Evacuation Modelling of Mixed-Ability Populations in Fire Emergencies

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Abstract

UK statistics have shown that a significant percentage of fatalities in fires have suffered from some kind of disability. In this context 'disability' relates to a person's physical or mental condition that impinges on their ability to react and move promptly in an emergency. Various evacuation modelling techniques are being adopted to study the movement of occupants during emergencies since the exposure of people to fires for experimental purposes is unethical. However, many evacuation models have ignored the effects of disability on escape potential and therefore tend to predict optimal evacuation times. Moreover, whilst providing some valuable insights into certain factors affecting occupant movement, current models are generally presented in isolation and fail to define a general framework for designing solutions to fire safety engineering problems.

The purpose of this research programme was to develop a more general methodology for predicting evacuation times of mixed-ability populations. This was made possible through the development and use of a novel concept of *evacuation performance index* (EPI), which is the relative ease of evacuating a disabled person compared to an able-bodied person, founded on a consideration of the effects of disabilities and mobility aids on evacuation times. The author shows how this concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. She contends that the *evacuation performance index* of a class of individuals is primarily dependent on these three categories.

Experimental data to verify the above claim was collected from carefully monitored evacuation drills involving a group of disabled people. Their EPIs were determined along a pre-defined route from which their evacuation times were calculated. Comparisons between predicted times using the EPI concept and measured times from alternative empirical data were seen to be in reasonable agreement. An iterative design procedure is also suggested; one that is capable of predicting worst possible evacuation times by incorporating measures of EPI and escape route dimensions and details.

The EPI concept provides fire safety engineering with a logical design philosophy, which is flexible and easily comprehensible. It endeavours to increase understanding of evacuation of disabled people, and provide a simplified mechanism for fire safety design and planning of evacuation procedures.

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Declaration

I declare that this thesis has not been submitted for publication anywhere else neither has it been submitted for an alternative award. All the work in the thesis is the author's own work.

Dedication

I would like to dedicate this thesis first and foremost to the Lord Jesus Christ in whom my confidence is. I would also like to dedicate it to my parents, Prof. J.D Rubadiri and Mrs. Gertrude Rubadiri, and the Clan Rubadiri, for all that you mean to me.

CHAPTER 1

Introduction

National UK fire statistics reveal that over 800 people die in fires every year. Of this number a significant proportion have some kind of disability. In this context the main problem resulting from disability is the potential to reduce mobility which has serious consequences on evacuation capability of occupants during fires. In addition, the unsympathetic design of an environment can be 'handicapping' in itself and can act as a hindrance to occupant movement. Therefore, there is a need to understand the relationship between occupant movement and the environment in which they move in order to adequately design for fire-safe conditions in emergencies.

1.1 Structure of the Thesis

In summary, the key issues analysed in this research programme are: first, the extent of the problem of occupant disability in a fire safety context, which has not yet been sufficiently investigated. To date there is no adequately documented classification of disabilities affecting occupant movement, which would be an ideal starting point to analysing this problem. Secondly, there is insufficient information on the effects of disability on predicted evacuation times during fire emergencies. Moreover, there is some discrepancy regarding the techniques used to predict evacuation times of mixed-ability populations. 'Mixed-ability' in this context refers to the differences in the ability to move unassisted along a given escape route.

Chapter 2 defines the objectives of the research programme. Chapter 3 begins with a review of recent UK statistics on fatalities in fires who were disabled. Current research techniques used to observe occupant movement and behaviour during fire emergencies are also analysed in this chapter. These techniques are all grouped under 'evacuation modelling' and are adopted in place of experimental studies of occupant behaviour in real fires which is unethical. However, in the majority of models, occupants are all assumed to be able-bodied. Those that do include disabled people tend to acknowledge their presence in a rather broad context and recognise only the global effects that they have on an evacuating crowd. There is reason to believe that individual differences in evacuation capability may have significant influences on crowd movement.

Chapter 3 continues by defining the basic principle of evacuation modelling which briefly, is to ensure that for a proposed building design the maximum time taken for tenability levels to exceed their allowable limits for different classes of fires will be greater than or equal to the maximum likely evacuation time for occupants to leave the building. Throughout the research programme there is a continual attempt to identify the sub-components that comprise the total evacuation time. However, certain significant drawbacks have been encountered when attempting to identify these sub-components. These include the need to make numerous assumptions regarding occupant behaviour and movement during fires. For example, the presumption that all occupants will respond promptly to a cue to evacuate. Such assumptions are common since not many empirical studies have been carried out on a representative population.

In Chapter 4, the author attempts to present an approach which could lead to the resolution of the main limitations of models discussed in Chapter 3. This is a coherent approach to evacuation modelling based on a safety criterion that is derived from traditional engineering principles. A novel concept called the *evacuation performance index* (EPI) is introduced which is defined as the relative ease of evacuating a disabled person compared to evacuating an able-bodied person, founded on a consideration of the effects of disabilities and mobility aids on evacuation times. The EPI concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. The author believes that the evacuation performance index of a class of individuals is primarily dependent on these three categories. However, any appropriate subsets may be considered under these three main categories and it is noteworthy that the influence of any given external factor that affects evacuation capability of an occupant can be accounted for. In order to reinforce this point, demonstrative experiments are carried out on a group of students with different disabilities and their respective EPIs are calculated along sections of a pre-defined evacuation route in one of the office buildings at the University of Central Lancashire. The results reveal important aspects of evacuation capability at each section of the route and are used in a suggested design procedure which enables evacuation times for each category of occupants to be calculated.

In Chapter 5 the author uses the results from Chapter 4 to show how EPI predictions compare with measured evacuation times from empirical data collated from alternative evacuation studies by a different researcher. In these evacuation exercises the movement of four wheelchair users is observed in a series of hotel evacuations.

Chapter 6 discusses the conclusions and recommendations drawn from the research and provides ideas for further development of the EPI concept.

It is noteworthy that throughout the thesis there is a frequent interchange of the terms used to indicate some measure of ability to evacuate: evacuation capability, escape potential and EPI.

CHAPTER 2

Objectives of the Research Programme

Evacuation modelling techniques are commonly used to study occupant movement and behaviour during fire emergencies. Although their findings are useful, certain problems are evident in the various approaches used. This chapter identifies the main drawbacks in evacuation modelling and describes the author's attempt to resolve most of them by developing a methodology for predicting evacuation times based on a novel concept called the *evacuation performance index*.

2.1 Drawbacks in Evacuation Modelling

The evaluation of current evacuation modelling approaches that investigate movement of mixed-ability populations identifies the main drawbacks as follows:

- In several evacuation models a global approach to human behaviour is adopted which assumes a uniform response from occupants during emergencies. Some models ignore occupant behaviour which has been shown to significantly influence evacuation times.

- The populations in most models are assumed to be able-bodied. For example, it is from observing the movement of able-bodied occupants that speed-density relationships have been derived. Alternative speed distribution curves are generally limited to elderly people. There have a small number of empirical studies that have included disabled people but these do not provide sufficient data for general use in evacuation models. Furthermore, it is unfortunate that there is at present no classification system of disabilities that influence occupant movement. Such information would provide more insight into the types of disabilities that have a significant effect on occupant movement. Moreover, the methods adopted to investigate the effects of disabilities on evacuation capability are presented in isolated, disjointed studies.

- On the whole, whilst providing valuable insights into some of the factors involved in fire safety, the approaches adopted to quantitatively analyse evacuations involving mixed-ability populations fail to define a general framework for designing solutions to fire safety engineering problems. Each approach is presented in isolation with little possibility for integration with others. Often there is a limited application of suggested approaches, to specific building types or scenarios. What is lacking is some common unifying thread, for instance, a design philosophy embodying a clear safety criterion, such that the approaches can be understood as elaborations of different aspects of the safety criterion, or techniques for computing some of its components.

2.2 Objectives

The goal of fire safety engineering can be described as the creation of structural and managerial arrangements which in the event of a fire emergency ensure that some pre-determined proportion of occupants of a building can safely evacuate. That is, to ensure that the time occupants would take to evacuate a building is less than that required for tenability levels to exceed allowable limits.

The objective of this research programme was to design a framework wherein critical factors that influence available evacuation time could be identified and measured with a view to creating the required structural and managerial arrangement for fire-safe conditions in a given building. The steps taken to meet this basic objective are described as follows:

- Firstly the author recognised the fact that in order to predict the time an occupant would take to evacuate a building, it was necessary to have a quantifiable attribute which defined his/her evacuation capability and which was sensitive to variable external conditions, for example, in building design. In this programme this measure of the intrinsic evacuation capability of an occupant is described as that person's *evacuation performance index* (EPI), which is defined as the relative ease of evacuating a disabled person compared to the ease of evacuating an able-bodied person. The individual characteristics most significantly affecting this index are believed to be an occupant's disability and his/her mobility aid.

- Secondly, a framework for devising engineering solutions to fire safety problems involving disabled people, based on this notion of EPI was established. It was founded on an analogy with traditional engineering design and incorporates explicit notions of a *safety criterion*, *imposed loading* and *strength*. The definitions of these terms in fire safety engineering terms were provided but greater emphasis was laid on investigating the concept of "the strength of a class of disabled people". The framework provides a coherent and transferable approach for predicting evacuation times such that any given factor affecting evacuation capability can be accounted for and measured.

- Thirdly, experimental methods were designed in the form of carefully monitored fire drills, to analyse the variations in EPIs of occupants with different disability-mobility aid combinations in various managerial, behavioural and environmental settings. A number of the experiments were carried out to demonstrate the use of the EPI concept.

