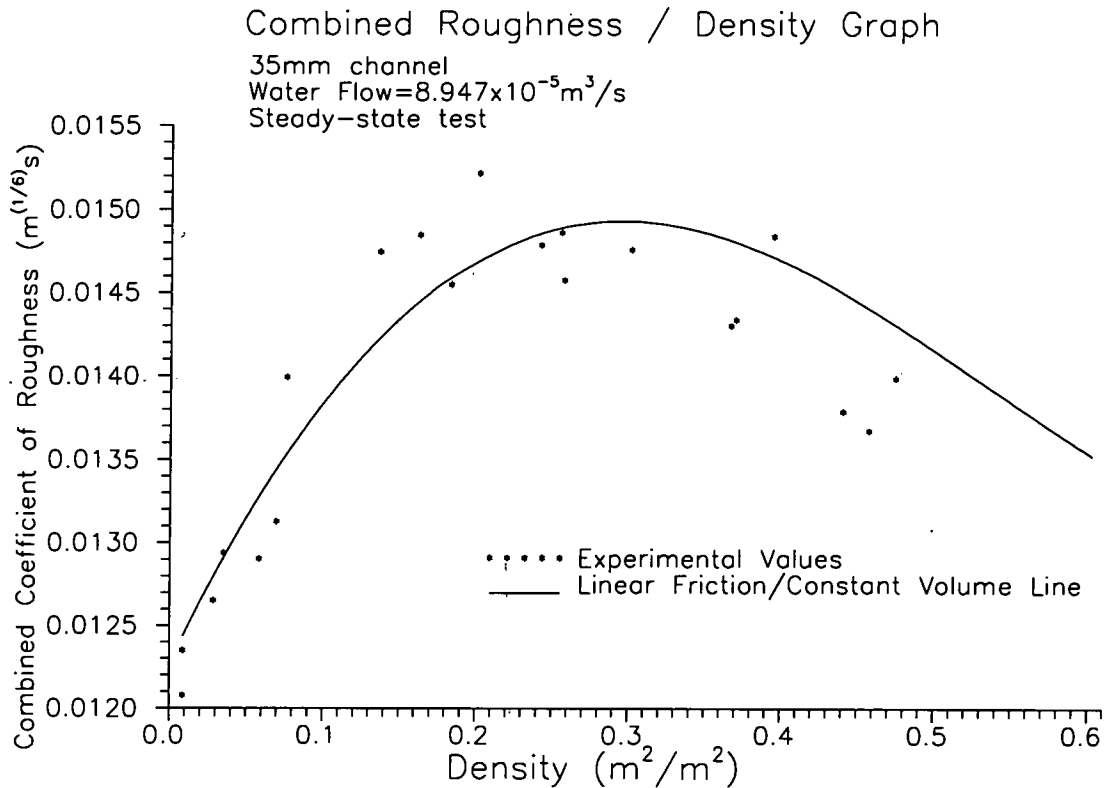


Figure 10. Graph of Combined Coefficient of Roughness against ball concentration (density).

The experimental values of Combined Coefficient of Roughness, when multiplied by the total wetted surface area, form the graph of Total Roughness Factor, plotted in Figure 11. The 'best fit' line for the experimental values shown in this Figure is reproduced below, in Equation 10 and forms the basis for the Linear Friction/Const. Volume Lines drawn in Figures 6 and 10. That is, the experimental results are used to derive a best fit equation for Total Roughness which is then fed back into the adapted form of Mannings Equation.

$$(\eta + NF) = \frac{((10.99 + 3.323D) \times 10^{-3})}{A} \quad \dots(10)$$

Notation; η, N, F, D, A as before.
 D is calculated by Equation 3

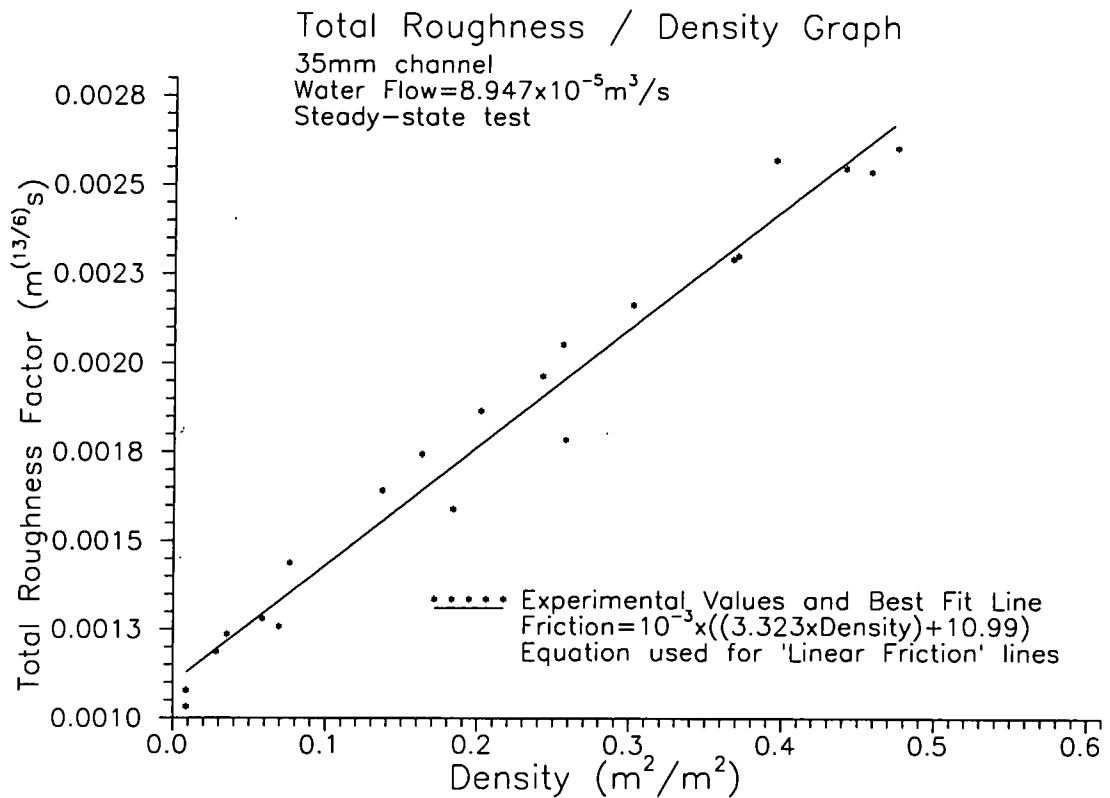


Figure 11. Graph of total roughness against ball concentration (density).

The Linear Friction/Constant Volume Lines illustrated in Figures 6, 8, 9 and 10 were plotted by using the 'best fit' Equation 10 for the Total Roughness Factor, in conjunction with the other Equations 4, 6, 7, 8, and 9 to illustrate the individual parameters that are required for the use of the adapted form of Mannings Equation. The system requires many complex calculations in order to obtain the smooth graphical curves, so the formulae were used in a spreadsheet program and executed for many values of N. The results are encouraging. Particular emphasis should be placed upon the line calculated for Equation 4, because the prediction of ball (or model person) velocity values are the final objective of the entire set of equations. The system is successful in predicting the effect of ball density (concentration) on velocity.

6.2 MECHANISM OF THE MODEL

In this physical crowd flow simulation, fluid pressure in the open channel is analogous to psychological pressure (the invasion of personal space). As ball (or 'model person') density increases, water height increases resulting in increased fluid pressures and a decrease in the overall system speed and flow rate.

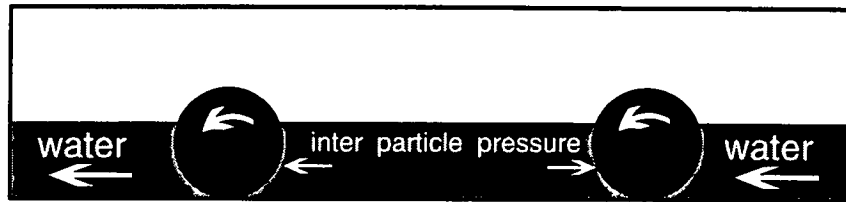


Figure 7. The mechanism of '2-phase' flow

7.0 APPLICATION OF THE HYDRAULIC MODEL

The '2-phase' hydraulic model is to date, the only physical fluid model to demonstrate any of the characteristics of crowd flow, and should be useful for certain predictive aspects of modelling crowd movement. It is envisaged that, under conditions where the crowd movement is uni-directional, the effect of exit shapes and fluctuating corridor widths be assessed, and compared to some of the real-life observations of Peschl (10), Predtechenskii & Milinskii (4) and Hankin & Wright (6).

7.1 FURTHER DEVELOPMENT

Further tests are in progress and the available range of variables will be examined in the search for a good correlation. A large number of 'steady state' tests using small scale corridors of equivalent sizes 0.7 - 2 metres wide are to be executed. Complex geometries will be tested by dropping a grid of balls into a shallow water flow and assessing the fluid / mass escape behaviour of the system around various walls and obstructions. This would employ the early 'initially static' methods in order that system 'jams' or 'body arches' can occur, and the full extent of velocity reductions obtained.

8.0 CONCLUSION

The early 'initially static' tests produced the first correlation between observed results of crowd movement and simple fluids experiments. The shapes of the experimental curves are encouraging, in that they reproduce the trend of changing velocities caused by increases in the crowd density. A significant proportion of the values of mean velocity obtained, was dependant upon the time taken for the water flow to impel the static balls forward, and accelerate them to a constant flow velocity, so the 'steady state' tests were undertaken. These 'steady state' tests produced velocities whose absolute values were not reduced to the same extent, but did display a similar trend when the concentration of the balls was increased. These continuous flow tests were not dependant upon the time taken to accelerate balls from zero velocity, and were therefore simpler for the purpose of mathematical analysis. The modified Mannings Equation successfully describes the general system behaviour and demonstrates that the apparatus obeys standard physical rules. Further work is currently underway to observe the effect of changing the water flow rate in

order that a fully predictive equation can be formulated. In addition, a series of tests spanning different width corridors and complex geometries will be undertaken.

The model cannot simulate the more complex behaviour patterns of people such as; reaction to alarm, aggressiveness, family groupings, and re-entry to a building. These factors should not be forgotten if a more complete analysis of an evacuation system is to be executed. What the model does attempt to simulate is the effect of building geometries and crowd density upon the overall crowd velocity and forward movement. It simulates the 'exit capacity' of a building layout.

The experiments described have produced the first encouraging results from the crowd / fluid flow analogy and the potential for real correlation now exists. The model consists of moving particles, with individual mass and frictional properties whose movements are dictated by the surrounding fluid. The fluid, whilst providing the motive force for the balls also has the ability to propagate pressure fluctuations between individual balls and hence, is the medium for the mutual effect of one ball, or 'model person', on another. This situation where moving masses have the ability to effect each others movement, even without contact, forms the basis for the observed relationship between crowd transit and fluid motion.

10. ACKNOWLEDGEMENTS

Thanks to Les Russell for building the 'steady state' apparatus, and for having a large input into the design.

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APPENDIX 1.3

"SIMULEX: DEVELOPING NEW TECHNIQUES FOR MODELLING EVACUATION"

This paper was presented at the "Fourth International Symposium on Fire Safety Science", 13-17 June, 1994 at the National Congress Centre, Ottawa, Canada, and will be enclosed in the in the proceedings, published by Elsevier Science Publishers, London.

SIMULEX; DEVELOPING NEW COMPUTER MODELLING TECHNIQUES FOR EVACUATION

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ABSTRACT

Many computer models for evacuation have been developed over the past fifteen years, primarily in the form of network-node analyses. These models, by their nature, are severely restricted and cannot accommodate geometrical complexity or compound irregularities in crowd transit. If modern buildings are to be accurately analysed in terms of their evacuation characteristics, then more sophisticated simulation techniques must be adopted. This paper details the development of a computer program that is based on new methods for modelling the motion of individual people in a building. The program makes use of the power of modern P.C.s and is based upon complex spatial analysis and computer-generated route-finding techniques. Particular emphasis is placed upon the incorporation of real-life data into the basic structure of algorithms, and how the performance of the program relates to the Building Regulations [1].

KEYWORDS

Movement, simulation, speeds, parameters, spatial analysis, contours, overtaking, behaviour, validation.

1. INTRODUCTION

The development of SIMULEX began by identifying the shortfalls of some of the computer programs developed over the past fifteen years. Network-node models such as EVACNET+ [2] made use of simple flow parameters of crowd motion. The user defined a number of rectangular spatial blocks and connecting arcs that modelled rooms and pathways in a building. Crowds were treated as homogenous masses, in terms of speed or

flow rate, and various assumptions were made about their movement. Behavioural analyses, such as EXITT [3] adopted a different approach by assigning individual speeds, and concentrating much more on the psychological aspects of escape, by using rules formulated by the programmer. These early behavioural models made similar assumptions about the building space, by dividing the building into discrete spatial blocks. The networking of large rectangular spatial blocks may be satisfactory for buildings with simple floor plan layouts, but modern shopping malls, office blocks and stadia are becoming ever more complex and their spatial configurations cannot be considered as individual areas connected by pathways in a network of rooms. The network-node approach requires a high degree of user-input and cannot accommodate obstructions or highly irregular shapes within the building plan.

The most advanced form of the network models in the U.S. is EXIT 89 [4]. This was the first program to achieve the processing of large numbers of individual people and incorporates some modelling of the effect of smoke spread upon the occupants. Within each rectangular space all occupants are assigned the same walking speed, unless impeded by smoke. This model has been incorporated into the HAZARD1 package, in an attempt to combine the simulation of fire growth, smoke spread, fire detection, and evacuation. Some degree of correlation with a real-life evacuation of a multi-storey building has been achieved. The program is still under development.