- The final step in the research programme was the formulation of a robust procedure for computing the worst-case evacuation times for different mixed-ability population distributions in varying managerial and environmental settings. This procedure could be adopted by building designers at the preliminary stage of design or by management personnel of an existing building who have the responsibility of maintaining adequate safety standards. Examples of the evacuation times using this procedure are provided in latter chapters and were compared with measured times from other empirical studies.

It is anticipated that by providing fire safety engineering with a logical design philosophy, there will be an increase in understanding of the factors affecting evacuation of disabled people. The philosophy will also provide a simplified mechanism for fire safety design and planning of evacuation procedures.

CHAPTER 3

A Survey and Evaluation of Evacuation Modelling of Mixed-Ability Populations in Fire Emergencies

3.1 Preamble

This chapter discusses the methods used to analyse the movement of mixed-ability populations during fire emergencies. It begins with a brief review of the available statistics on fatalities in fires who had some form of disability which reveals significant gaps in statistical knowledge of disabled people in fires. Moreover, the limited data available emphasises the fact that disabled people are at considerable risk as they comprise a large proportion of the fatalities in fires. The probable reason for this is the movement difficulties that result from the disabilities of occupants and the handicaps or obstacles caused by building design.

A variety of evacuation modelling techniques have been used to investigate the movement and behaviour of occupants in fires and a few of these are discussed in section 3.3. In this section, a comparative analysis of evacuation models is carried out by categorising current models into two basic groups: mathematical and psychological models. Each group is further sub-divided and their underlying principles, strengths and weaknesses are discussed. The objective of this analysis is primarily to compare the models and to emphasise their major perceived limitation: that most of them fail to recognise the effects that disabled people have on overall evacuation movement and time.

Fire safety has been an issue of growing concern for decades. UK legislation to safeguard life and property from the disastrous effects of fire has been predominantly prescriptive in nature from as far back as the Great Fire of London in 1666. Following this important event, the first rules regarding separation between buildings and acceptable forms of construction for fire safe conditions were introduced [1]. These rules were mainly structure-oriented, focusing on construction.

Reports such as the National Bureau of Standards, "Design and Construction of Building Exits" [2] and Post War Building Studies [3] were the first studies to analyse occupant movement in fire emergencies. In these reports empirical studies were described which provided a basis for design of evacuation route elements including stairwells, corridors and exits. These studies concentrated on able-bodied populations consisting of fit, able-bodied men and little was done to investigate the movement of disabled occupants, young and elderly occupants; both male and female with mobility problems.

The growing demand during the late 1970's and early 1980's for access for disabled people was acknowledged in the amendments of the building regulations in operation at the time. Shortly afterwards in 1988, a UK standard was introduced with provisional guidelines on egress of disabled people. This was the British Standard (BS) 5588 Part 8 on the 'Code of Practice for Means of Escape for Disabled People' [4]. It included qualitative guidelines that were useful to management personnel planning for evacuation of disabled people in multi-storey buildings, but failed to provide guidance to suitable data for input to the numerical design of means of escape [5]. The shortage of useful empirical data, available to building designers, on evacuation of disabled people highlighted the need for further research in this area.

3.2 Statistics

There are currently at least six million people in the UK with some form of disability [6]. National statistics confirm that elderly persons of 65 years and over generally have some form of disability as a result of age although they are not officially classified as disabled. Comparatively higher death rates are generally experienced in fires in this age bracket than in younger age groups. In fact statistics that are presently available (1988 - 1992) [7] reveal that the highest death rates in fires per million population occurred for occupants aged 80 and over. The most probable reason for this is that the older age groups may have mobility problems that would hinder evacuation during emergencies in which swift movement is required.

However, statistics on disabled people who die in fires tend to be of limited use due to the broad and rather vague delineations of the categories of disabled people. From 1985, Merseyside Fire Brigade [8] began to collate more detailed information on the personal circumstances of occupants dying in fires in Merseyside. The only information that could practicably be identified was where some form of physical impairment played a significant part in leading to death. From the Fire Officers' stand-point, anything related to a person's physical or mental condition which impinges on their ability to comprehend, or react to an emergency situation is a factor to be considered and should be classified as a disability. Merseyside fire deaths from 1985 to 1991 showed that the number of casualties where some form of disability was present, according to the above definition, was substantial. Over the whole period, some 24% of the fatalities involved alcohol or drugs, and 29% an identifiable disability. Often the casualties fell into both categories. Further analysis of the data showed that persons over pensionable age comprised about 17% of the Merseyside population but accounted for approximately 46% of fire fatalities. In total, over the period from 1987 to 1990, approximately 33% of all fatalities in Merseyside area could be classified as disabled. These regional statistics suggest that nation-wide there may be a significant and substantial number of disabled people dying in fires every year. In contrast, Home Office statistics for 1987, for example, showed that approximately 3% of recorded fatalities were disabled. This was probably because of the above mentioned vague definition and categorisation of disability in the national statistics.

A more comprehensive nationally-acceptable system of classification of disabled people is essential and is currently being devised with the anticipation that any statistical information involving disabled people will be unambiguous [5]. However, while more extensive studies involving the collection and analysis of data on disabled people in fires are encouraged, figures alone are not sufficient in themselves to stress the severity of the risk that surrounds disabled people in such emergencies. The risk to which they are exposed would be better appreciated if the specific needs of disabled people during emergencies were identified and an actual measure of their evacuation capability was available. One would expect that disabled people would require different types and degrees of assistance and may in most cases have lower evacuation capabilities than able-bodied people.

Having briefly described the statistical background of disabled people in fires, the next section describes the analysis of evacuation capability of people in fires in order to predict evacuation times by 'evacuation modelling'.

3.3 Evacuation Modelling

Evacuation modelling serves as a tool for identifying and analysing the factors that influence evacuation time and escape potential of occupants in fire emergencies. These factors include dimensional aspects, such as travel distances, and occupant behaviour resulting from stressful conditions such as 'panic'. There are critical relationships that exist between these factors which are crucial to building designers and management personnel attempting to design for fire-safe conditions. The following sub-sections discuss the basic purpose, principles, processes, strengths and limitations of evacuation modelling.

The basic purpose of evacuation modelling is to identify critical parameters and their interactions during fire emergencies. In Fire Safety Engineering, modelling is employed to explore the complex, dynamic and interactive processes in operation during the development of a fire. It provides a basis for studying stages in the development of a fire and the consequent responses of occupants in a building. Modelling helps to simplify reality by limiting the factors analysed in a system, while trying to ensure that all important factors are represented as well as their inter-relationships [9]. The choice of 'relevant factors' is generally determined by such considerations as the discipline of the model developer. Psychologists, for example, tend to emphasise human behavioural aspects while engineers may, in contrast, emphasise structural and mechanistic aspects of fire safety and development. There are loopholes in both these approaches and ideally a balance between them would be desirable, in the form of a unified model that incorporates a multi-disciplinary approach to evacuation behaviour.

Evacuation modelling is also useful as a predictive tool. The ability to predict evacuation times has much practical value in indicating evacuation procedures that result in unacceptably slow evacuation times. Evacuation modelling also serves as a design tool for building designers in planning for fire safety. The relationships derived from modelling provide some insight into the design of means of escape routes. For example, the dimensions of stairwells and exits are particularly important as they are the restricting sections of an evacuation route in crowded situations. It is usually at these sections that bottlenecks and queuing occur, with the undesirable result of slow evacuation times during fire emergencies.

The basic principle of evacuation modelling is to ensure that for a proposed building design the following condition is satisfied: $t_{TL} \geq t$, where t_{TL} specifies the minimum time for tenability levels to exceed their allowable limits for different classes of fires, and t specifies the maximum likely evacuation time for occupants to leave a building.

The time for tenability levels to exceed their maximum acceptable limits depends on a number of factors, but primarily on the size and type of the fire source. The fire size determines the volume of effluents produced, and its type determines the chemical nature of these effluents. Furthermore, the fire itself can directly cause injury both to occupants and to property. It should be recognised that a building must be able to retain its strength under fire conditions in order to allow for occupant escape time. Tenability levels are influenced significantly by structural measures such as the presence or otherwise of sprinklers, compartmentation and pressurisation. This research project does not focus on these aspects and the author can only urge for further research into the effects of measures such as sprinkler design and compartmentation on the development of untenable conditions.

In order to clearly understand the factors that govern the evacuation time t, it would be useful to identify attributes of occupants that change with environmental conditions during a fire. These attributes could be outwardly visible, for example, the movement speed of an occupant, or they may be inconspicuous and psychological, and therefore not easily identifiable or quantifiable.

In summary, modelling principles provide a basis for deriving relationships between occupant behaviour and parameters relating to fire growth, building design and environmental factors.

There is no standard procedure for developing models. Nevertheless, a few of the processes of model development are typical and could be described briefly as follows: A model developer would be required to identify the critical parameters intended for investigation and justify the choice of parameters. Predictions of the behaviour of these parameters might be made, followed by actual observation of their interaction using laboratory experiments or by observing the behaviour of people during simulated emergencies. From the data collected, the relationships between parameters can be modified and tested further.

There are a significant number of problems experienced in evacuation modelling, because it is an area that does not lend itself to precise observation or analysis. Several assumptions are made during the development of models. According to Kendik [10] who has analysed a number of major evacuation models, "..all of them appear to make several assumptions partially to overcome gaps in technical literature which makes their validation against real-world events or fire drills necessary..". There will generally be uncertainties associated with parameters in a model. In numerical models these may be expressed as 'errors' or 'confidence limits'. Beard [11] cautions against attaching unjustified significance to numbers resulting from model calculations. He argues that the 'unknowns' should be understood in the right context. The basic underlying principles in a number of models are hidden behind complex scientific notations, and as Pauls [12] argues, there is a danger of being side-tracked by their sophistication.