Two programs that have recently been developed in the U.K. use the network-node analysis technique, but on a much finer scale. EGRESS [5] applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagonal node represents the volume space of one person, and may be 'occupied' or 'empty'. Each person steps from one position to the next depending on certain rules, and speed is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real-life experiments will be carried out later in 1993. EXODUS [6] is primarily intended for use on mass transport vehicles and the environment space is represented by a network of nodes, connected by arcs that define the available path of movement from one position to the next. Each node represents a small spatial area, and is regarded as either occupied or empty. Many character traits are described, and input from a fire / smoke spread program can be received and used to affect the behaviour of the occupants. An early validation exercise was executed by comparing EXODUS output to some aircraft evacuation tests and the experimental trends were simulated. Some of the simulated evacuation times were similar to the real-life tests, but not consistently so. This was possibly due to the lack of specific data for the traits of individuals in each evacuation.

The VEGAS system [7] has arisen from the recent developments in virtual reality techniques. The system illustrates fire growth, smoke spread, and occupant behaviour using real-time animation. The psychological aspects modelled are; group behaviour, alarm awareness and the effects of smoke. Each person chooses a direction by assessing user-

specified target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived. Unlike other models, this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic, the mutual obstruction of escaping people and forces acting on their bodies at crowded doorways. One of the primary advantages of this system is its ability to communicate the building environment to the user, due to the clarity of the 3-dimensional graphics.

All of these models require a high degree of user-input. Any program that depends heavily upon a very large number of user-defined parameters or pathways may produce results that vary considerably when used by different engineers. EGRESS [5] and EXODUS [6] both use algorithms that set up a value of potential distance to exit at each node, but the directions of movement are only accurate to sixty degrees and ninety degrees respectively. This is however, a significant improvement upon the earlier network models, due to the resolution of the grids involved, and creates more spatial accuracy with less numerical user-inputs.

2. PRIMARY OBJECTIVES OF SIMULEX

A number of definite objectives were formulated at the outset of this project. They dictated the basic structure of the model and determined the underlying approach to solving problems that arose. The program sets out to;

- (i) Define the building space with only the building plan as a user-input.
- (ii) Input the building plan using graphical techniques, and a 'mouse' in order to reduce the time taken to define the building space. CADD package outputs should eventually complement this process.
- (iii) Automatically define both the building space and escape routes through any building geometry, with a high degree of accuracy. Flexibility should also be incorporated in order that the user can change the nature of the escape routes, if desired.
- (iv) Define individuals by creating a stack of person characteristics and co-ordinates using inputs based on population density figures from the Regulations [1] or research data. There will be a random distribution of occupant characteristics such as age and walking speed.
- (v) Incorporate flexibility into the definition of escape routes, so that overtaking and similar behaviour consisting of localised route deviation can occur.

- (vi) Incorporate; speed reduction effects due to the proximity of other individuals; overtaking and 'jostling' algorithms, and floating point arithmetic for the assessment of angles of orientation and position.
- (vi) Produce a plan view of the evacuation process, displaying a clock and a graphical representation of each person's movement with the passage of time.

3. THE SUITE OF PROGRAMS IN THIS PROJECT

The following programs were written to contribute to this project;

- (i) DRAWPLAN - allows the user to define the building geometry.
- (ii) GRIDFORM - handles output from DRAWPLAN and segments the building space into a fine mesh of spatial squares. Once this is done, the routines create a map of boundary exits and distance contours throughout the building space.
- (iii) ONEMAN - uses data from DRAWPLAN and GRIDFORM, and uses this data to animate one person's movement from the most remote point in the building to the nearest building exit.
- (iv) SIMULEX - uses data from DRAWPLAN, GRIDFORM, and user-specified inputs describing population characteristics. A simulation of the building evacuation is then animated and analysed.

4. DRAWING THE BUILDING PLAN WITH 'DRAWPLAN'

The graphics program DRAWPLAN allows the user to draw in the building plan using the 'mouse' and a few key controls. Speed of input is obtained by creating walls and obstructions by defining rectangular 'building blocks', of any orientation and width. Only two 'clicks' of the mouse are required to draw a solid wall, so that the plan may be input as quickly and easily as possible. It is envisaged that the final version of this program will handle CADD outputs as an option.

5. DEFINING SPACE AND POTENTIAL EXIT ROUTES WITH 'GRIDFORM'

This program processes the data from DRAWPLAN and automatically forms a high definition integer distance grid where all walls or solid objects are assigned the maximum value, and exit values are set to zero. Within this grid the program sets up a fine mesh of data points whose assigned values are equal to their geometrical distance to the nearest exit. The plan area that each data point represents is equal to 0.0625 square metres.

The optimum route to exit from any point can be evaluated by assessing the pattern of surrounding values. The easiest way of visualising the route-finding system is to represent the 'spatial mesh' values in bands, as contours of distance from the nearest exit. The shortest route to exit at any point is obtained by heading at right angles through the contours. The distance contour map shown in Figure 1 is set up so that the optimum direction to the nearest exit is accurate to within 2 degrees, while computer processing time remains relatively short.

The system is fairly flexible. Before the mesh is formed, the values at exits can be altered (instead of automatically set to zero) and this affects the whole pattern of the final 'distance map'. If an exit value is increased before the 'distance map' is formed, a bias is created, making exits more or less desirable. Research has proved that occupants often prefer to evacuate through more familiar escape routes, but comprehensive data is not yet available.

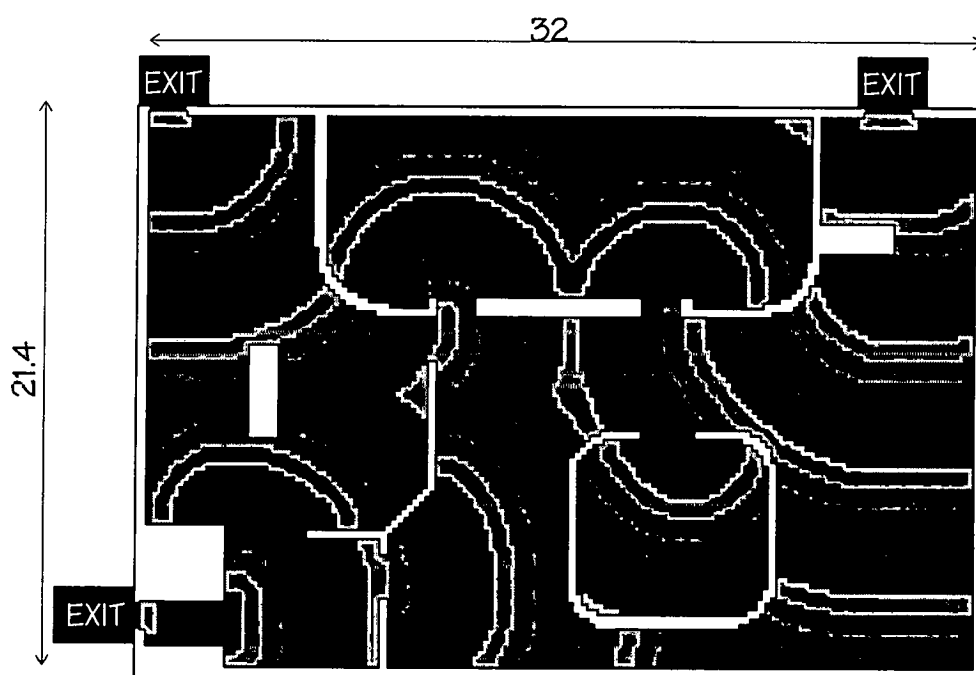


Figure 1. Distance Contour Map for a Complex Office Space

6. ASSESSING TRAVEL DISTANCE WITH 'ONEMAN'

This program uses the building plans and contour maps already formed. The point that is most remote from any exit is automatically identified by the computer. The route

taken by a single person from this point to the nearest exit is then animated, with the time and distance travelled displayed as motion progresses. The final output displays the total route, the time taken and the distance travelled. The distance travelled is equal to the 'travel distance' as defined by the Building Regulations [1]. The angle of travel is accurate to two degrees. Accuracy can be increased, if desired, by increasing the area of the scanning arrays used to set up the distance contour map.

7.0 MODELLING EVACUATION WITH 'SIMULEX'

The main program, SIMULEX, uses the building plan data compiled by 'DRAWPLAN' and 'GRIDFORM'. On execution, the program requests the name that has been assigned to the data files for one building, and then loads them. The building plan is displayed with a dialogue box at the bottom of the screen. The user is asked firstly if 'movement traces' are desired, and secondly about details of the population densities. If 'movement traces' are selected then individuals leave coloured trails behind them as they move, creating a graphical display of all of the escape routes taken. If 'movement traces' are not selected, then individual movement is animated, and the lines of individual escape routes are not displayed. The population density is input by specifying one density over the whole building, or different densities for different areas. The program then begins initialising the simulation.

7.1 POPULATION CHARACTERISTICS

At present, SIMULEX assumes that the building population consists of people with ages randomly distributed between 12 and 55, with male and female genders. Thus, the unimpeded walking speeds of individuals vary from 0.8 to 1.7 m/s, and are assigned automatically when the stack of population characteristics is formed. These figures are based on the data from Ando et al [8], and can be adjusted if different characteristics are desired. The orientation of each individual's body is randomly distributed amongst the population when the 'character stack' is created. The co-ordinate position of each person is defined by creating a regular plan grid of people. The distances between people in this grid are calculated from the densities specified by the user at the outset.

7.2 RUNNING SIMULEX

When SIMULEX commences, all the movement algorithms are invoked for each individual, nine times per second. This frequency of assessment was chosen because the fastest person in the system could progress no more than 200mm between each movement assessment scan. Individual motion is evaluated by the methods described in Sections 7.3 - 7.6. The dialogue box displays the time clock, the number of people in the building, and the file name. When the last person leaves the building, the total evacuation time is displayed.

7.3 ASSESSING ROUTE TO EXIT

In the first instance, each person uses the contour map to assess the optimum direction to exit (in terms of distance). This is done by looking in the direction that is perpendicular to the distance contours at that position. If the speed algorithm decides that motion is potentially impeded in this direction, then the overtaking and jostling algorithms are invoked.

7.4 FLUCTUATIONS IN INDIVIDUAL WALKING SPEEDS

The essence of simple crowd flow is the relationship between the proximity of individuals and their walking speed. As the distance between people in a crowd is reduced, the crowd density increases and the overall speed of forward motion in the group decreases. When the proximity increases to such a degree that bodily contact is incurred, then 'shuffling' and further irregular speed reduction occurs. At very high crowd concentrations 'body arching' or jamming can cause major speed reductions, and halt the forward motion of the crowd. This pattern of behaviour has been observed and collated by many researchers, some of whose results are summarised in Figure 1. Note that the units are those used by Ando *et al* [8], and the other data values from Fruin [9], Hankin & Wright [10] and Predtechenskii & Milinskii [11], have been converted from different units

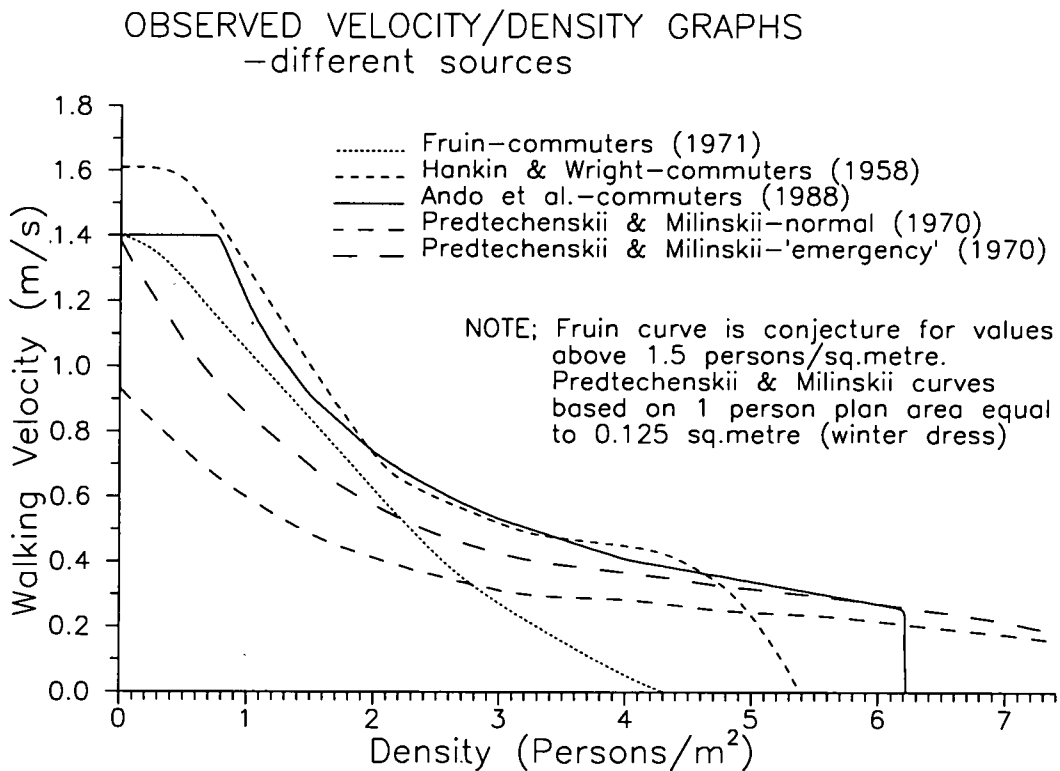


Figure 1. A comparison of available data on the crowd velocity / density relationship

Speed reductions due to the proximity of others are calculated using an approximation of the speed / density curve presented by Ando *et al* [8]. Unfortunately, the curve assesses speed in relation to crowd density over a given area, so it is necessary to convert the data to a form that relates speed to distances between individuals. SIMULEX requires data in this form in order that individual movement can be evaluated.

For the purposes of the program, the speed is related to the inter-person distance 'd' between centre co-ordinates of the assessing and obstructing persons, as illustrated in Figure 2.

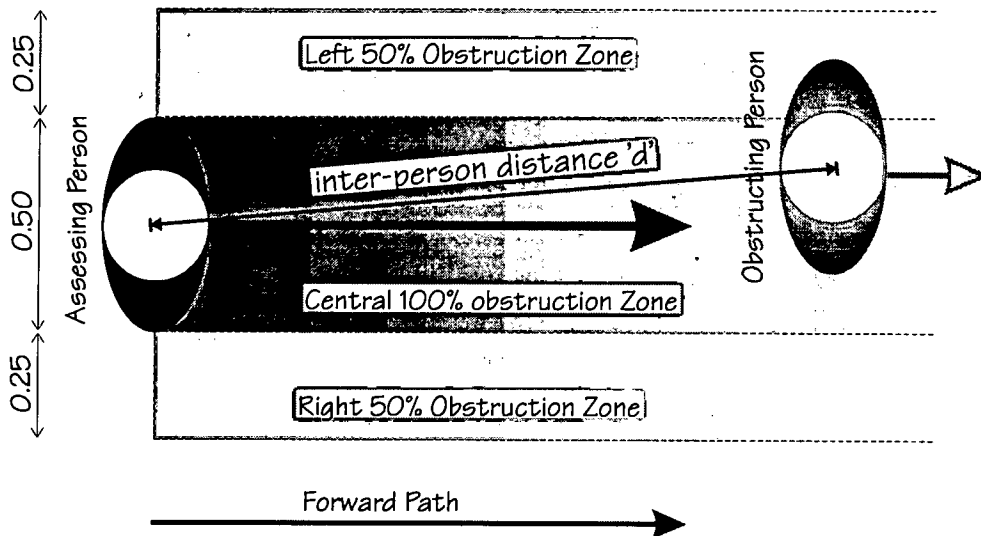


Figure 2. Obstruction Zones For Speed Assessment

Fruin [9] and Ando *et al* [8] observed regular packing characteristics in uniform crowds. Equation (1) is based upon these observations, and assumes that in a crowd of evenly spaced people, the area per person is equal to the square of the average inter-person distance. Using this spatial assumption, the velocity/density relationships described in Figure 1 are approximated in terms of inter-person distance by Equation (2). The graph of the final data, derived from the figures from Ando *et al* [8] is shown in Figure 3.

$$d = \sqrt{\frac{1}{D}} \quad \dots(1)$$

$$reduced.speed = \left(\frac{V(d - 0.25)}{0.87} \right) \quad \dots(2)$$

Note: d is inter-person distance (m), D is density (Number of persons/m²), V is unimpeded walking speed (m/s). NOTE: if $d < 1.12$ then speed is assumed to be unimpeded. This 'distance threshold' of 1.12m can be adjusted if desired.

The formula is fully applied when the nearest obstructing person is within the 100% zone (Figure 1). If the nearest obstructing person is within a 50% zone, the speed reduction is multiplied by 0.5, and a second 'nearest person' in either of the other two zones will also incur only half of the speed reduction effect.

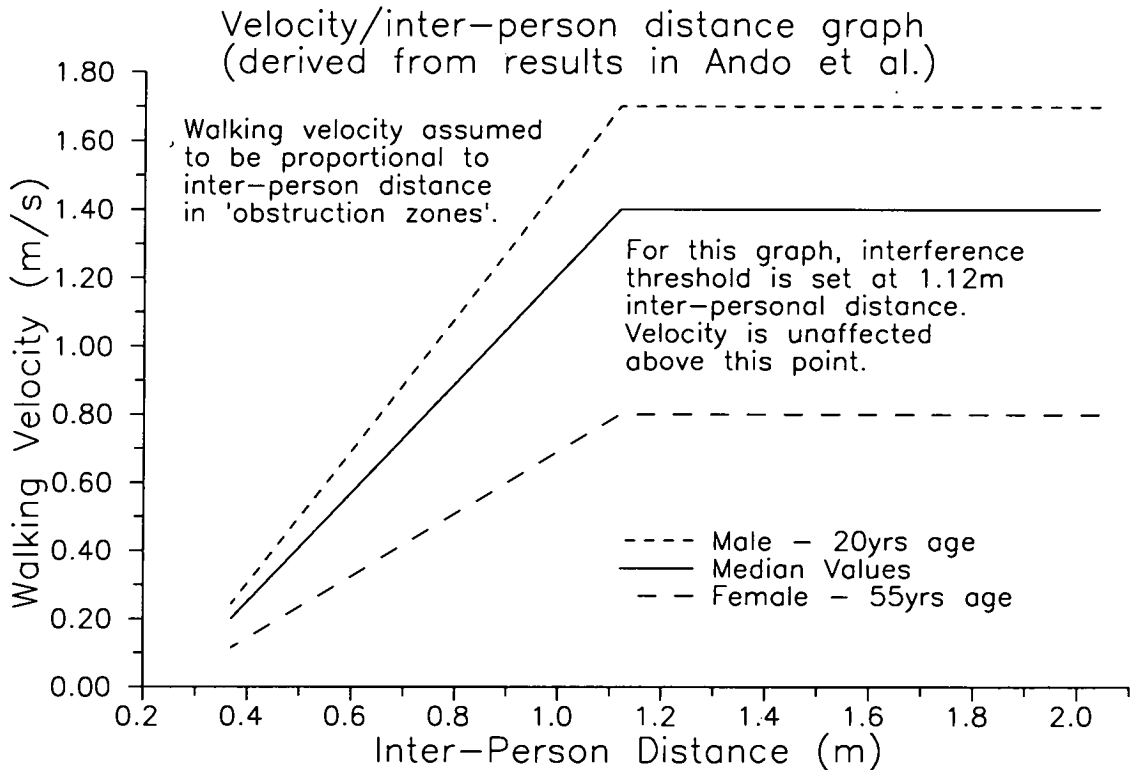


Figure 3. The velocity / distance graph used by SIMULEX

To check that SIMULEX displays the suitable range of speeds, and associated variation in speed within the population, it is possible to convert the data shown in Figure (3) back into units of density instead of inter-person distance. Thus, the emulated graph of velocity against density was obtained by using Equations (1) and (2) and is illustrated in Figure 4.

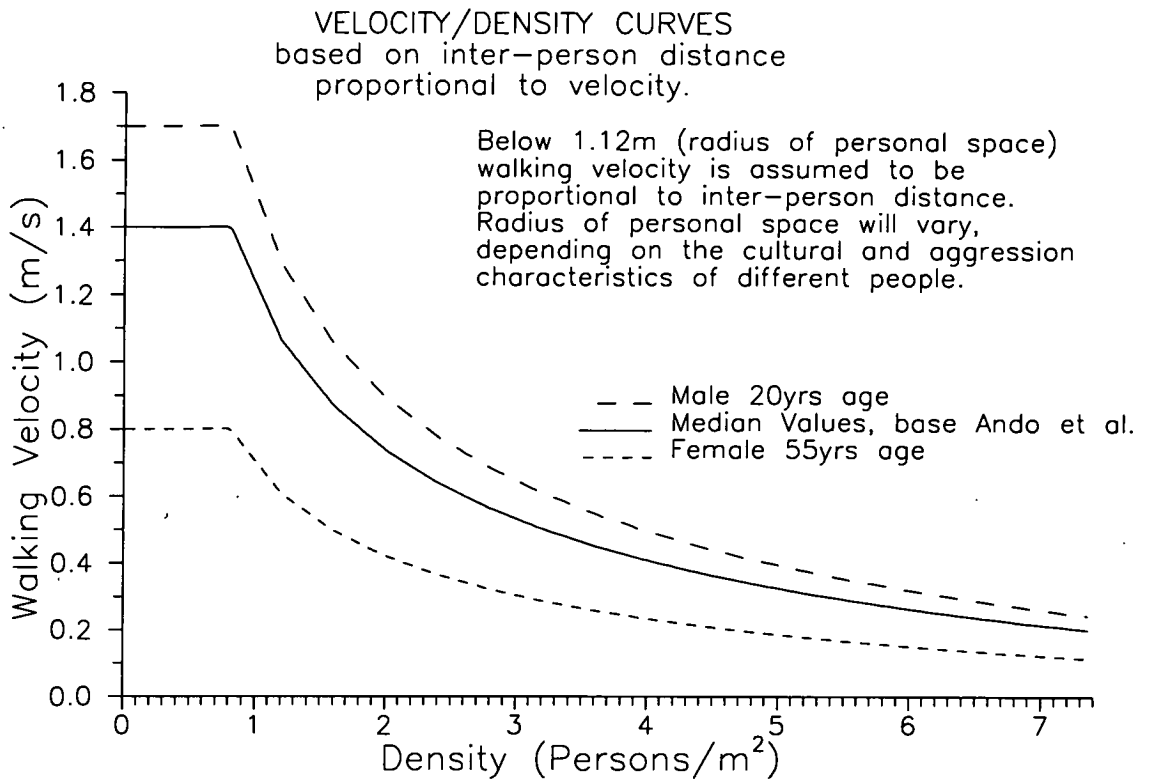


Figure 4. The velocity / density curves emulated by SIMULEX

7.5 OVERTAKING AND LOCALISED ROUTE DEVIATION

If the walking speed of an individual is impaired by the proximity of one or more obstructing persons, then the overtaking routines are invoked. The program scans either side of the direction of travel, and if a significant improvement in speed is obtained, then the direction of travel changes to the new deviated angle. The angle of deviation, or 'overtake angle', increases as an obstructing person becomes closer. Overtaking and localised deviation of route is observed frequently, and the deviation routine produces a degree of jostling in the higher density crowds.

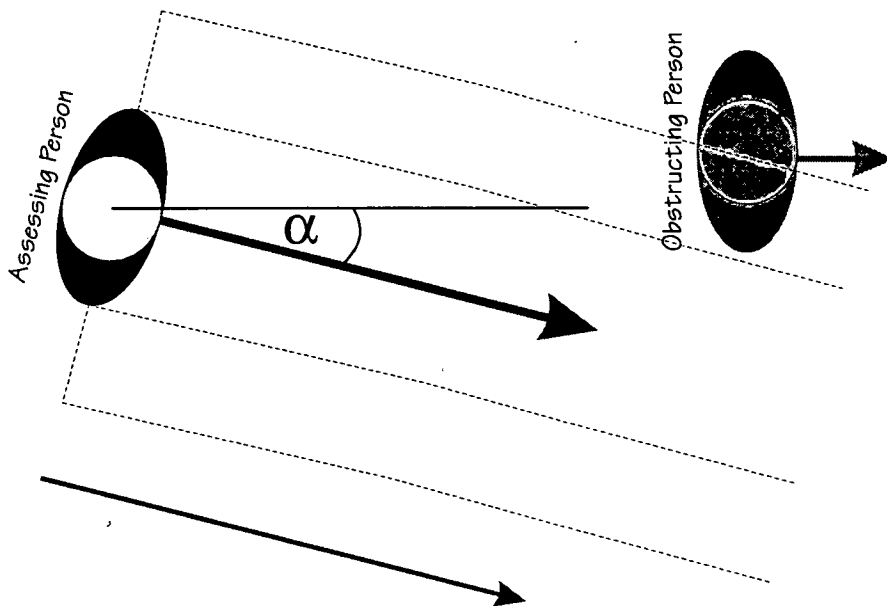


Figure 5. Localised route deviation caused by the proximity of another individual.

7.6 MOVEMENT CHARACTERISTICS

The program, by its nature, models queuing inherently. The speed calculations never yield a zero value, but each person is only allowed to move into unoccupied space and will therefore become stationary if exactly behind another person. Twisting movements of the body are restricted by an 'available twist factor' which is currently set at 0.01 seconds/degree. This twist factor is to be checked and updated, depending on the results of forthcoming observational research. As yet, no pushing or pressure build-ups are modelled.

8. EARLY SIMULATION RUNS

In order to assess the maximum flow capacity of a doorway width, the program was used to model high density, non-panicking crowds at doorways of different widths. With slight changes of the overtaking/jostling algorithm and the order in which speed assessment occurs (scanning from [most remotely positioned person] first, to [person at exit] last, or visa versa) then the flow rate 'q' can vary from 1.5 to 1.9 persons/m/s. Real-life observations of q include 1.5 ('Fire & Buildings' [12]) and 1.8 persons/m/s (Melinek [13]) This correlation of simulated value to real life observation is encouraging, especially in view of some of the assumptions made in the speed assessment routine.

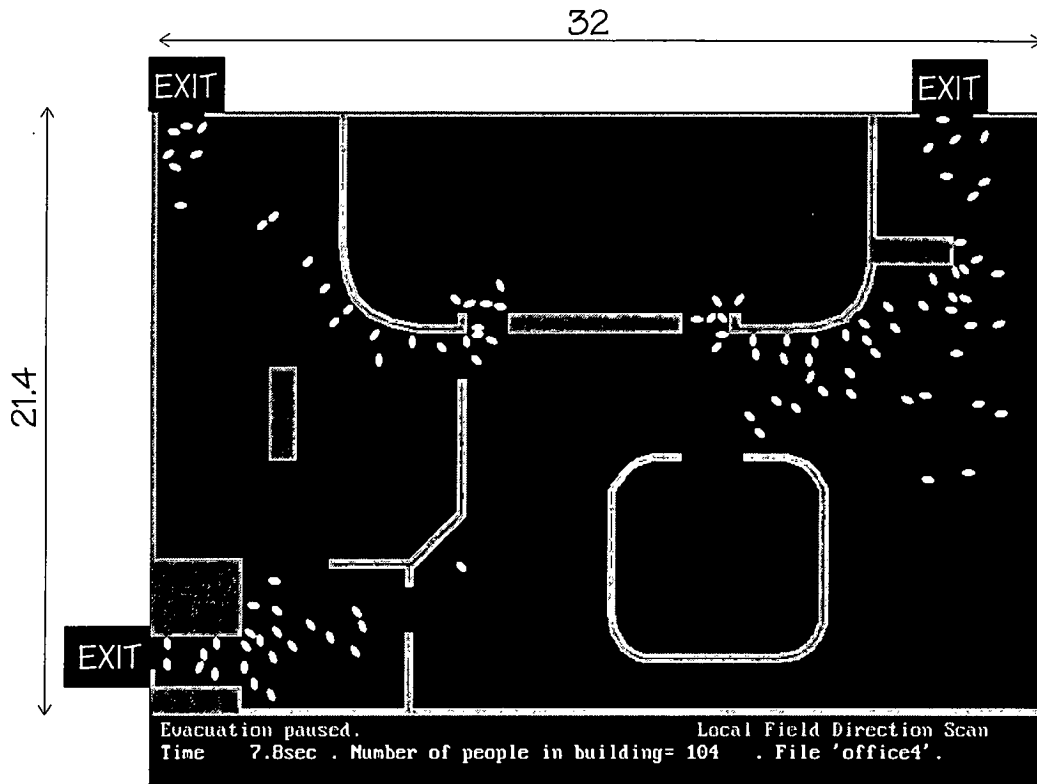


Figure 6. Sample Screen Display for an office space evacuation. Dims.(m).