One common drawback is the requirement to validate models which is a difficult, costly and time-consuming exercise. However, validation is essential if the credibility of a model is to be ascertained.

In several cases the scope of a model is limited to specific occupancy types. Apparent similarity of models does not guarantee technical similitude. Some models, for example, are designed specifically for simple residential settings with small populations while others are designed to simulate complex building layouts with large populations.

Models sometimes include a large number of parameters in which case they may lack sufficient detail and depth, which is essential in analysing the inter-relationships between the parameters. Alternatively, other models concentrate only on a few critical parameters and analyse these with considerable depth. A realistic balance between the two approaches is essential even though there is no hard and fast rule for the number of parameters that can be included in a given model. In addition, there is a need for some kind of objective function capable of assessing the scope and depth of any given model.

Many models are closed and cannot be easily extended to include new ideas and knowledge. According to Hinks [13] there is a need for an expandable model that can absorb new research findings and developments, that is, one which is flexible and grows with the knowledge base and that helps indicate knowledge shortages.

Mixed-ability populations contain a range of occupants with varying evacuation capabilities, a concept which is often ignored in model development because of limited quantitative data available on the movement of disabled people. Such data would include information on evacuation speeds, a measure of the ability of occupants to move along various sections of an evacuation route, a measure of the amount of assistance required etc. A group of isolated quantitative studies have provided useful data on disabled people in particular occupancy types [14, 15, 16, 17], but there is no general framework which allows the results of these studies to be appropriately channelled as input data into any given model.

3.4 A Description and Comparison of Current Evacuation Models

It is useful to analyse and compare evacuation models by grouping them into different categories according to their basic underlying principles. In so doing, their overall strengths and weaknesses are easier to identify. Whereas previously models were categorised as either deterministic or probabilistic [18] (Fig. 3.1), this author has chosen to adopt alternative categories - psychological and mathematical models. Notably, both these categories may be deterministic or probabilistic. The basis of the division between the two groups lies in the fact that psychological models emphasise occupant behaviour and have a more qualitative and descriptive character. Mathematical models, on the other hand, emphasise physical parameters associated with occupant movement and building dimensional aspects.

Psychological models can be sub-divided into two groups, namely: those with a time-based approach described by specific behavioural stages and those with a time-based approach defined by discrete time frames. The fundamental difference between the approaches lies in the fact that the former emphasises the stages in behaviour that occupants experience as a fire develops and environmental conditions change. These stages are described as occurring within a series of time frames with no specific duration. For example, Proulx's model [19] describes behavioural changes under stressful conditions in fire emergencies.

In the latter group, at every discrete time frame of a specific duration the action of an occupant can be determined as a result of analysing the surrounding environmental conditions. In this group the development of stages in behaviour are not discrete because they are governed by momentary changes in the surrounding conditions and are not necessarily manifested in clearly defined stages, for example, BFires II [20] which is described in subsequent sections.

Most models are predominantly mathematical in that their underlying relationships are described by mathematical functions. Alternatively, mathematical models can be described as phenomenological in that they simulate the actual physical phenomena that affect safety. They can be further divided into several groups which include: analogue, empiric, systemic and knowledge-based models as shown in Fig. 3.2. The author believes that these groups are typical examples of mathematical models that contain easily comprehensive functions.

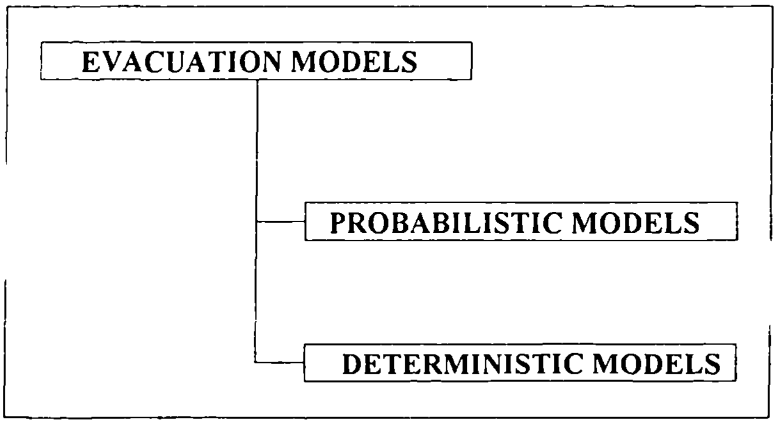

Fig. 3.1: The basic traditional categories of evacuation models

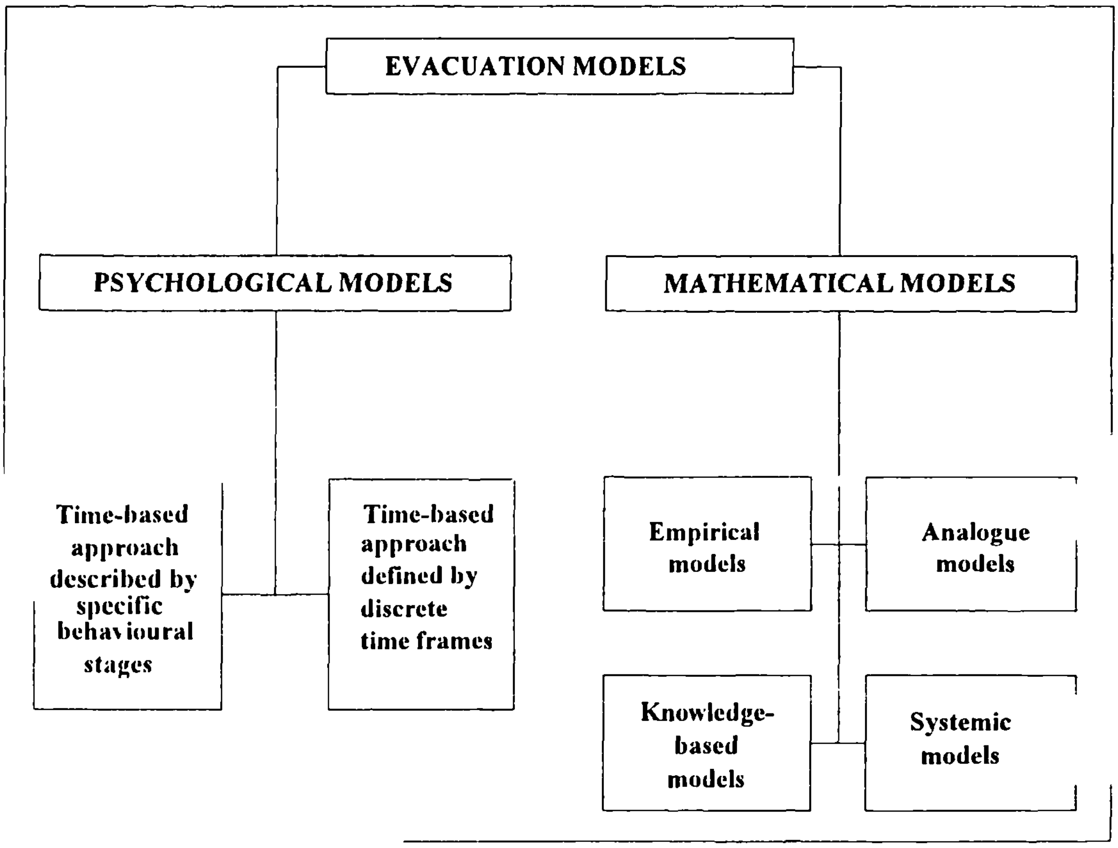

Fig. 3.2: Classification of the various types of evacuation models

In the following section the general principles of each model category are described in terms of their scope, strengths and weaknesses particularly with regard to their acknowledgement of the effects of mixed-ability populations on evacuation times.

3.4.1 Psychological models

Psychology can be defined as the scientific study of behaviour and mental processes [21]. Behavioural or psychological models are founded on the underlying principles of cognitive psychology and examine the actual decision-making processes that produce particular behavioural patterns during fire emergencies. For decades researchers have sought to analyse more closely the decision-making processes that occupants undergo during fires and have met with a number of difficulties because human behaviour is not easily predictable and is not easy to analyse quantitatively. The development of fundamental inter-relationships between behaviour-related parameters is feasible but laborious. In the late 1960's, Wood [22] made the first attempt to carry out a systematic study into human behaviour in fire emergencies, focusing on a general analysis of occupants' actions in a fire, in their evacuation of buildings and in their movement through smoke. His approach to human behaviour in fires could be described as having an escape/no escape orientation in that emphasis was laid on occupants either escaping or failing to escape. A detailed analysis of occupant actions was not deemed essential to the prediction of evacuation time. As a result of his studies, the need for a structured and fundamental approach to behavioural studies was recognised [23].

A decade later, modern psychological principles were adopted in the study of human behaviour in fire emergencies which was no longer limited to an escape/no escape orientation but rather governed by multi-dimensional changes in behaviour, some of which would lead to 'fight or flight' response. Researchers including Canter [24], Sime [25] and Bryan [26] were pioneers of studies on pre-evacuation behaviour, panic and the effects of various fire warning systems on occupants, among other aspects. The techniques used in studying behaviour included statistical analysis which entailed the use of 'act dictionaries', a sequence of actions identified as being experienced by occupants during fires, and 'decomposition diagrams' and matrices enabling the probabilities of response actions in fire scenarios to be determined. Over the last 25 years or so, the techniques used have not changed significantly, rather there has been a shift in emphasis to specific aspects of behaviour that have been considered to critically influence evacuation movement and behaviour. The other evident change, unrelated to the actual study of behaviour, is the use of improved graphical representations simulating occupant movement, for example, video-disc simulation [27] and virtual reality [28].