Figure 6 demonstrates the ability of the program to cope with complex geometries and obstructions of any size. In the example shown, immediate reaction to alarm was assumed. It became clear from watching the progress of various simulations that the presence of a narrow obstruction in the centre of a 1.8 metre wide opening significantly reduced flow capacity, even though the total combined opening width was only reduced by 0.1m.

9. CONCLUSIONS AND DEVELOPMENT

SIMULEX adopts a new approach to modelling the evacuation of buildings. It combines the ease and speed of user-input with geometrical complexity and a population with individual characteristics of movement and speed. The aim is to produce a program that accepts population density requirements from the Building Regulations, but uses modern research and computing power to evaluate the potential evacuation of a complex building with a high degree of accuracy. At the same, it illustrates to the user any restrictive areas of the building where bottlenecks and 'jams' occur, in order that the design may be adjusted and optimised for the purposes of evacuation.

The route-finding techniques that have been developed are geometrically accurate and 'travel distance' is automatically assessed. A choice of exit can be achieved by overlaying various distance contour maps based on different available final exits, and the effects of smoke spread could be simulated by the progressive addition of weighting factors to the contour maps over increasing areas of the building. At this stage, staircases have not yet been modelled because validation on a single storey, flat plane is required first.

More complex psychological factors affecting the building population are currently under investigation. One important factor is the time taken for individuals to react to an alarm and begin the physical escape process. This 'first stage' of evacuation is affected by an individual's awareness, eagerness to move, and the nature of the alarm. Studies, such as those carried out by Proulx [14] could be used as a basis for numerical values, but the data available at present does little more than suggest that the reaction time to alarms can vary from 10 seconds to 15 minutes. Other complex psychological factors such as the familiarity of routes and aggressiveness will be incorporated in a later version, but additions such as these must require a greater degree of user-input.

The strong correlation between test results and real-life values of crowd flow rate per unit exit width is very important. More large scale validation is required, and observational tests on evacuating people are to be carried out in the spring of 1994 in order that the accuracy of the computer methods can be determined. Results such as overtaking behaviour, twisting ability, and general route deviation will be logged and compared to the performance of the computer algorithms. Any parameters or assumptions found to be inaccurate in any way will be identified and adjusted. The future development of SIMULEX will be based upon combining progressive advancement with the results from real-life observations and tests.

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APPENDIX 1.4

"COMPUTER MODELS FOR ESCAPE MOVEMENT"

This paper was presented at the conference "Fire Safety Modelling and Building Design", 29 March, 1994, held at the University of Salford, Manchester, England. It is enclosed in the proceedings which are available from Dr. John Hinks at the Department of Surveying at the University of Salford.

COMPUTER MODELS FOR ESCAPE MOVEMENT

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Abstract

Modern research into 'escape movement' has been primarily concerned with analysing the general movement of crowds as a whole. These observations have been used as the basis for approximate rules that attempt to simulate crowd speeds and flow rates in fairly simple geometries.

The 'general rule' approach has come under increasing scrutiny in recent years, and the sophistication of modern computer modelling techniques demands that the data available should be of a more specific and quantitative nature. The accuracy of any computer model is wholly dependant upon the exactness and nature of the data that is available to it. The effects of people's reaction to alarm has been observed by Proulx [1], and other researchers both in the U.K. and the U.S.A.. The dependency of an individual's unimpeded walking speed upon age and gender [2] and disability [3] has been collated, and there have been many observations of overall crowd speeds and flow rates by Predtechenskii & Milinskii [4], Pauls [5], and Hankin & Wright [6], but there has been little research into the 'mechanics' of crowd movement. It is understood that crowd speeds decrease when the concentration of people increases, but there is a lack of knowledge about the interactive dynamics that cause this behaviour. Laws for the velocity and directional behaviour of a crowd's individual constituent members need to be developed if simulation models are to become more sophisticated and more accurate. This paper details some of the ongoing research into the computer modelling of crowd movement.

1. COMPUTER MODELLING TECHNIQUES

Various computer models for evacuation have been developed to date, but only a few are capable of handling large numbers of people, while still processing the movements of each person individually. An outline description of some of the more recent models is given in the following paragraph.

1.1 EXIT 89 [7]

EXIT 89 was the first program to achieve the processing of large numbers of individual people and incorporates some modelling of the effect of smoke spread upon the occupants. The program treats a building as a room network-node system of linked rectangles. Within each rectangular space all occupants are assigned the same walking speed, unless impeded by smoke. This model has been incorporated into the HAZARD1 package, in an attempt to combine the simulation of fire growth, smoke spread, fire detection, and evacuation. Some degree of correlation with a real-life evacuation of a multi-storey building has been achieved. The program is still under development.

1.2 EGRESS [8]

In an attempt to bring some probabilistic modelling and artificial intelligence to the field, this program applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagon may be 'occupied' or 'empty'. An occupied hexagon represents the volume space of one person. Each person steps from one position to the next depending on certain rules, and speed is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real-life experiments will be carried out later in 1993.

1.3 EXODUS [9]

The movement model in EXODUS bears some resemblance to that incorporated in EGRESS, in that movement is accommodated by a person stepping from one 'cell' or node to the next. The program is primarily intended for use on mass transport vehicles and the environment space is represented by a network of nodes, connected by arcs that define the available path of movement from one position to the next. Each node is the size of one person, and is regarded as either occupied or empty. Many character traits are described, and input from a fire & smoke spread program can be received and used to affect the behaviour of the occupants. An early validation exercise was executed by comparing EXODUS output to some aircraft evacuation tests and the experimental trends were simulated. Some of the simulated evacuation times were similar to the real-life tests, but not consistently so. This was possibly due to the lack of specific data for the traits of each person in each evacuation.

1.4 VEGAS [10]

The VEGAS system has arisen from the recent developments in virtual reality techniques. The system illustrates fire growth, smoke spread, and occupant behaviour using real-time

animation. The psychological aspects modelled are: group behaviour, alarm awareness and the effects of smoke. Each person chooses a direction by assessing pre-set target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived. Unlike EGRESS and EXIT 89 this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic, the mutual obstruction of escaping people and forces acting on their bodies at crowded doorways.

None of the computer programs outlined above have yet undergone the extensive validation procedures required before they could be used a quantitative assessment tool, but their application does provide some interesting qualitative insights.

2. THE NEED TO DEVELOP NEW COMPUTER MODELS

Existing computer models either make large assumptions about the speed and direction of travel of each person, or accommodate each person's position by use of a grid cell network where each cell is the size of one person. The one exception is the VEGAS package which processes each person's precise co-ordinates. The VEGAS package contains many psychological factors and physical shape characteristics but the direction finding capabilities are dependent on user-specified target points dictating the exit route. There remains a need for a program that treats each person individually, assigning individual characteristics (including age, disability, eagerness to escape) that can cope with infinite geometrical possibilities for escape. It should automatically assesses the entire escape route for each person, whilst re-assessing the route (both locally and globally) at each time step of motion. There is also a need to model overtaking, queuing, and other behaviour characteristics. The VEGAS package does achieve many of these factors, except for complex overtaking routines and the automatic assessment of the direction of individual routes through an infinite geometry. When applied to the building types for which it is designed, it does yield a useful graphical insight into the whole escape process. All 'egress' and 'escape' computer models require validation with real-life behaviour tests and crowd flow characteristics, but the adoption of more realistic movement parameters and methods should ensure that the comparison to real-life observations becomes more rewarding.

3. SIMULEX - developing some new techniques

The SIMULEX program is being developed in order that individual movement can be modelled more realistically, through any geometry of building plan. This is made possible by the use of distance contouring. Other parameters that are built into the program include; walking speeds, overtaking, body twisting, and queuing.

3.1 ASSESSING ROUTE TO EXIT

Firstly, the building plan is drawn on the screen using the mouse and a simple drawing package designed for this program. This plan is then processed and automatically converted to a high definition integer distance grid where all walls / solid objects are assigned the maximum value, and exit values are set to zero. Within this grid the program sets up a

contour map of distance from the nearest exit which emanates through all of the open space available to people. The contour map shown in Figure 1 is set up so that the optimum direction to the nearest exit is accurate to within 2 degrees, while computer processing time remains relatively short. The routine can also be used to assess minimum travel distance from the most remote point of the building, as required by the statutory regulations [11].

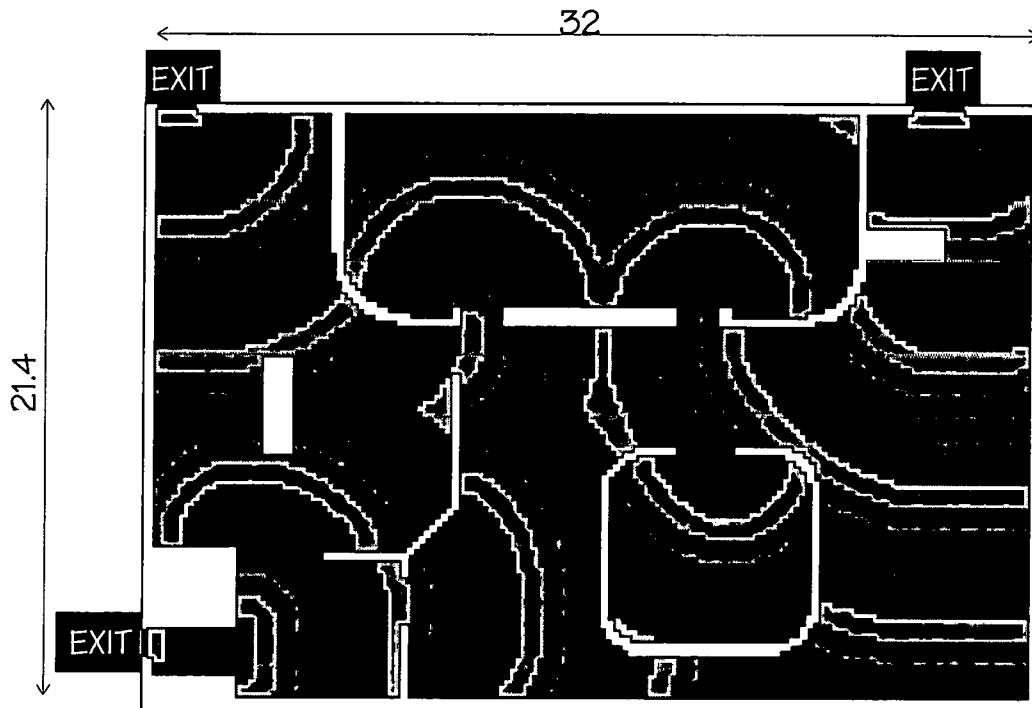


Figure 1. Distance Contour Map for a Sample Office Space

3.2 WALKING SPEED

Each person's speed is assessed individually at each time step (0.1 sec.). Each person is assigned a random unimpeded walking speed of between 0.8 m/s (an elderly woman) and 1.7 m/s (an eager, young man of 20 years). Speed reductions due to the proximity of others is calculated using an approximation of the speed / density curve presented by Ando *et al* [2]. Unfortunately, the curve assesses speed in relation to crowd density over a given area, so some data manipulation is required to yield a method of assessing speed reduction caused by the proximity of other individuals.

For the purposes of the program, the speed is related to the inter-person distance 'd' between centre co-ordinates of the assessing and obstructing persons, as illustrated in Figure 2. Equation (1) assumes that in a crowd of evenly spaced people, the area per person is equal

to the square of the inter-person distance. Using this spatial assumption, the velocity/density relationship described by Ando *et al* [2], is approximated in terms of inter-person distance by Equation (2).

$$d = \sqrt{\frac{1}{D}} \quad \dots(1)$$

$$\text{speed.reduction} = \left(\frac{V}{1.4}\right) \left\{ 1.4 - \left(0.25 + \left(\frac{d-0.4}{0.6309} \right) \right) \right\} \quad \dots(2)$$

Note: d is inter-person distance (m), D is density (Number of persons/m²), V is unimpeded walking speed (m/s), 0.6309 is a time factor (sec). If $d > 1.12$ then speed reduction = 0.

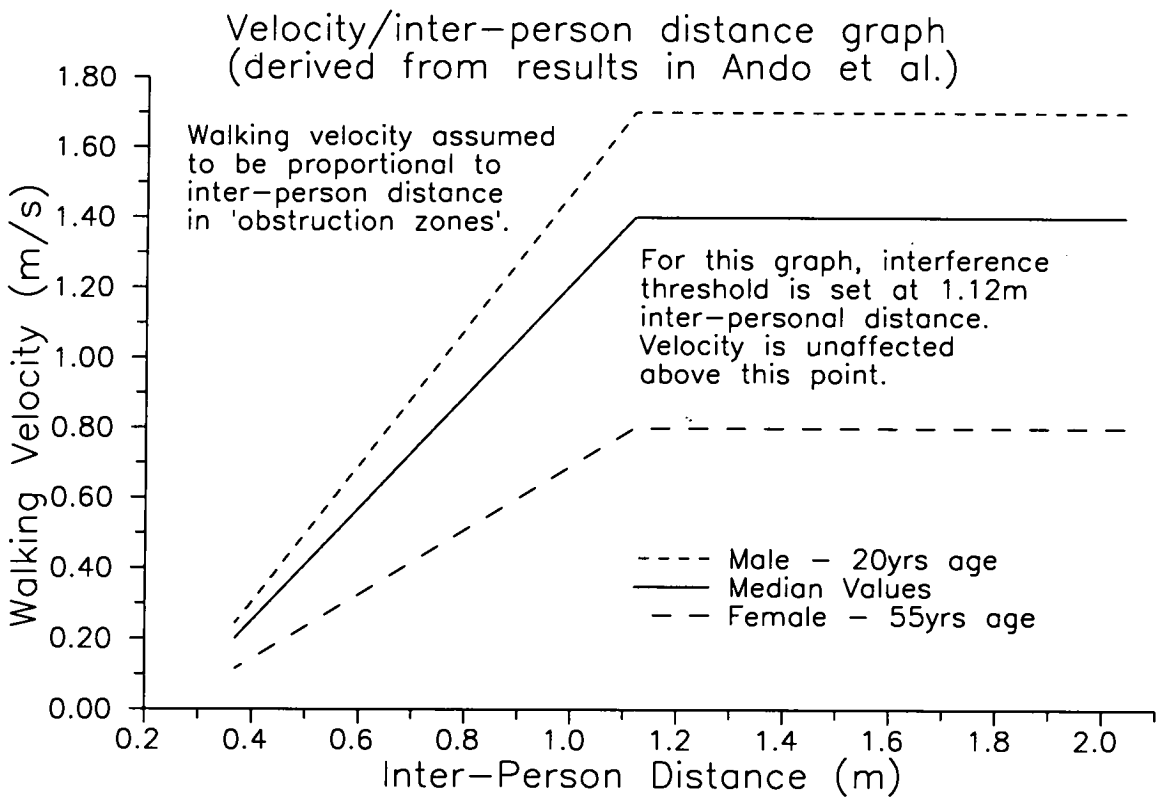


Figure 2. The Velocity / Distance data used by SIMULEX

The formula is fully applied when the nearest obstructing person is within the 100% zone (Figure 3). If the nearest obstructing person is within a 50% zone, the speed reduction is multiplied by 0.5, and a second 'nearest person' in either of the other two zones will also incur only half of the speed reduction effect.

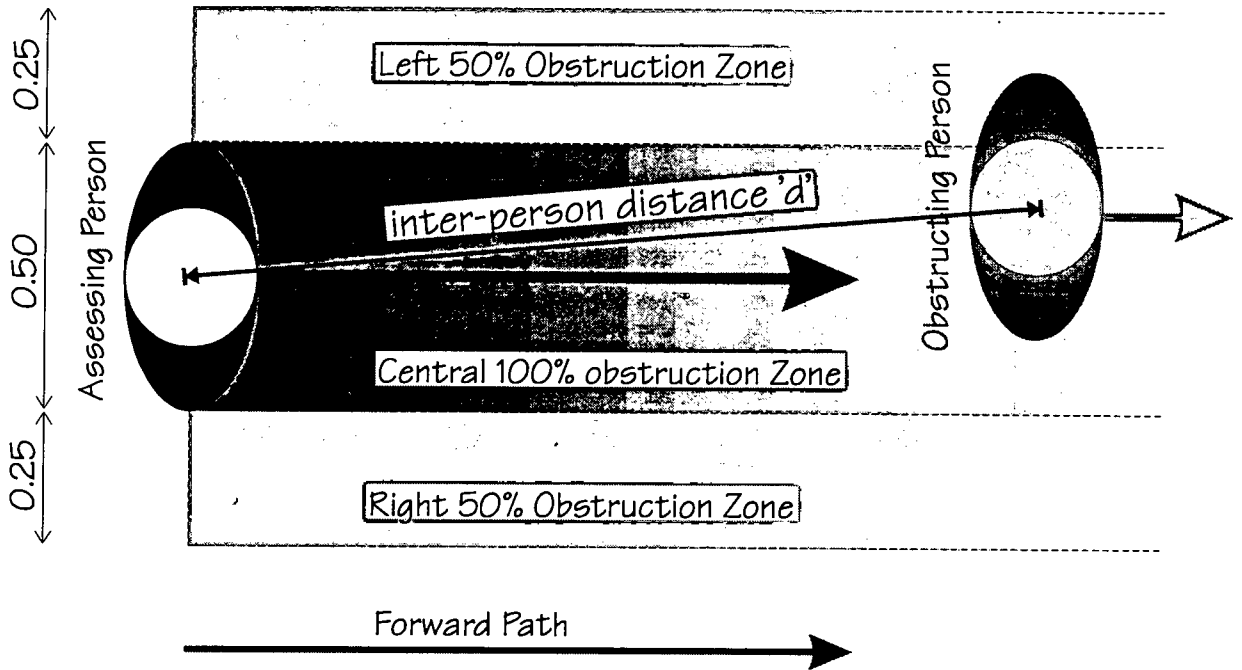


Figure 3. Obstruction Zones For Speed Assessment

3.3 MOVEMENT CHARACTERISTICS

If the walking speed of an individual is impaired by the proximity of one or more obstructing persons, then the overtaking routines are invoked. The program scans either side of the direction of travel, and if a significant improvement in speed is obtained, then the direction of travel changes to the new deviated angle. The angle of deviation, or overtake angle, increases as an obstructing person becomes closer. Overtaking and localised deviation of route is observed frequently, and the deviation routine produces a degree of jostling in the higher density crowds.

The program, by its nature, models queuing inherently. The speed calculations never yield a zero value, but each person is only allowed to move into unoccupied space and will therefore become stationary if exactly behind another person. Twisting movements of the body are restricted by an 'available twist factor' which is currently set at 0.01 seconds/degree. This twist factor is to be checked and updated, depending on the results of forthcoming observational research. As yet, no pushing or pressure build-up is modelled.

3.4 EARLY SIMULATION RUNS

Simulation runs begin with the user specifying a uniform density of persons per unit area evenly over the building plan. The program also asks if movement traces are to be shown. These movement traces map out the path that each individual has followed during the course of an evacuation, describing where overtaking, and other manoeuvres have taken place. The

program then creates each person's co-ordinates, unimpeded walking speed (dictated by age and gender), and initial angle of orientation of the body. A delay can be programmed in for reaction time to alarm, delaying the initial movement of individuals depending on their awareness and eagerness to move. More complex psychological factors such as the familiarity of routes and aggressiveness will be incorporated in a later version. The program has been tried on many plan layouts. At this stage, staircases have not yet been modelled because validation on a single storey, flat plane is required first.

In order to assess the maximum flow capacity of a doorway width, the program was used to model a single, large room that possessed one narrow doorway, and a large number of people. The simulation was intended to recreate a high density, non-panicking crowd at a doorway. In this test q (flow rate, persons/(metre width)/second) was found to be 1.8. With slight changes of the overtaking/jostling algorithm and the order in which speed assessment occurs (scanning from [most remotely positioned person] first, to [person at exit] last, or visa versa) then q can vary from 1.5 to 2 persons/m/s. Real-life observations of q include 1.5 ('Fire & Buildings' [12]) and 1.8 (Melinek [13]) persons/m/sec. This correlation of simulated value to real life observation is encouraging, especially in view of some of the assumptions made in the speed assessment routine.

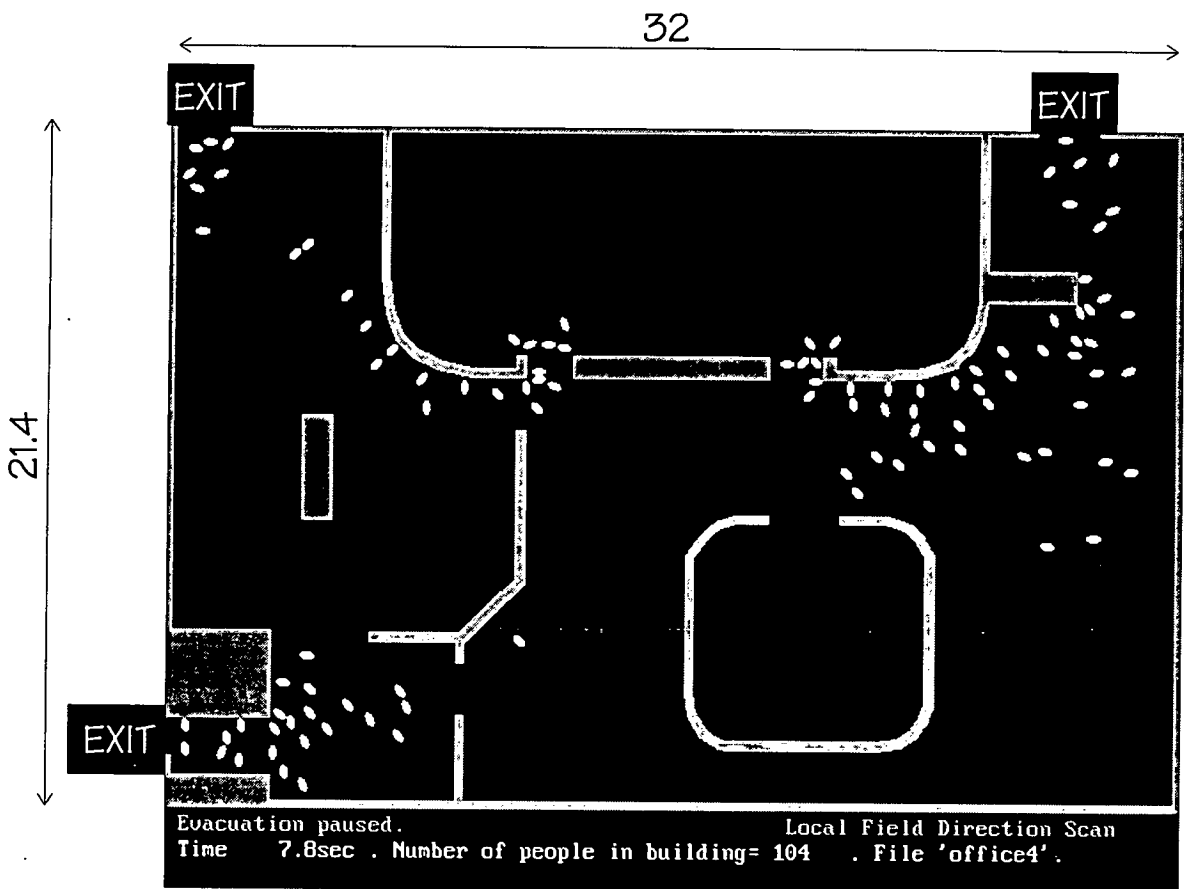


Figure 4. Sample Screen Display for a Complex Office Space Evacuation . Note dims.(m).

Figure 4 demonstrates the ability of the program to process complex geometries and obstructions of any size. In the example shown, immediate reaction to alarm was assumed. It became clear from watching the progress of various simulations that the presence of a narrow obstruction in the centre of a 1.8 metre wide opening significantly reduced flow capacity, even though the total combined opening width was only reduced by 0.1m.

4. CONCLUSIONS AND DEVELOPMENT

To date, one of the most notable results from SIMULEX is the correlation between test results and real-life values of crowd flow rate per unit exit width, but more large scale validation is required. The route finding algorithms automatically reassess exit routes at each time step, and the only input required is the building plan itself. All exits in the building are recognised automatically and any geometry of obstruction can be accommodated. The program is restricted to fairly small areas at present but is currently being adjusted for large memory usage in order to model areas the size of large sports stadia.

The computer methods adopted in SIMULEX show promise because of their flexibility in handling infinite spatial variations combined with the automatic exit route assessment routines. The program is written to incorporate aspects of disability, aggressiveness and different body shapes as part of the future development. A choice of exit could be achieved by overlaying various distance contour maps based on different available final exits, and the effects of smoke spread could be simulated by the progressive addition of weighting factors to the contour maps, over increasing areas. It is envisaged that additional parameters will be incorporated into the speed assessment routines of SIMULEX.

Observational tests on evacuating people are currently being carried out in order that the accuracy of the computer methods can be determined. Results such as overtaking behaviour, twisting ability, and general route deviation have been logged and will be incorporated into the model algorithms.

The future of computer modelling in the field of life safety is assured. The models that are currently being developed in the U.K. require more 'validation' and testing, but the techniques that they use are far in advance of the previous models, notably the coarse network-node methods. The paper has been primarily concerned with the computer model SIMULEX, but EGRESS[8], EXODUS[9], and VEGAS[10] are each important developments in the field of computer modelling for escape movement.

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APPENDIX 1.5

"COMPUTER AND FLUID MODELLING OF EVACUATION"

This paper has been accepted for publication in the international journal "Safety Science", and will be included in a forthcoming issue. Due to the format of documentation of the journal, all figures are enclosed at the end of the paper, after the references.

COMPUTER AND FLUID MODELLING OF EVACUATION

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ABSTRACT

One of the most important areas in the field of 'Life Safety' is the escape movement of individuals in emergency situations. It is not yet possible to accurately model very complex psychological reactions, such as panic and confusion, but many parameters can be simulated, especially in the case of crowd movement. These basic parameters include speed fluctuations; crowd flow behaviour; travel distances and overall evacuation time, based upon certain assumptions. The evacuation characteristics of a building can be assessed in different ways. The statutory regulations (BSI, 1983) use general rules based upon the maximum crowd flow rates through specific exit route widths. These figures are based upon data produced in the 1950s (Hankin and Wright, 1958) that were intended primarily for application in building plans with fairly regular room / corridor plan configurations. This paper discusses two techniques for assessing crowd movement; fluid modelling and computer simulation. The fluid modelling is intended to provide a greater degree of understanding about the mechanism of crowd flow. The computer model SIMULEX combines spatial analysis with the escape movement of large numbers of individuals in a building, and is intended for eventual use as a design tool.

1. FLUID MODELLING OF ESCAPE MOVEMENT

When people are densely packed into a group, individual movement is prevented, as observed by Fruin (1971) in his "no touch zone" configuration. Individuals are carried along by the crowd as a whole and their movements are dictated by the group flow. This movement is normally in one direction in a passageway, and certain characteristics (such as pressure increase) have been observed to be "fluid" in behaviour.

The possibility of fluid modelling has been under discussion for more than twenty five years. Peschl (1971) suggested that the flow properties of gases, liquids, and plastically viscous materials have been investigated exhaustively and it has not, so far, been possible to establish a law that governs the passage of large numbers of people through doors and narrow passages. The first "Green Guide" (HMSO, 1973) made the positive recommendation that the escape flow paths in stadia should be designed as pipe network systems. Riddel & Barr (1991) attempted to model the flow of people around crush barriers in a sports stadium by using coloured water flowing over a tilted table which contained model obstructing walls. From close analysis of known data, it is evident that the fluid models described by Peschl and Riddel & Barr cannot combine the complex speed / flow / density relationships, arching characteristics, and flow interactions observed in real life (Weston and Marshall, 1972 and Predtechenskii and Milinskii, 1969). A graph of the real-life speed / crowd density relationship is illustrated in Figure (1).