The two main techniques in psychological modelling are analysed below: those with a time-based approach described by specific behavioural stages and those with a time-based approach defined by discrete time frames.

3.4.1.1 Time-based approach described by specific behavioural stages

In this group of models the total evacuation time is generally expressed as a summation of sub-components of time which according to Sime [29] may include: the time from ignition to perception, t_P, the time from perception to beginning of safety action, t_A, and the time from initiation of a safety action to time to reach a place of relative safety, t_{RS}. The expression for the basic safety criterion therefore becomes, $(t_P + t_A + t_{RS}) \leq t_{TL}$, where t_{TL} is the time for development of untenable conditions. The time components can be further sub-divided to include other components that define t. Sime [30] emphasises the recognition phase, which is the time from being alerted by a cue to evacuate to the time to acknowledging that there is an emergency. He argues that this time component is affected by thirteen critical factors that include the communication methods used, the role of an occupant, mobility, familiarity with a building layout and alertness. Although it is possible to identify the critical factors that govern such time components, he stresses the danger of assuming that a direct mathematical or predictive relationship can be found between time needed and time available.

Still in the same realm, other psychological models avoid the use of time inferences and analyse the emotional stages and decision-making processes an occupant undergoes due to changing environmental conditions during a fire. Proulx's stress model [19] is the most recent published behavioural model. She argues that the cognitive processes associated with decision-making during fires are accompanied by stress resulting from the surrounding threatening environment, and that stressful conditions impair the ability to make decisions. She suggests methods by which this stress factor can be reduced to in order to simplify occupants' decision-making processes, for example, by providing adequate information on ideal evacuation routes which ultimately reduce evacuation times. A similar approach had been adopted by Bryan and Withey [31] who define various conceptual processes experienced by an individual trying to cope with a threatening situation.

There are not many probabilistic models in fire safety design. Ramachandran's probabilistic framework [32] is an example of a model used to determine design evacuation times and presents an alternative approach to modelling human behaviour with time inferences. His equation is identical to the basic safety criterion stated earlier. He suggests that all the time parameters are normally distributed random variables.

In order to obtain estimations of design values for t and t_{TL} it is necessary first to determine 'characteristic' time values for particular fire scenarios. Simulations for different positions of fire origin and combustion products are obtained from fire modelling computer programs such as TENAB [33] and ASKFRS [34]. These provide means and standard deviations of the time for onset of lethal conditions on escape routes. The mean and standard deviations for t_{TL} are required as input to the model while the values for t are outputs provided by the model. Standard normal distributions are used to obtain the coefficients in the probability expressions used. The mean and standard deviations for t_p, the discovery time, is required for buildings with various fire detection systems, for example, those with and without sprinklers. It would be necessary to carry out evacuations to obtain estimations of t_A, the recognition time. Since t_{RS}, the design evacuation time is the ultimate output parameter desired, Ramachandran contends that an estimate of its coefficient of variation is sufficient, which is obtained from simulations of computer programs providing the relevant data on movement of occupants to a place of relative or ultimate safety. This, however, introduces the same errors or inaccuracies of deterministic computer models that predict design evacuation times.

The main objective of Ramachandran's model is to evaluate the risk of death to a group of occupants attempting to escape from a fire; where risk is expressed as the probability of occurrence of one or more deaths. The validity of the results produced by the model depends on the accuracy of the mean and standard deviation of each of the input time components.

3.4.1.2 Time-based approach defined by discrete time frames

While the behavioural approach emphasised developmental stages in behaviour of no specific duration, models defining discrete time frames demonstrate changes in behaviour at specific times and do not simulate the actual decision-making processes. BFires I and its derivative BFires II [20] is one such model. It is a dynamic stochastic computer simulation of emergency egress behaviour of occupants during emergencies. It conceptualises a building fire as a chain of discrete 'time frames' (t_1, t_2, t_3,..., t_n) and for each such time frame it generates a behavioural response for every occupant. The output provides information on occupants' escape scores, time spent in the smoke-filled environment and other time-related data. According to Stahl [20] the data predicted by the model compares well with measured values from his validation studies. EXITT [35] is another example of a model with a similar approach.

More recent models include VEGAS (Virtual EGress and Analysis Simulation) [28] which creates a three-dimensional virtual environment which may be used for real-time 'what if' and worst case scenarios, simulations and risk assessments. It models behavioural response under variable stress conditions created through fire growth, toxicity levels and psychological containment factors. The model adopts 'proximity logic' in modifying the behaviour of occupants at given instances. Behaviour is considered to be dependent on immediate environmental conditions, for example, obstructions and occupant density increases at doorways.

Strengths of psychological models

- The individuality of occupants is maintained in that each occupant's actions are considered in a given simulation. This is a concept which models with a 'global' approach ignore since they assume uniform group behaviour.

- Such models provide detailed information on decision-making processes and result in a greater understanding of actions of occupants in fires. They also serve as good post-hazard analysis tools.

Assumptions and limitations

- Previously psychological models tended to exclusively analyse stages of occupant behaviour during their actual escape. Pre-evacuation time [29], during which occupants seek further information concerning the cause of the emergency, was rarely considered which meant that predicted evacuations times were actually minimal times.

- The scope of most psychological models is limited as each tends to cover only certain specific settings or occupancy types making model comparison difficult.

- Only a few empirical studies have been carried out with disabled people which identify the similarities and differences, if any, of their behaviour and that of able-bodied occupants. It would normally be assumed that the behaviour of able-bodied occupants would not be significantly different from that of disabled occupants in an emergency. However, constraints imposed by the environment may create some differences in behaviour in some instances. Passini and Proulx's study [36] involving the analysis of way-finding techniques of visually impaired occupants showed that congenitally blind participants made significantly more detailed decisions related to way-finding when planning journeys than a sighted control group. This shows that although the primary goal in a fire emergency may be to evacuate a building, the actions taken to achieve this goal may differ depending on the disability of an occupant and building design constraints.

- Information on human behaviour in fires is limited and there are still no generally accepted relationships between, for example, building design and the attributes that define behaviour and movement. Such relationships would provide critical information on the actual measure of the effects of external influences on escape potential of occupants. Presently, several assumptions are being made, for example, with regard to movement. Mobility factors are often assigned to occupants of varying ability solely on the basis of the mobility aids they use. The effects of external influences on a given disability-mobility aid combination are rarely considered and may have significant effects on occupant movement.

- In this approach the decision-making process is not formally defined to allow refutation of the underlying principles of the models.

3.4.2 Analogue models

According to certain sources [37] an analogy is understood to be information that is congruent in amount and organisation to target material, but which is about a different topic. In analogue models, evacuation behaviour is likened to the operation of dynamic systems which do not directly relate to human behaviour and movement but provide an adequate representation of these factors during emergencies. The underlying principles of models in this category are generally based on analogies with established mechanistic scientific theories. For example, pressure gradients in a flowing liquid could represent motivation to escape, or the density of the liquid could represent the crowd density of a population. From these examples it is evident that the interaction between parameters that operate during emergencies can be 'measured' by comparing variations of their analogous counterparts in the scientific relationship.

The types of analogue models the author has chosen to discuss hereafter include graph (flow), magnetic and kinetic theory models. The first two types have actually been adopted in published models while the third is an example of an analogue model that can generate conceptual ideas to simulate occupant behaviour.

3.4.2.1 Graph (Flow) models

Under graph models, normally referred to as flow models, five main categories can be identified and are considered in this section. Deriving their basis in graph theory, these models vary primarily in their levels of complexity; with the most elementary being simple continuous flow models [38], followed by parallel continuous flow models [39], variable flow models [40, 41] and network models [42, 45] at the highest level. Somewhere on an intermediate level are models based on flow through restricted sections of an evacuation route [3, 43, 44] which are difficult to place since they analyse specific sections of a given route and are in a class of their own. In the first two groups, the flow rates through sections of an evacuation route are constant, while in the third group, variations in density and velocity are analysed at points where merging of occupant flow occurs. Network models are slightly more complex in their use of mathematical algorithms that relate density and velocity and calculate minimal evacuation times for a given route. The last group of models analyses the relationships that describe movement through restricted sections of an evacuation route as stated earlier. This is a factor that is superficially analysed in continuous flow models.

a) Simple continuous flow models

The hydraulic flow model is the simplest example of a continuous flow model [38]. Here, flow is defined by two phases. The first phase is the 'start-up' phase that is motivated by an immediate, appropriate, self-initiated decision by occupants to evacuate a building during a fire emergency. The second phase is the 'egress' phase which consists of deliberate progression towards an exit with each occupant moving in his or her own power in tight formation with other occupants. The model suggests that there should be no surges or queues but rather a constant use of an exit to near full capacity or until the last occupant safely clears the exit. No interaction or interdependence between evacuees is considered.

The model makes the assumption that building occupants are alert, able-bodied and ambulatory and that fire safety depends on the 'safe end' of the evacuation system, that is, the protected stairwells and exit doors marking safe exiting during an emergency. The model also assumes that there is a high occupant density which during a fire emergency limits the reasonable options for evacuation that are available to building occupants.

b) Parallel continuous flow models

This group of models has been described as having parallel continuous flow, in the sense that two or more evacuation routes may be interconnected. However, the flow through each route is individually analysed with a view to identifying the optimum evacuation route. The optimum route is the shortest and occupants following this route are assumed to travel through it in minimal evacuation time.

Francis [39] developed a model of this type and argues that in order to determine the minimal evacuation time for a given route the following conditions need to be satisfied:

- Assume that a building has k people to be evacuated by n routes, with each route having a single exit. Let $t_j(x_j)$ denote the time for x_j people to clear a route j exit, where j varies from 1 to n. Assume further that for each j, t_j (0) = 0 and that t_j is a given monotonic increasing and continuous function.

  Ignoring integrality requirements, the expression of interest is as follows, where z is the time for the last person to leave the building:

$$\text{minimize}\,(z) \equiv \max[t_j(x_j): j = 1,\ldots,n]$$

  subject to

$$x_1 + \ldots. + x_n = k$$
$$x_1, \ldots\ldots, x_n \geq 0$$

Two assumptions are made: that each evacuee has reasonable access to every route exit and that the time to clear a route exit depends only on the number of people using that exit.

c) Variable flow models

Pretechenskii and Milinskii [40] describe a flow model which incorporates variations in physical flow parameters of egressing populations. The model adopts a deterministic approach to predicting the movement of an egressing population on a horizontal or sloping route at a given instant in terms of its density and velocity. It avoids the tendency to assign fixed values to flow densities or velocities, and incorporates the effects of anthropometric data of different populations, such as perpendicular projected areas of occupants which significantly influence density values. The main conditions for free flow are satisfied in that equivalent flow capacities are experienced on successive parts of an escape route. The variations in density and velocity that occur when flows merge are analysed.

Takahashi et al. [41] designed a flow model that predicts the movement behaviour of groups of occupants along all sections of an evacuation route with the additional element of observing patterns of movement around different obstacle arrangements. The principles they adopt are based mainly on flow rate equations. Similar to the continuous flow models mentioned above, the distribution of occupants through exits is designed in such a way that minimal evacuation times are achieved. Variations in velocity with crowd density are analysed with an approach similar that of Pretechenskii and Milinskii [40].

d) Network models

Network models are primarily based on fluid flow principles but include additional input from other mathematical algorithms. These models consist of paths or routes by which objects or energy may move from one point to another [45]. Starting and ending points are called 'source' and 'sink' nodes, respectively, and 'arcs' connect the two types of nodes. Translating this into building terms, nodes would represent rooms with a given occupancy while arcs represent corridors, stairwells or any space element connecting the rooms. The sinks signify places of relative or ultimate safety including refuge areas or assembly points outside a building. Network models share the same objective as parallel flow models which is to minimise evacuation time and to identify optimal evacuation routes.

Evacnet+ [45] is a commonly referenced network model. It is founded on advanced capacitated network flow transhipment algorithms specialised in solving linear programming problems with a network structure. It is 'time-dependant', describing evacuation behaviour during the development and spread of a fire in a given duration. The model requires a significant amount of detailed input information, for example, the number of occupants in each node prior to evacuation, stairwell flow capacities, etc. Results predicted by Evacnet+ when compared to observed results from a fire drill or validation study, showed that the predicted evacuation times in the monitored stairwells were not closely comparable to the measured times. However, the developers contend that, in general, a comparison of drill results with predicted model results could be used to suggest areas in which improvements in evacuation procedure could be made since the model provides a feel for the amount of time that could be saved by using optimal evacuation strategies. Recent models adopting similar concepts include EGRESS [46] and ESCAPAID [47], although EGRESS integrates behavioural elements with its movement model.

e) Flow through restricted elements of evacuation routes

Flow through restricted sections of an evacuation route, such as exits and stairwells, is an important aspect of occupant movement because significant changes in flow patterns occur at these sections. These changes in flow patterns ultimately influence evacuation times. Some researchers have attempted to analyse occupant flow through these sections and the resulting relationships that they derived have served as useful input data for continuous and variable flow models. The author has chosen to analyse these models separately to emphasise their importance and relevance in evacuation movement

Post War Studies [3] included some of the first studies on occupant movement through exits and stairwells. General flow rates were calculated from observations of tests involving fit, able-bodied men. The analysis of movement through exits was continued by researchers such as Pescl [43] who analysed queuing aspects in detail and observed effects of 'arch formation' at crowded exits. Arch formation is the development of an arch shape around a crowded exit resulting from a surge of occupants waiting to use the exit. Pescl provided a quantitative relationship describing flow through exits as did Togawa [44] who stated that for an exit of width b m, the time t_E for a crowd of q people to pass through the opening is given by:

$$t_E = \frac{q}{nb}$$

where n is the flow rate per metre width. This formula only applies until the exit becomes congested. On average, n is about 1.7 persons m^{-1} s^{-1} and has a maximum value of about 2 persons m^{-1} s^{-1}.

Strengths of flow models

- These models can help identify potential congestion in stairwells and at exits. This information is useful as an evaluation tool for designers assessing capacities of escape route elements.

- In variable flow models the changes in physical flow parameters are recognised and therefore constant flow rates of occupant movement along an evacuation route are not assumed.

- A major asset of network codes, in particular, is their ability to solve very large and complex problems. Any complex building layout that is representable as a network, can be modelled [45].

Assumptions and limitations

- The models do not consider the effects of mixed-ability populations. The speed-crowd density relationships that they adopt are similar to those of researchers such as Pretechenskii and Milinskii, and Fruin [40, 48] which represent movement of able-bodied occupants. In some cases, for example, in studies carried out by Ando et al. [49], speed-density relationships are not restricted to able-bodied populations but also include elderly people who comprise the category of 'disabled people'. It is evident that elderly people, who do not have similar mobility to able-bodied people, comprise only a limited proportion of the disabled population.

- Contra-flow of occupants during their attempt to egress is not considered, with emergency evacuation behaviour assumed to be uni-directional only.

- A global perspective of occupants is adopted and the individuality of occupants is ignored.

- Many behavioural concerns such as perception of cues, investigation of cues and general coping behaviour that does not involve actual movement towards exits or along egress routes do not seem to be readily representable by these flow models. Evacuation time is solely dependant on the population using each escape route.

- All occupants are assumed to have reasonable access to every exit route. In addition, often it is assumed that the shortest route is optimal.

3.4.2.3 Magnetic theory model

According to Coulomb's Law [50], there exists a force of attraction between two oppositely charged poles which is indirectly proportional to the square of the distance between the poles. This magnetic force can be used to represent the motivation of an occupant to move towards a specific goal, most likely an exit leading out of the building or a place of relative safety.

Okazaki and Matsushita [51] describe a model based on magnetic theory, in which the movement of an occupant is represented by the motion of a magnetised object in a magnetic field. A positive charge is assigned to occupants and any obstacles such as walls and columns. An occupant's goal or destination and corners around which s/he moves is assigned a negative charge. The force acting on an occupant is calculated using Coulombs' law. If a large crowd is simulated then occupants are 'grouped' and each group is treated as a single entity with identical velocity, direction and orientation. Velocity is determined by random values generated by a normal distribution. A maximum velocity of occupants is input into the model, to avoid an indefinite and therefore unrealistic increase in velocity due to the acceleration parameter in Coulomb's law.

The model acts as an evaluation tool to identify possible points of congestion for complex building layouts. The predictions of the models clearly show the congested areas during a given simulation. In addition, the pattern of movement through the openings on the layout of the building plan are clearly evident.

Strengths of magnetic theory model

- In this model three methods of movement are considered. In the first, a sequence of corner numbers is assigned and a given occupant follows these corners which are temporary goals along the route possessing opposite charges to that of the occupant. The second method adopts the shortest route out of the building, similar to the optimal routes derived by flow models. The third method is a way-finding method, in which a decision-making philosophy is adopted by occupants seeking their goal. Few models provide optional methods of movement. This is an improvement on flow models that simulate uni-directional continuous flow of egressing occupants.

- Queuing aspects and methods of movement within queues in heavily congested areas are analysed. The model is also capable of simulating merging and contra-flow aspects.

Assumptions and limitations

- Speed distributions do not include mixed-ability populations. It is also usually difficult to determine maximum speeds and in this model the upper speed limit does not appear to be founded on empirical observation.

- Pre-evacuation or starting times for individuals or groups are not provided.

- Although three methods of movement are considered it appears that only one can be used at a time in each simulation. Therefore, during a given scenario the method of movement cannot be altered and would be adopted for the entire scenario.

- The fact that 'group movement' is considered in heavily congested conditions makes the assumption that occupants in a given group will move in the same direction as they proceed to a given goal. This contradicts the 'affiliation principle' that contends that it is members in a given group with psychological ties who will tend to evacuate together. In many cases family groups that are separated will attempt to look for each other during an emergency before they actually evacuate, as was evident in the Summerland Fire [52].

3.4.2.4 Kinetic theory model

In a simple evacuation case study [53], the author adopted the kinetic theory model to generate ideas that could simulate evacuation behaviour and movement patterns of occupants in, for example, a football stadium.

According to the kinetic theory [54], for a constant volume, the pressure of a gas varies linearly with its absolute thermodynamic temperature. Temperature is a measure of the kinetic energy of the molecules. Raising the temperature results in an increase in the velocity of the molecules and consequently, more frequent collisions between molecules and with the sides of the vessel containing them. This is manifested as a pressure increase. This basic behaviour shares certain similarities with that of a large number of occupants in a confined space during an emergency, at least in the two-dimensional sense.