2. TWO PHASE FLUID MODELLING

A crowd flow can be seen as a collection of particles whose mass and movement interact mutually. Looking at the problem logically, it would be incredibly difficult to create masses in a fluid model that control their own movement individually, unless each mass contained a complex " thinking computer " and its own motive system. However, in order to recreate high density system blockages at openings, as observed by Peschl (1971) and Predtechenskii & Milinskii (1969), some form of mass representation must be incorporated into a physical model. A moving fluid is the obvious choice to provide both the potential for pressure fluctuations and a universal motive force for the crowd particles. Early tests using a combination of rolling masses in fluid (Thompson, 1990) appeared to bear some correlation to real life observations.

2.1 EARLY TWO PHASE TESTS

The first tests using the 2 phase modelling system used 24 mm diameter plastic balls rolling in a shallow water flow. The balls were of the same mass density as water to maximise the ball / fluid interaction. The system was tested on a horizontal varnished plywood table, with plywood vertical walls to model corridors. The balls were dropped into the moving water over a 900mm length. The time taken for the last ball to travel the full 900mm was timed and recorded. Changing the number of balls initially introduced over the 900mm length changed the effective density of the modelled crowd flow. The units of density used were m^2 (occupied space) per m^2 (free space) because the maximum packing density of circles is $0.91 m^2 / m^2$ which is similar to the maximum packing density of crowds ($0.92 m^2 / m^2$) observed by Predtechenskii & Milinskii (1969). The experimental results are summarised in Figure (2).

A comparison of the results from Figures (1) and (2) reveals an encouraging similarity in the experimental and real life speed/density curve shapes. The commonly referenced flow / density curve shown in Figure (3) can be seen as a derivation of the speed / density curve and it is the flow / density relationship that forms the basis of maximum flow rates for design parameters.

One of the flow curves obtained by fluid experiments is illustrated in Figure (4). This graphical curve demonstrates similar characteristics to the real life readings ,shown in Figure (4), up to $0.6 \text{ m}^2/\text{m}^2$. Above this value, results could not be obtained due to friction in the apparatus and premature jamming which occurred below the maximum packing density value. For corridors less than 1.1 metres wide, data is scarce, but BS5588 (BSI, 1983) suggests a rapid restriction of flow as corridors decrease in width below 1.1 m. The preliminary two phase tests support this view. Although this is not a quantitative comparison, there is a reasonable similarity between graphs of the experimental results and real life measurements.

2.2 THE MECHANISM OF THE MODEL

It is postulated that the fluid pressure in the open channel represents psychological pressure (*i.e.* the invasion of personal space). As ball (or model person) density increases, water height increases resulting in an increase in fluid pressure and a decrease in overall system speed. This mechanism is illustrated in Figure (5).

2.3 CURRENT DEVELOPMENT OF THE MODEL

The first apparatus using fluid flow to motivate lines of initially stationary balls yielded some encouraging results. It was possible, however, that the total travel time for each ball was significantly effected by the time taken for the water to accelerate all of

the balls to their flow velocity. In order to consolidate the results, some form of constant circulation/steady state apparatus was required. This new apparatus has been developed and consists of a pulse generator that controls solenoid pistons which feed the balls into the fluid flow at a controlled rate. The balls roll in the water flow and once they leave the fluids table they are propelled by compressed air through a pipe and are recycled to the piston feed system.

The new system produces a continuous, variable flow of balls and fluid. These continuous flows have generated a 2-phase system in which the movement of either the balls or the fluid can be measured easily. The results from the new apparatus have shown that the velocity changes with people (ball) density changes are similar to the results generated in the original apparatus, but the velocity reductions due to increased concentrations of balls, are less significant. There is a possibility of testing complex geometries by dropping balls in over large areas via a grid network and assessing the fluid/mass escape behaviour of the system.

3. CURRENT COMPUTER MODELS

Various computer models for evacuation have been developed to date, but only a few are capable of handling large numbers of people while still processing the movements of each person individually. An outline description of some of the more recent models is given in the following paragraph.

3.1 EXIT 89 (Fahy, 1991)

EXIT 89 was the first program to achieve the processing of large numbers of individual people and incorporates some modelling of the effect of smoke spread upon the occupants. The program treats a building as a room network / node system of linked rectangles. Within each rectangular space all occupants are given the same walking speed, unless impeded by smoke. This model has been incorporated into the HAZARD1 package, in an attempt to combine the simulation of fire growth, smoke spread, fire detection, and evacuation. Some correlation with the real life evacuation of a multi-storey building has been achieved. The program is still under development.

3.2 EGRESS (Ketchell et al, 1993)

In an attempt to bring some probabilistic modelling and artificial intelligence to the field, this program applies certain rules and variables to each person. The building space is represented by a hexagonal grid system. Each hexagon may be 'occupied' or 'empty'. An occupied hexagon represents the volume space of one person. Each person steps from one position to the next depending on certain rules. The speed of each person is affected by the density of the surrounding crowd. The system is being developed for multi-storey buildings and it is intended that validation against real life experiments be carried out soon.

3.3 EXODUS (Galea et al, 1993)

The movement model in EXODUS bears some resemblance to that incorporated in EGRESS, in that movement is accommodated by a person stepping from one 'cell' or node to the next. The program is primarily intended for use on mass transport vehicles

and the environment space is represented by a network of nodes, connected by arcs that define the available path of movement from one position to the next. Each node is the size of one person, and is regarded as either occupied or empty. Many character traits are described, and input from a fire & smoke spread program can be received and used to affect the behaviour of the occupants. An early validation exercise was executed by comparing EXODUS output to some aircraft evacuation tests and the experimental trends were simulated. Some of the simulated evacuation times were similar to the real-life tests, but not consistently so. This was possibly due to the lack of specific data for the traits of each person in each evacuation.

3.4 VEGAS (Still, 1993)

The VEGAS system has arisen from the recent developments in virtual reality techniques. What is striking about the system is the complexity and detail of the 3-D graphics that illustrate fire growth, smoke spread, and occupant behaviour using real-time animation. The psychological aspects modelled are: group behaviour, alarm awareness and the effects of smoke. Each person chooses a direction by assessing pre-set target points along alternative escape routes. Escape only starts after the necessary threat triggers, such as alarm and smoke have been perceived. Unlike EGRESS and EXIT 89 this program does not use the commonly referenced speed / density curves, but instead looks at proximity logic and the problems of the complex geometry of the escaping persons, their mutual obstruction and pressure increases at crowded doorways.

None of the computer programs have yet undergone the extensive validation procedures required for use as a quantitative assessment tool, but their application provides some interesting qualitative insights.

4. THE NEED TO DEVELOP NEW COMPUTER MODELS

Existing computer models either make significant assumptions about the speed and direction of travel of each person, or accommodate each person's position by use of a grid cell network where each cell is the size of one person. The one exception is the VEGAS package which processes each person's precise co-ordinates. The VEGAS package contains many psychological factors and physical shape characteristics but the direction finding capabilities are dependent on user-specified target points dictating the direction of his/her chosen exit route. There remains a need for a program that treats each person individually, with individual characteristics (including age, disability and eagerness to escape) that can cope with infinite geometrical possibilities, whilst automatically assessing the entire escape route for each person, and reassessing the route (both locally and globally) at each time step of motion. There is also a need for overtaking, queuing, and other behaviour modelling. Each position should be precise and the crowd should be continuously displayed on the computer screen. The VEGAS package does achieve all of these factors, except for the automatic assessment of individual routes through an infinitely complex geometry. When applied to the building types for which it is designed, it yields a useful graphical insight into the whole escape process. As with all egress computer models, the prime need is for validation with real - life behaviour and crowd flow characteristics.

5. SIMULEX

In an attempt to achieve egress simulation through any building geometry a program was embarked upon that automatically defines an escape route map, using distance contouring.

5.1 ASSESSING ROUTE TO EXIT BY DISTANCE CONTOURING

Firstly, the building plan is drawn on the screen using the mouse to drive a simple drawing package designed for this program. This plan is then passed to a program which processes it and automatically sets up a high definition integer distance grid with all space occupied by walls / objects possessing high (solid) values, and exit (empty) values set to zero. Within this grid the program sets up a contour map (see Figure (6)) of distance from the nearest exit through the whole building space. This map is set up so that the optimum direction to nearest exit is accurate to within 2 degrees, while computer processing time remains short. The routine can also be used to assess minimum travel distance alone.

5.2 ASSESSING SPEED

Each person's speed is assessed individually at each time step. Each person is given a random unimpeded walking speed of between 0.8 m / second (i.e. an elderly woman) and 1.7 m / second (an able-bodied adult male). Reduced speed due to the proximity of others is calculated using an approximation of the speed/density curve presented by Ando et al. (1988). Unfortunately, the curve assesses speed in relation to crowd density over a given area, so some data manipulation is required to yield a method of assessing speed reduction caused by the proximity of other individuals. For the purposes of the program, the velocity of an individual is related to the distance 'd' between centre co-ordinates of the person in question and others in the obstruction zones.

From the relationship

$$d = \sqrt{\frac{1}{D}} \quad (\text{for a single obstructing person}) \quad \dots(1)$$

the following formula for walking speed was derived.

$$speed = \left(\frac{V(d - b)}{0.87} \right) \quad \dots(2)$$

Note: d is inter-person distance (m), D is density (Number of persons/m²), V is unimpeded walking speed (m/s), b is plan body depth. NOTE: if $d > 1.12$ then speed is assumed to be unimpeded. This 'distance threshold' of 1.12m can be adjusted if desired, depending on occupant characteristics such as aggression and familiarity.

The speed reduction effect is fully implemented in the 100% zone (Figure (7)) but only $1/2$ of the speed reduction factor is implemented in the 50% obstruction zones. Only the bodies nearest to the assessing person in each zone are considered. If both 50% zones contain bodies closer than any in the 100% zone, the 100% zone is ignored.

5.3 OVERTAKING & QUEUING

When the speed of a person is reduced, the program scans each side of the direction of travel of that person. If a significant improvement in speed is obtained, then the direction of travel changes to the new deviated angle. Overtaking and localised deviation of route is observed frequently, and these movement algorithms produce a degree of jostling in the higher density crowds.

The program, by its nature, models queuing inherently. The speed calculations never yield a zero value, but each person is only allowed to move into unoccupied space and will therefore become stationary if standing exactly behind another person, with no room to move sideways. As yet, no pushing or pressure build up is modelled.

5.4 TEST RUNS

The program has been tried on various plan layouts. At this stage, staircases have not yet been modelled because validation on a single storey, flat plane is first required.

Test runs start by the user specifying a density of persons per unit area distributed evenly over the building plan. The program sets up each person's coordinates and unimpeded walking speed, and then begins to move them immediately. No delay has yet been programmed in for reaction time and different types of alarm; this will be implemented in later versions. These psychological factors are far too important to ignore in a final version.

In order to assess the maximum flow capacity of a doorway width, tests of the type shown in Figure (8) were executed to simulate a high density, non-panicking crowd at a doorway. In this test the flow rate q was found to be 1.8 persons/(m width)/s. When slight changes are made to the overtaking/jostling algorithm and the order in which speed assessment occurs, then q can vary from 1.5 to 2 persons/(m width)/s. Real life observations of q include 1.5 (The Aqua Group, 1984) and 1.8 persons/(m width)/s (Melinek, 1975). This correlation of simulated value to real life is very encouraging, especially in view of some of the assumptions made in the speed assessment routine.

Figure (9) demonstrates the ability of the program to cope with complex geometries and obstructions of any size. It became clear from watching the progress of various simulations that placing a narrow obstruction in the centre of a 1.8m opening significantly reduced its flow capacity, even though the total combined opening width was only be reduced by 0.1m.

5.5 DEVELOPMENT OF SIMULEX

SIMULEX is being developed to model extremely large building plans. This phase of development should be completed by June 1994. Figure (10) is a screen display taken from the version of SIMULEX that is currently under development and illustrates the program's ability to assess travel distance from any specified point in a building plan. The algorithms that use the distance mapping techniques can also find the point in a building that is furthest from any exit ('most remote point') and then illustrates both the route to exit from this point and the total travel distance .

6. CONCLUSIONS

The two phase model has proved effective in simulating some of the characteristics of simple crowd flow. The development of the model using steady state rolling experiments has not yielded data of any more significance than the early tests, described in section 2. It has been observed from these tests that the system is useful in examining some of the fundamental principles of crowd flow, but is unlikely to be developed as any form of design tool. The model requires the water level to remain below the ball height, and as a result complex geometries would become very difficult to simulate because of the different fluid levels that would occur from mixing different

fluid flows. SIMULEX was not used to simulate the specific fluid experiments because friction factors in narrow corridors have not yet been applied to the program.

To date, one of the most notable results from the computer model test runs is the correlation between test results and real life values of crowd flow rate per unit exit width, but more large scale validation is required. The route finding methods adopted, automatically reassess exit routes at each time step, the only input required being the building plan itself. All exits in the building are recognised automatically and any geometry of obstruction can be accommodated. The program is being developed for large area building plans, and subsequently for the simulation of multi-level buildings.

The investigations described have provided an insight into the fluid flow analogy which opens up opportunities for the analysis of specific parameters of crowd flow. The computer methods adopted in SIMULEX show promise because of their flexibility in handling infinite spatial variations combined with the routines for automatic route assessment. The program is written to easily incorporate disability, aggressiveness and variation in body size and shape. In order that a choice of exit other than the nearest one be assessed (for each person) contour maps for different exits could be overlaid in computer memory, and familiarity weightings could be applied by increasing the initial contour value at an exit before the complete contour map is created. Smoke spread could be simulated by the progressive addition of weighting factors to the contour maps, over increasing areas.

Further work is being carried out to attempt to improve the flexibility and validity of both systems. Crowd movements in various locations and conditions around Edinburgh have been recorded with a video camera. Computer processing techniques have been used to analyse the recorded images. The results of these observations will be

used to assess movement parameters such as body twist, overtaking, speed fluctuations and various psychological factors. Further information is required to assess more complex psychological factors such as reaction to alarm and group interaction. It is particularly important that any simulation model in this field is based upon good experimental and observational data, and that all the assumptions made by the model are clarified before it is used.