Assuming that gaseous molecules can represent occupants, while the vessel containing these molecules represents a given building, a fire in any part of the building would stimulate some response from occupants. After they perceive the fire as endangering their lives they would attempt to leave the building to reach a place of safety. As a result of the fire, the speed of movement of occupants as they attempt to distance themselves from the danger, would most likely increase as might the number of collisions or impacts between the occupants and between occupants and the physical structures in the building. Thus 'temperature rise' or an emergency can be considered to have an effect on occupancy, management and structural arrangements. The concentration of gaseous molecules would signify crowd density, the uniformity or non-uniformity of the mixture would represent distribution of occupants and the type of molecules would be an indication of an occupant profile which would consist of disabled occupants and young people, for example. No numerical values of pressure, temperature and volume are provided in the model, but rather the concepts in molecular kinetic theory are used to identify the critical parameters that affect egress.

Strengths of kinetic theory model

- There are a significant number of similarities between molecular behaviour and crowd behaviour in serious emergency situations. The molecular theory is a useful tool for highlighting critical factors affecting movement that warrant consideration during evacuations, for example, effects of crowding.

- With regard to quantitative attributes such as occupant speed, it can be argued that the normal distribution of molecular speeds can be adjusted to correspond to occupant speed distributions using statistical techniques. Although this seems rather ambitious, it is a possibility.

- Although it has not been used in practice for this purpose, the model is useful as an evaluation tool for assessing occupant safety particularly in large venues.

Assumptions and limitations

- It is only the two-dimensional aspect of the kinetic theory model that can be assumed to simulate occupant movement. Movement of molecules in a vessel is possible in all directions while occupant movement is limited to two dimensions.

- The random movement of molecules is more exaggerated than occupant movement. During an emergency in which exits are not accessible or are blocked by fire, occupants will seek alternative routes out of a building but their choice of the direction will be based on their perception of the surrounding threat and environmental conditions rather than random movement from one point to another.

- This model cannot provide quantitative predictions of evacuation-related parameters.

3.4.3 Empiric models

It could be argued that results obtained from experimental observations provide a more realistic basis for model development. Most models have some degree of empirical input, but for our purposes, the term 'empiric models' will refer to those models which are defined by relationships that are predominantly founded on experimental observation.

Two main groups of empirical models are identifiable in this category: models based on studies of general movement patterns of occupants and those based on studies specifically related to individual movement capabilities of occupants. In the first group the most basic equation predicting evacuation time is a summation of flow times through exits and travel times along pre-defined distances. Some of the models ignore the time components relating to human behaviour, for example, the time taken to respond to a cue to evacuate or the time for any behaviour that would divert an occupant from his or her original path. In the second group, the factors of primary interest are the actual individual characteristics of occupants that determine their movement ability and ultimately influence their evacuation times.

3.4.3.1 Studies of general movement patterns of occupants

This group of models analyses general movement patterns of mixed-ability populations using experimental observations. At the start of this chapter the author stated that studies in the UK, such as the Post War Studies [3], provided some data on movement patterns of able-bodied occupants. Togawa [44], Fruin [48] and Pauls [12], among others, developed these studies to the level where they defined relationships between widths of stairwells and flow rates of occupants, investigated effects on flow of occupants around bends or down slopes etc. However, these researchers restricted their studies to able-bodied populations and only in a few isolated cases did Pauls [12] consider the general effects of slower moving disabled people on crowd movement.

Three fundamental parameters: density, speed and flow provide a basis for empirical relationships. Flow times and total evacuation times, derived from these parameters are of primary interest. 'Flow' is defined as the number of occupants that pass some reference point in a unit of time, for example, flow through an exit may be 2.0 persons/s. Flow time is a function of crowd flow through a usable width of a particular circulation element and the population moving through it. Evacuation time is more difficult to predict than flow time because it incorporates components relating to actual movement through the evacuation route elements and the time taken by complex human behaviour that precedes or accompanies egress [12]. Two sub-components that are normally found in design codes and related documents are: the flow times through elements of the evacuation route (usually the longest time is considered) and the travel time of an occupant moving along the most direct evacuation route. The sub-components relating to occupant behaviour are generally ignored in simple engineering analysis of evacuation, implying that the evacuation times predicted are really minimal times.

Fruin's studies [48] focused on the variations in velocity resulting from changes in crowd density by describing six 'levels of service' (A through F) for walkways, stairways and queuing. Level A represented the highest crowd density with the greatest chance of congestion and Level F represented the lowest crowd density. The mid-levels levels C, D and E were prescribed for use in ordinary design procedure because they are more frequently experienced crowd densities. Fruin's studies is one of the few that investigate contra-flow movement although not quantitatively. He observed that for two-way corridors with 'not very high' crowd densities, the total flow is only slightly less than that for uni-directional flow.

Pauls' studies [12], based on knowledge of mean flows and observed evacuation starting times, concentrated on the flow of occupants through stairwells of high-rise buildings. His analysis led to the development of the 'effective width model' which is defined as follows:

$$f = 0.206(w - 0.3)(p/(w - 0.3))^{0.27}$$

where,

f = flow rate (persons/s)

p = evacuation population (persons)

w = the actual stairwell width (m)

(w - 0.3) = effective width of a stairwell, obtained by subtracting 0.3 m from the actual width to allow for ordinary swaying movements associated with the motion of walking (m).

The model provides reasonable predictions of flow rates for high density populations when stairwells are filled to near capacity. When Pauls observed movement of mixed-ability populations he found that if a disabled person was present in an evacuating crowd, the flow rate of the crowd would be reduced only in the vicinity of the disabled person after which the crowd flow rate would build up again. There is a similar effect created during occupant movement around a bend in Togawa's model [44] which is discussed shortly.

In Pauls' study [12] a prediction curve and a regression equation for flow expressed as a function of the population was used to determine total evacuation time. He found that the time during which evacuation flow occurred was obtained by dividing the population per metre of effective width by the flow of occupants per metre of effective width. Adding a 0.68 minute starting time, the following equation provided the total evacuation time (for populations less than 800 persons/m effective stair width):

$$t = 0.68 + 0.081p^{0.73}$$

t = total evacuation time (minimal time in minutes to complete uncontrolled total evacuation) (min)
p = evacuation population per metre of effective stair width (persons/m). This parameter is measured just above the discharge level of the stairwell.

The 0.68 minute time component accounts for travel time plus some of the sub-components of evacuation time which are not specified. Pauls argues that the adequacy of this time value depends on the experience of building occupants of fire emergencies and the manner in which the evacuation is run.

For populations above 800 persons per metre of effective stair width, the total evacuation time was modified to:

$$t = 0.70 + 0.0133p$$

In his research, Togawa [44] ignored the time sub-components relating to behaviour before and during evacuation and instead concentrated on predictions of minimal evacuation times for buildings where stairs were extensively used. He derived the following equation to calculate escape times through an escape route with doorways along the path followed:

$$t_E = \frac{n_A}{b'n'} + \frac{k_S}{v}$$

where,
t_E = escape time (s)
n_A = total number of escaping people (persons)

n' = number of outflowing people from the second doorway of an evacuation route per metre width of doorway per second (persons/m.s)
k_S = distance from the first doorway to the gathering point of the evacuating crowd (m)
v = walking velocity of crowd (m/s)
b' = breadth of second doorway (m)

In his consideration of the effects of building design on occupant flow, Togawa's findings also revealed that minor restrictions caused by slight projections along an evacuation route had little effect on flow rates. He also observed that corners and bends had no significant effect on occupant flow rates although speeds were reduced and crowd density increased on the inside of a bend. The opposite effect was experienced on the outside of the bend.

Strengths of models relating to general movement pattern of occupants

- Pauls [12] includes the effects of human behaviour in the time sub-components that he analyses. The nature of occupant behaviour has been shown to significantly affect evacuation time.

- Although Togawa's work [44] omitted behavioural aspects, his extensive studies of flow through exits, along passageways, ramps and stairs have revealed flow patterns that have provided a basis for means of escape design in the Building Regulations [55].

- Fruin's 'levels of service' [48] are useful for planning occupant densities for emergencies in a limited space.

Assumptions and limitations

- The whole basis of Pauls' model [12] alters when low populations are considered in high-rise buildings. With low populations, evacuation time is governed by evacuees' free speed of descent and building height. It appears that there are no equations relating unimpeded speed and building heights to evacuation times.

- Pauls argues that optimum densities stated for stairwells should be applied cautiously, as their effects on flow could change significantly by altering stair dimensions. His studies demonstrated this fact and highlighted significant changes in flow that occurred when there was a small variation in stair riser and tread dimensions.

- Togawa and Fruin's work [44, 48] is only useful for calculating minimal flow times as they disregard effects of behaviour, which according to Pauls significantly influence evacuation times.

- When modelling a given scenario, a fixed walking velocity of a crowd is assumed. The ranges of speed values for mixed-ability populations are not generally considered.

3.4.3.2 Studies relating to individual capability to move

With increasing emphasis on designing for safe egress of occupants with disabilities, there are an increasing number of empirical studies being carried out to measure occupant evacuation capabilities with a view to creating structural and managerial arrangements, which will enable them to evacuate safely when required. It is therefore necessary to identify the critical factors that affect evacuation capabilities during emergencies and several approaches have been adopted to analyse these factors.

Codes of practice including British Standard BS 5588 Part 8 [4], Building Regulations Part M [56] and K [57] provide qualitative guidelines on evacuation procedures of disabled occupants. They also include information on acceptable stairwell dimensions and handrail heights etc. that enable easier movement of occupants around buildings. The Personal Emergency Evacuation Plan (PEEP) [58] adopts a questionnaire approach that draws information from disabled people themselves, in order to identify ways in which they can be assisted during emergencies. It is a subjective measure of evacuation capability of disabled people that is useful to management personnel who may be in charge of people with disabilities and are planning for safe evacuation strategies.

In terms of quantitative approaches, there are two distinct measures of evacuation capability using ratios. These are the speed ratios relating solely to individual abilities of occupants to move, unhindered in their movement and those relating to individual abilities of occupants when influenced by external factors.

In the first category, a measure of evacuation capability is determined by obtaining the ratios of movement speeds of occupants as a result of their own physical and psychological efforts. Although it is evident that movement speeds are influenced by building design, environmental conditions and provision of assistance, in this category the intrinsic speeds of occupants are all that are of interest, and the effects of external factors are not measured. For example, Pearson and Joost [17] carried out evacuation studies with blind occupants, wheelchair users, elderly people and young ambulant occupants in a residential setting and based their comparisons of evacuation capability on speed. Their results showed, for example, that on average it took nearly three times longer for the blind occupants and wheelchair users to complete the evacuation scenario as compared to the able-bodied occupants. Shields' Evacuation Time Ratio [5], compares the mean speed of evacuating a wheelchair user to the mean speed of evacuating an able-bodied person. He considers two interpretations of travel speeds, which are those determined by using unweighted averages of distances and times and those determined from the ratio of cumulative distance travelled by all participants to the total time taken. It is interesting to note that these calculations can provide significantly different results and stresses the importance of using consistent methods of calculating speeds. Although these examples are reasonable methods for measuring evacuation capabilities of disabled people, the values are route-specific.

In the second category evacuation capabilities include effects of external factors, for example, the amount of assistance provided to an occupant. A measure of evacuation capability termed as the Evacuation Difficulty Index introduced by Grover et al. of NFPA [15], later modified by Hallberg [14] and the recent NFPA Life Safety Codes [59], is a ratio of the amount of assistance required by residents evacuating a board and care home (group home) and the availability of staff to provide assistance. Another example is the Patient Mobility Factor (PMF) introduced by Marchant and Finucane [16], which is the ratio of the number of hospital staff actions, for example, in assisting a patient out of bed, and the number of patients in a hospital ward. In these studies although external effects were analysed the measures of evacuation capability used are also route-specific.

Strengths of models relating to individual capability to move

- These models provide reasonable quantitative measures of evacuation capabilities of disabled people. This information is useful for the design of suitable means of escape.

- In some of the models, for example, the Personal Emergency Evacuation Plan [58], the information on suitable evacuation procedures comes from disabled people themselves, who would know what makes their movement around buildings easier.

Assumptions and limitations

- Most of the studies described have been carried out for specific occupancy types Methods of measurement of evacuation capability cannot be easily transferred from one occupancy type to another. For example, evacuating a wheelchair user from a residential setting is a significantly different scenario from evacuating a wheelchair user from a high-rise office building.

- Whilst providing valuable insights into some of the critical factors affecting evacuation capability, the approaches fail to define a general framework for designing solutions to fire safety engineering problems involving mixed-ability populations.

<u>3.4.4 Systemic models</u>

'Systemic' by general definition means 'pertaining to a bodily system as a whole'. A systemic model consists of a combination of interacting systems contributing to each other in order to enable the whole system to operate as required. According to Beard [11] the nature of fire safety which encompasses social values and engineering hardware is only fully understood when it is considered as a 'dynamic whole'.

The working of a systemic system in deciphering a problem will, in general, require cycling through stages of methodology in such a way that a never-ending series of iterations may be required. The statement of the problem and understanding of it will change with time and intermediate solutions will be formulated at different points in the problem. The methodology provides guidance for tackling a problem which never actually leads to a single solution but to a series of solutions that can be progressively modified.

A systemic model is a combination of interactive sub-systems. The objective of such a model is not simply to identify direct relationships between items in a sub-system but to find a super-ordinate system in which they are connected or defined by their positional and functional value within the system. Therefore, the dual mechanism of inter-relating items and assessing their significance in a given design problem, creates an environment in which a designer can analyse safety objectives more usefully [11].

Currently, there is increasing interest in designing for fire safety using the systemic approach. Developers of the British Standards Institution (BSI) Code [1] and International Standards Organisation (ISO) document [60], for example, are attempting to adopt a systemic approach to develop a framework consisting of fire safety sub-systems interacting with each other. They anticipate that this will enable more strategic assessment of the effectiveness of fire safety systems in a given environment. The following examples describe the approaches used by the above mentioned authorities and one researcher, Hinks [61]:

a) Information bus-bar approach

In this approach the iterative stages in a systemic framework are likened to the operation of an information bus-bar, analogous to an electrical bus-bar, which shows how sub-systems interact and feed information onto a bus (inputs) and take information from the bus (outputs) [1, 60]. Fire safety problems in such models are thus solved by a continuous exchange of information from the sub-systems, relevant to the problem.

b) Network representation

The process of feeding and transferring information from one system to another is also represented in Hinks' [61] heuristic structure used to determine escape potentials of occupants. He arranges the components affecting escape potential into a hierarchical structure differentiating those contributing to escape and those contributing to degradation of the building environment. As a result of the large degree of interaction between and across levels of the hierarchy he introduces an interactive network to link all the components in the hierarchy, in this way constructing some kind of systemic model.

Moreover, Hinks' heuristic network structure is not designed solely to examine interactive relationships of fire safety aspects but also to actually observe the degree of influence these factors have on escape potentials of occupants. His acknowledgement of the varying effects of external factors on escape potentials, during the development of a fire, are commendable. However, the shortage of available reliable data to provide an actual measure of the effects of external factors on escape potential is a major limitation. Such quantitative factors would be ideal in measuring the importance of various components or factors at a particular level in the hierarchy.

Strengths of systemic models

- The systemic approach involves the operation of a number of sub-models within a system that attempts to answer a relatively limited question within a broader context. It is argued that these sub-models in a system enable a better understanding of relationships that exist within the system itself [11].

- The flexible nature of the approach allows incremental modification by incorporating information from ongoing research. New information can be included in a sub-system without causing an imbalance in the main system.

- A given sub-system can operate in isolation if a problem requires information solely from that sub-system. For example, in predicting movement of smoke in a compartment, one may not necessarily require information on occupancy, but only sub-systems relating to smoke, fire spread and geometry of the compartment. However, output obtained may be useful to any of the other sub-systems not initially involved in solving the given problem.

- As systemic modelling is an iterative process, the assessment of a given solution is made possible during any stage of the problem-solving process.

- One can identify the specific causes of failure in a fire safety system and also identify areas where further research is needed.

Assumptions and limitations

- The iterative procedure can be time-consuming and tedious.

- Any loopholes in a particular sub-system are likely to affect the entire system eventually.

- Hinks [61] identifies a problem with overlaying apparently similar part-models or sub-models of different backgrounds in a given systemic model. For example, the set of components considered in evacuation studies include observational information on occupant behaviour obtained by using either mechanical approaches or network flow principles which may not provide compatible results.

3.4.5 Knowledge-based models (expert-systems approach)

The use of an expert-systems approach in evacuation modelling has opened up a new school of thought in analysing occupant behaviour and movement in emergencies. An expert system is composed of interacting sub-models, for example, human behavioural or smoke movement models. The most recent expert system evacuation model is EXODUS [62]. A brief analysis of this model will provide some insight into the use of expert systems approaches in evacuation modelling.

An expert system is a computer program that encodes a significant amount of heuristic and procedural knowledge about a specific problem and uses this knowledge in problem-solving. Generally, the knowledge encoded in the system is obtained from experts in the application domain. A typical expert system consists of a user interface, for example, used to describe a building layout and population distributions; a knowledge base containing rules describing occupant behaviour, movement, etc.; a working memory and an inference engine to apply the knowledge contained in the knowledge base to the information stored in the working memory by the user interface [63]. Fig. 3.3 illustrates the inter-relationship between the various components.