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8. LIST OF FIGURES AND CAPTIONS

- 1 Observed velocity / density graph (different researchers).
- 2 Velocity / density graph for fluid experiments in 35mm channel.
Scale width = 0.74m. Ball diameter = 24mm.
- 3 Crowd flow / density graph. Source: Predtechinskii & Milinskii (1969)
- 4 Fluid experiment - flow / density graph for 64mm channel.
Scale width = 1.35m. Water flow= 4.01×10^{-4} m³/sec.
- 5 The mechanism of two phase flow.
- 6 Sample distance map for a room with a rectangular obstruction
(dims. metres).
- 7 Obstruction Zones For Speed Assessment (dims. metres).
- 8 Evacuation of a high density population from a simple room geometry with a
1.1m wide doorway (dims. metres).
- 9 Sample screen display of SIMULEX applied to a more complex geometry
(dims. metres).
- 10 Screen display of travel distance analysis in SIMULEX (dims. metres).

OBSERVED VELOCITY/DENSITY GRAPHS
 -different sources

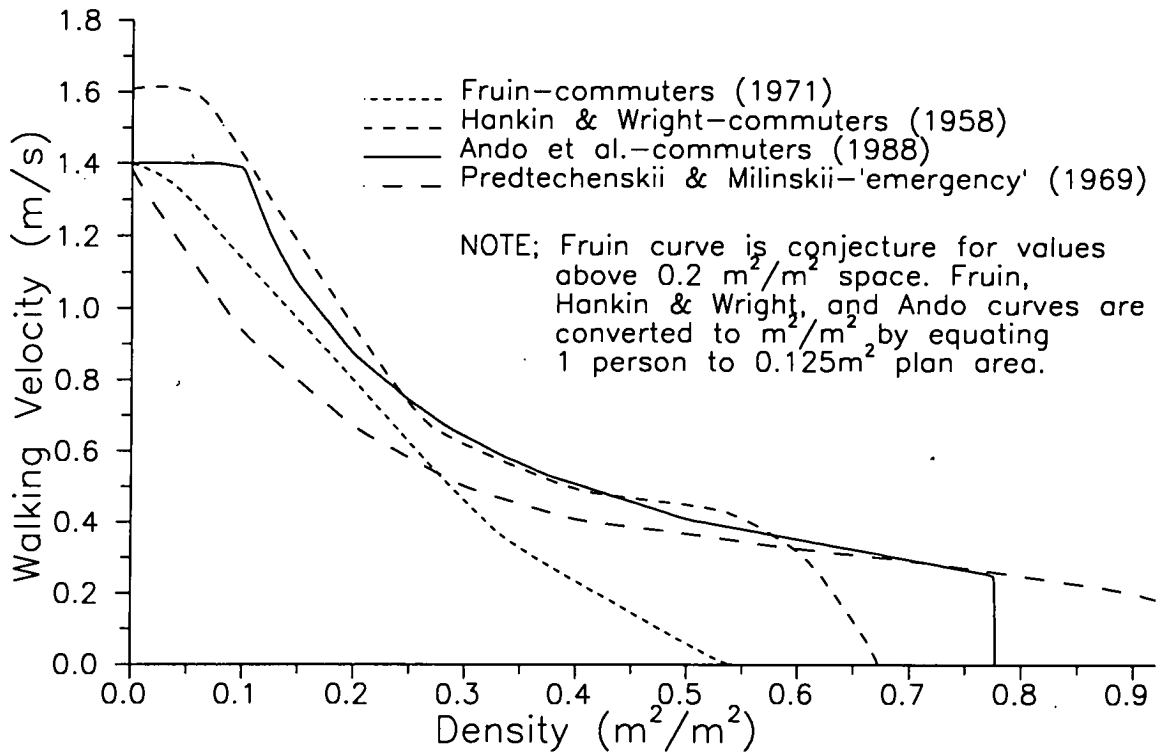


Figure 1.

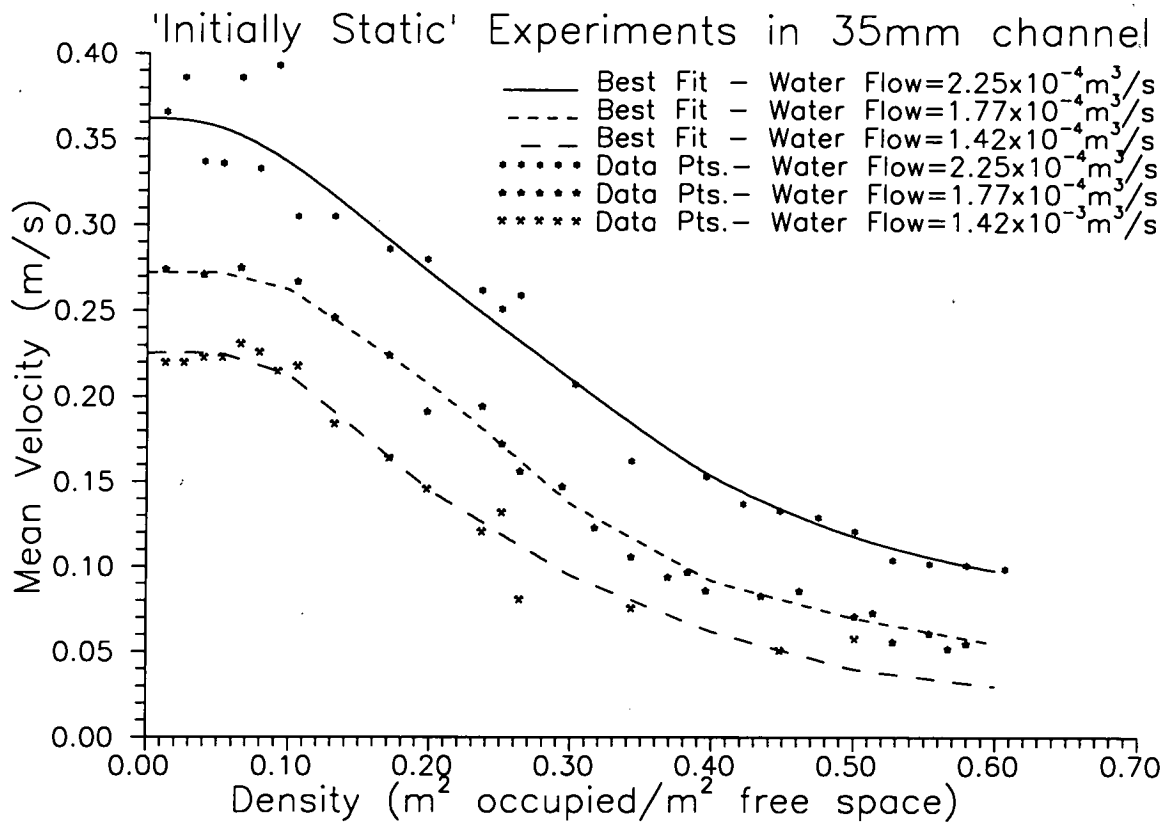


Figure 2.

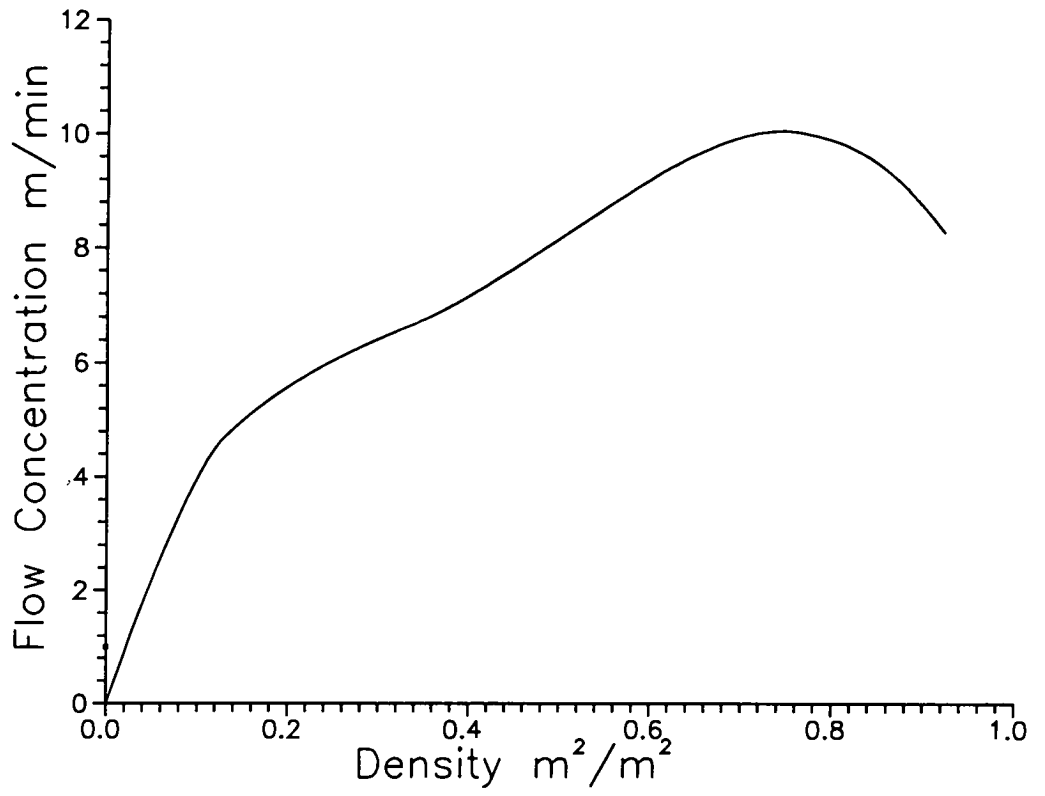


Figure 3.

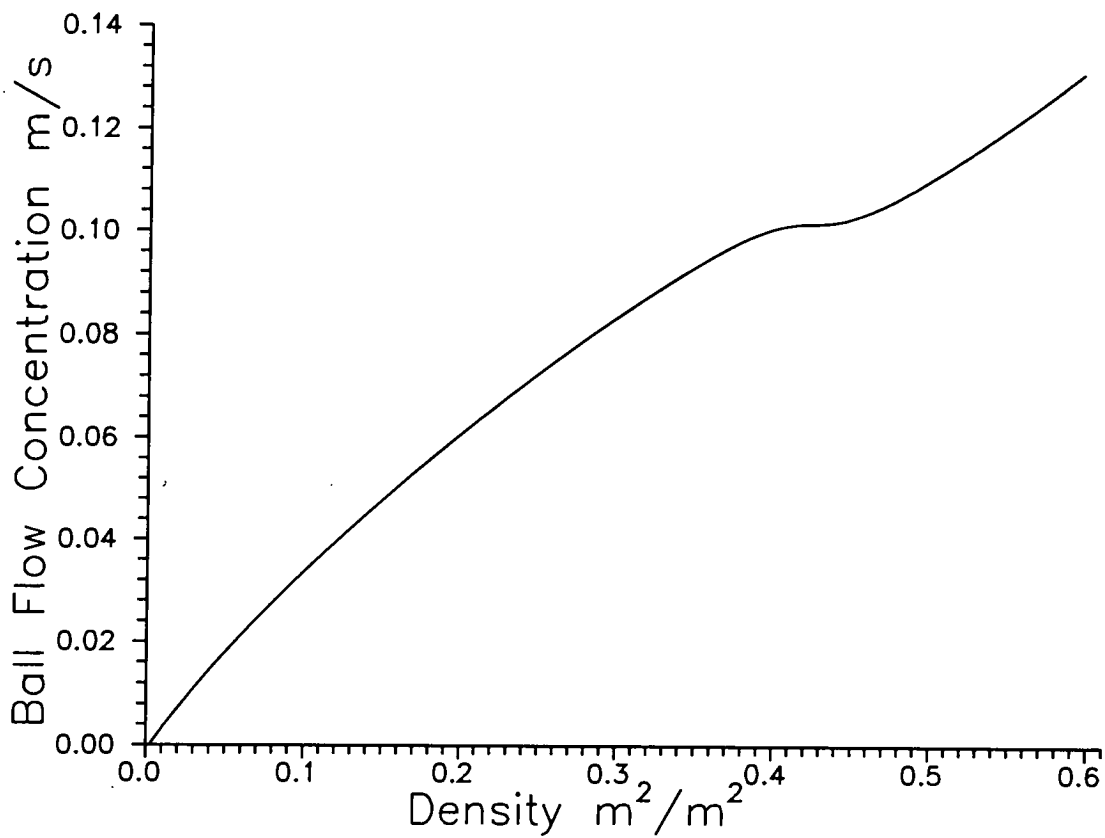


Figure 4.

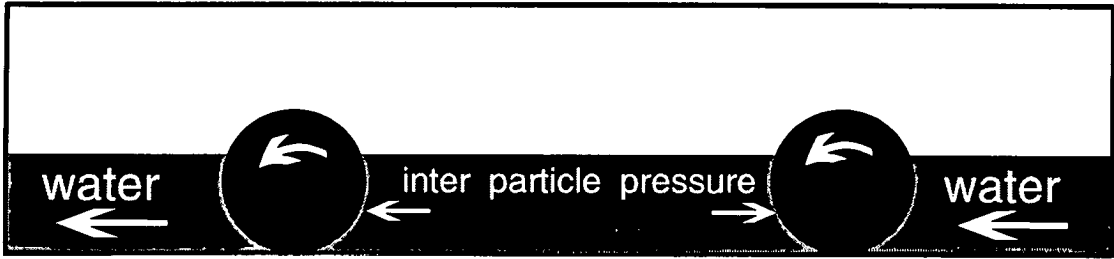


Figure 5.

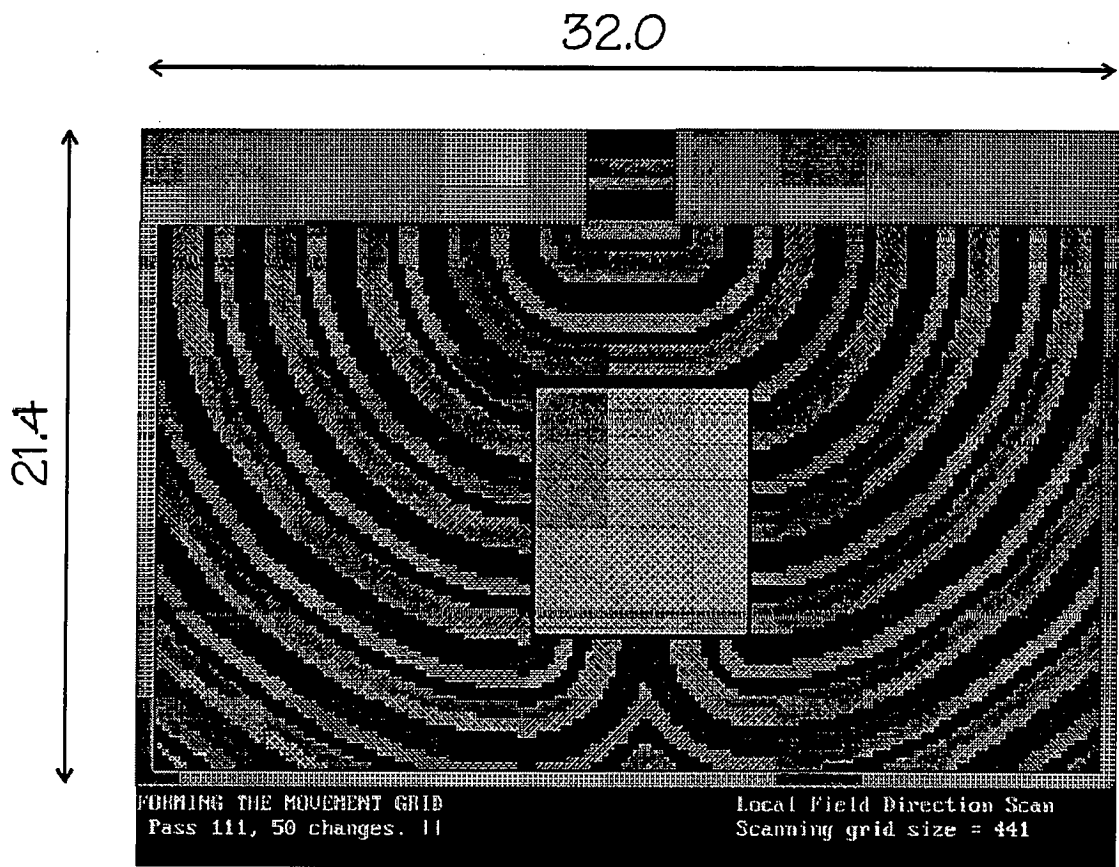


Figure 6.

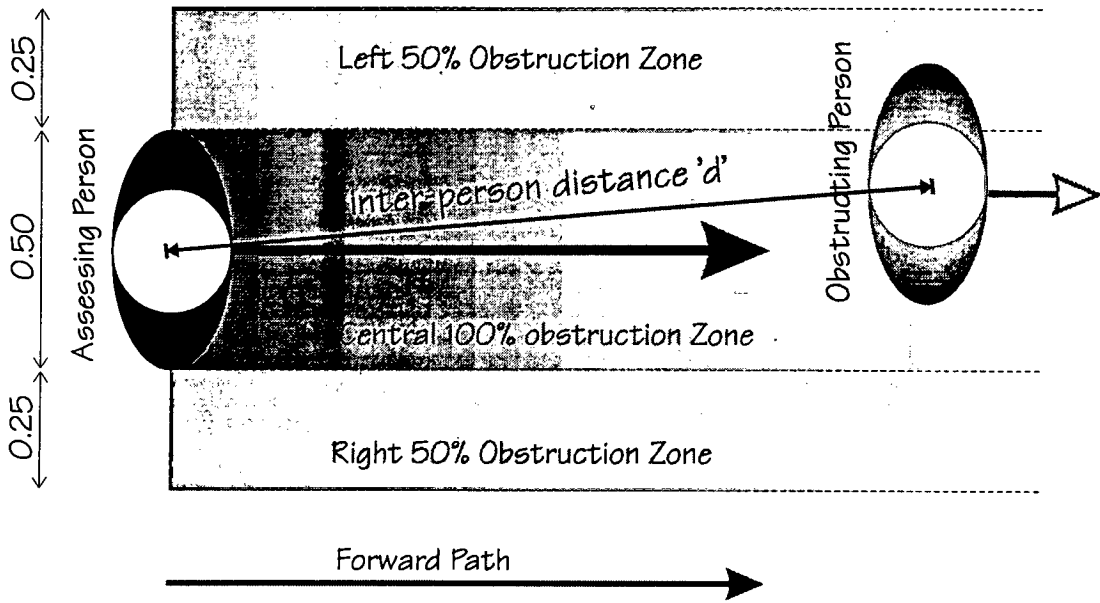


Figure 7.

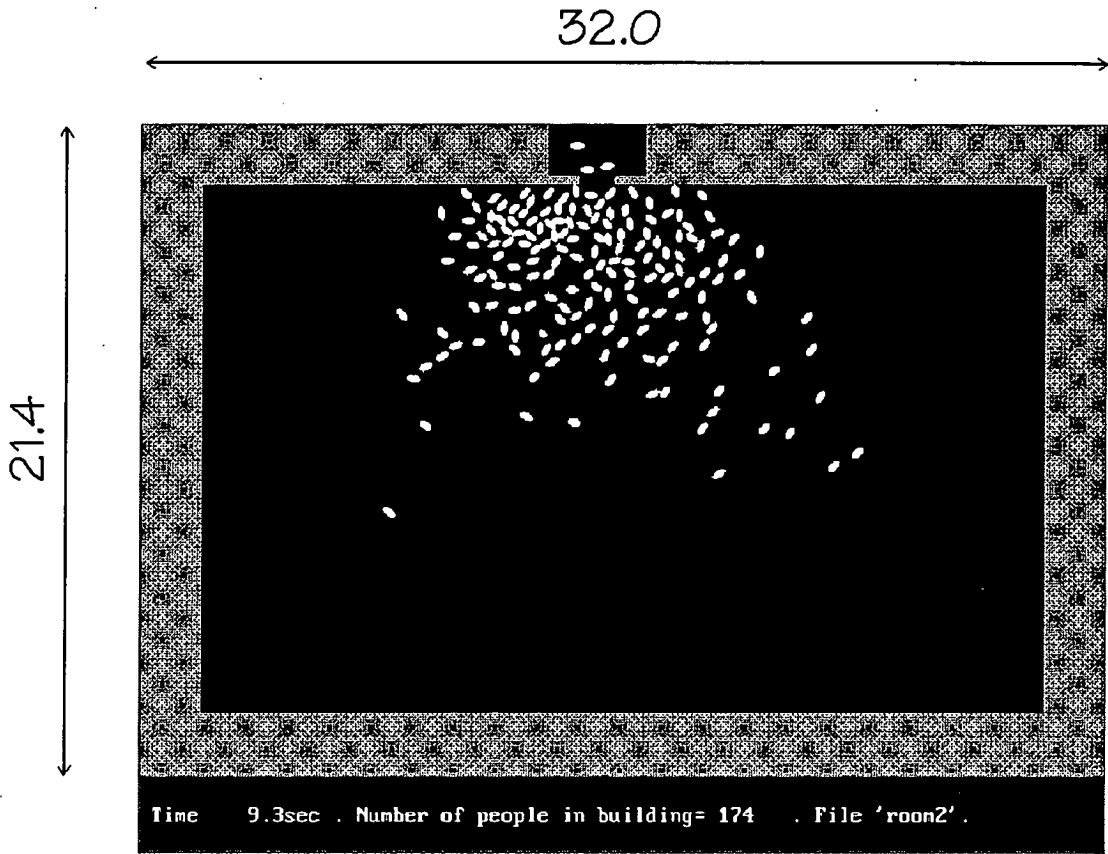


Figure 8.

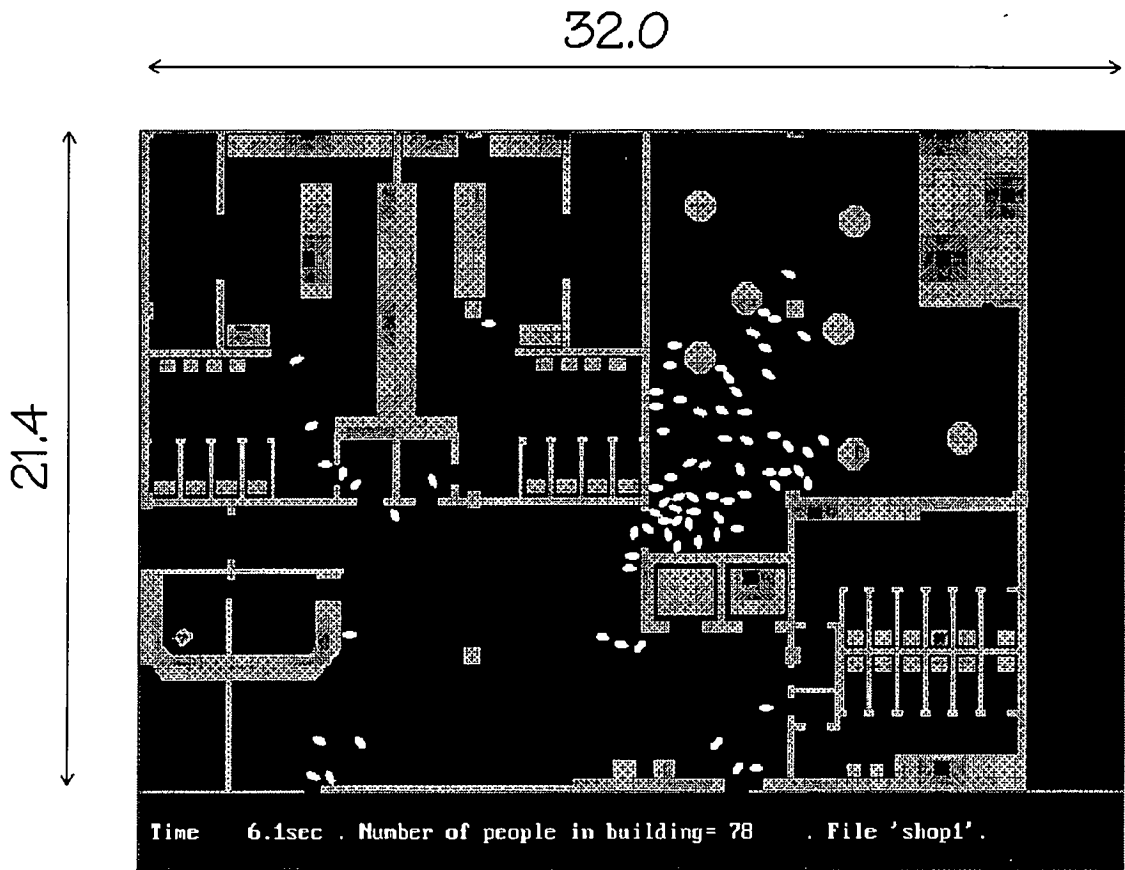


Figure 9.

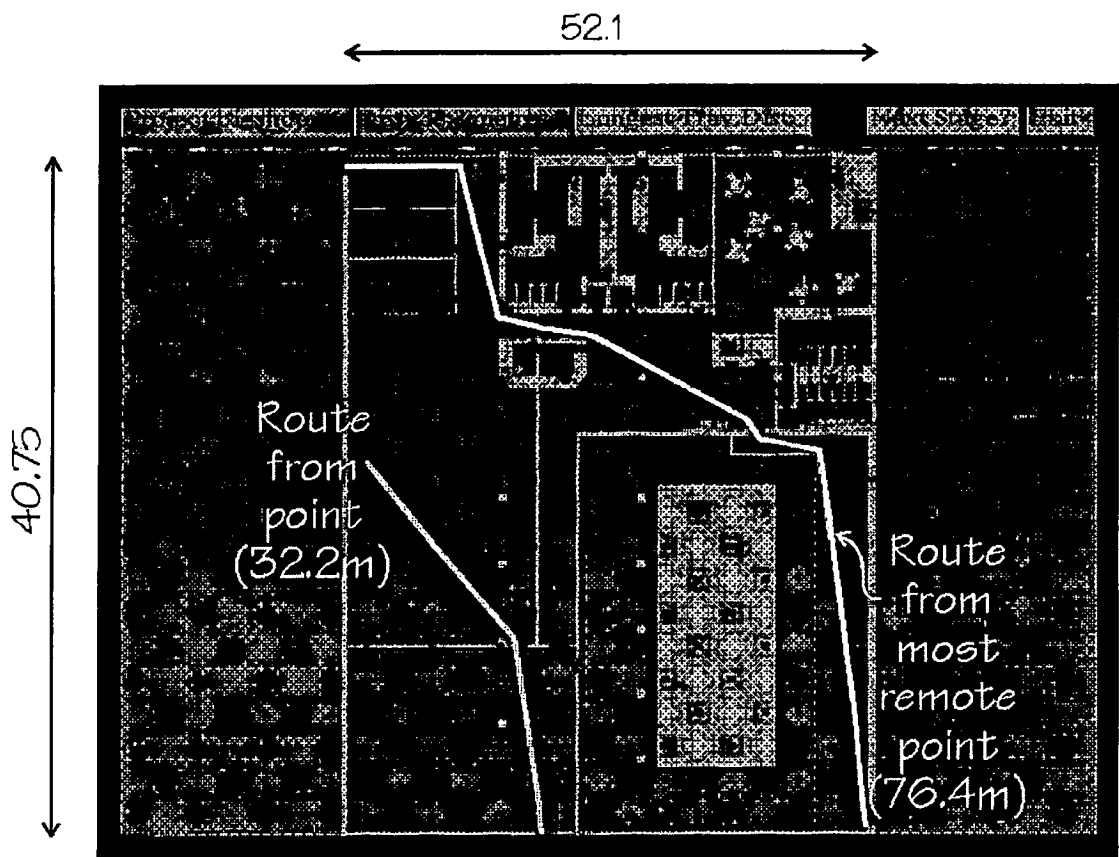


Figure 10.