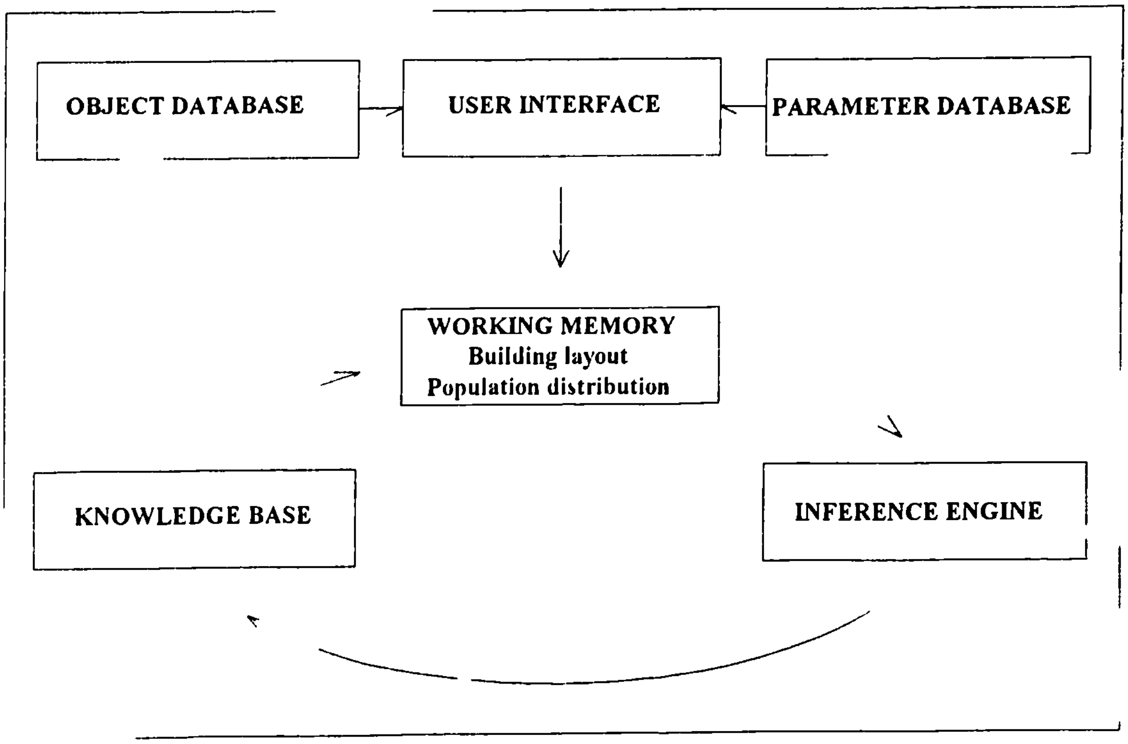

Fig. 3.3: The architecture of a rule-based model

EXODUS [62] is a prototype egress model simulating evacuations of large populations. It is intended primarily for mass transport vehicles such as aircrafts and trains but can be applied to large single-room buildings such as cinemas and theatres.

The model comprises five core interacting components: movement, behaviour, passenger, hazard and toxicity sub-models. A range of attributes describe occupant status and include factors such as age, weight and mobility. There are a total of nine progress variables used in the model. Two of the progress variables relate to movement, such as, personal escape time and travel speed. The remaining seven are physiological and are part of the toxicity sub-model. They describe an occupant's degree of exposure to narcotic gases and convective heat. Some attributes remain fixed throughout a simulation while others like speed, agility and mobility change as a result of inputs from sub-models. The additive effects of external factors on escape potential are simulated in the model although actual measures of their effects have not yet been determined.

The behavioural model functions on two levels, firstly, by the global response to an emergency and secondly, by occupant response to local conditions. In the former case, decisions such as exit choice are governed by proximity to an exit which is contrary to Sime's findings [27] which seem to indicate that familiarity with an exit is an over-ruling influence on exit choice. As a result of exit choice being based on proximity, the model provides minimal expected escape times. Local responses include decisions such as whether or not to jump over seats or to wait for an opening in a crowd in order to move forward. The model considers four methods of movement: walking, running, jumping and crawling. As far as speed patterns are concerned the model shies away from generally accepted speed-density relationships [48] and relates speed to immediate surrounding conditions of occupants.

Strengths of knowledge-based models

- The model has in-built provisions to simulate quantitative effects of external influences, such as building design aspects, on escape potentials of occupants.

- The model uses a 'simulation clock' which defines the time frames at which occupant status can be analysed. This means that individual escape times can be easily determined and occupants can be 'interrogated' about their condition during a fire at any time during a simulation.

Assumption and limitations

- Current research studies have led to the development of general relationships between mobility aspects and travel speeds; yet, there is still no readily available data that can be used to quantify these relationships. There is insufficient data to demonstrate the actual changes in these attributes when environmental conditions change. As a result a significant number of assumptions relating to occupant mobility are used that have not been verified.

- The EXODUS [62] model requires significantly more input from research. The model developer intends to incorporate a wide range of behavioural traits and escape route planning capabilities in the future.

- The types of layouts considered appear to be centred on a specific type of seating arrangement. The ability of the model to simulate complex obstacle arrangements is not evident.

- Further validation tests need to be carried out. In the meantime, validation is limited to one primary experiment, an aircraft evacuation, in which some similarities in movement patterns in the validation study and the model were observed.

- Other limitations of expert systems in general is their inability to learn. They also depend on non-experts to elicit expertise and convert it into rules.

Summary

The main drawbacks of modelling have been discussed in this chapter. The attempt to resolve them are addressed more specifically in the following chapter in which a framework is developed that is capable of analysing the effects of external factors on evacuation capabilities of disabled people. This is carried out by adopting a novel concept called the *evacuation performance index* (EPI), which is defined as the relative ease of evacuating a disabled-person compared to evacuating an able-bodied person. Experimental methods for measuring EPIs are described as well as a design procedure that enables worst-case evacuation times to be predicted.

CHAPTER 4

Evacuation Performance Index

Having identified the major drawbacks in evacuation models in the previous two chapters, the author has found the most significant limitation to be the lack of a coherent, definitive approach to investigating occupant movement. There is a need for one such approach that is capable of assessing evacuation capabilities of occupants; an essential factor in the prediction of reasonably accurate evacuation times.

In this chapter, the author describes, the *evacuation performance index* (EPI) concept which was first introduced in Chapter 2. It identifies two primary factors that influence an occupant's speed and these are, the disability of the occupant and the device or mobility aid used to assist movement. In this thesis, these two factors are continually referred to as an occupant's disability-mobility aid combination. Whereas this combination is understood to be a key determinant of occupant speed, certain primary factors are observed to further modify this intrinsic speed: individual characteristics of occupants, provision of assistance, building design and environmental factors.

The chapter reports experimental work which measures the EPIs of a group of disabled students with different disability-mobility aid combinations. The evacuation behaviour of these students was observed as they evacuate along a defined route. The layout for the experiment was a typical evacuation route used for normal circulation in an office building at the University of Central Lancashire. Only effects of building design were considered because of their permanent nature which was easier to control in an experimental setting and comparatively easier to measure than environmental factors or those relating to the provision of assistance.

The inevitable changes in EPI observed along each section of the evacuation route and a comprehensive design procedure incorporating these EPIs is introduced. This design procedure provides a method of predicting evacuation times. Certain idiosyncrasies arose in the use of the EPI concept and these are discussed in the final part of the chapter.

4.1 Safety Criterion in Fire Safety Engineering

The need for a basic safety criterion in Fire Safety Engineering can be best understood by first reviewing the underlying assumptions and philosophy on which design in some traditional engineering fields, for example civil engineering, are based [64]. Design in civil engineering can be grossly defined as *the creation of a structure that safely performs some pre-specified functions;* whereas in fire safety engineering, it is viewed as *the creation of structural, design and managerial arrangements which in the event of a fire emergency ensure that some pre-specified proportion of the occupants of a building can safely evacuate.* Concentrating for the moment on the civil engineering definition, and ignoring its reference to functions and structure, the concept of safety remains. For each class of civil engineering design problem, there is an explicitly defined safety criterion which must be satisfied by all proposed solutions to the problem. This criterion generally states that the intrinsic strength of structural elements must be capable of withstanding the loads imposed on them, or $f_S \geq f_L$, where f_S denotes the strength of a structural element, and f_L, its imposed loading. This criterion is applicable to different types of structural arrangements and a range of techniques are employed to compute strength and loading values.

In the attempt to transpose traditional design principles to fire safety engineering, a clear understanding of the equivalents of the following factors would be required: (i) safety criteria, (ii) loading, (iii) strength, and (iv) how different structural and managerial arrangements impact on loading and strength. With these concepts in mind, the fire safety engineering analogues of these terms are described in subsequent sections.

As was stated earlier, the primary goal in fire safety engineering is to ensure that in the event of a fire emergency, occupants have sufficient time to evacuate the building without becoming incapacitated. Essentially therefore, the safety criterion should define relationships between different classes of fire emergencies and time to safely evacuate, or in other words, should embody the notion of tenability limits. In mathematical terms, this criterion can be expressed in agreement with the basic underlying principle of evacuation modelling introduced in Chapter 3, as $t_{TL} \geq t$, where t_{TL} specifies the time for tenability levels to exceed their allowable limits for different classes of fires, and t specifies the total evacuation time of the occupants of the building. Comparing this equation with the one presented earlier from the civil engineering field, and noting that because the fire engineering criterion is expressed in terms of time, t_{TL} correlates to f_L and should embody the notion of loading, while t correlates to f_S and should embody the notion of strength.

4.1.1 Loading

The concept of loading can be understood in a number of ways: the downward pressure of a superstructure, the resistance to an engine or motor apart from friction, or the amount of electrical energy required from a source. In fire safety terms, the fire and any factors affecting its growth, the types of effluents produced and the movement of these effluents determines the imposed loading. Again, this concept was discussed in greater detail in Chapter 3 under, 'Evacuation Modelling'.

4.1.2 Strength

The civil engineering concept of strength, the built-in resistance of structural elements to imposed loading, will in fire safety engineering correspond to the intrinsic capacity of occupants to evacuate a building. Thus, some quantitative attribute of a person is required, for which, given a building layout and the amount and type of assistance available to the person, it is possible to predict that person's evacuation potential and evacuation time.

The most suitable attribute is that of 'movement speed', which is a measurable time-based parameter. Ideally, reducing the available evacuation time component t by increasing occupant speed is a primary goal towards ensuring safe egress. Several external factors affect occupant speed, and the purpose of this chapter is to identify the primary factors that influence speed and to propose methods of measuring their effects.

It would be unrealistic to expect that for a building occupied by a thousand people, for example, exact values of all their individual speeds would be known in advance in order to enable design to proceed. Furthermore, utilising a single nominal speed is inappropriate, since this fails to consider the wide range of speeds of disabled people in particular. A reasonable compromise is to experimentally determine nominal speed values for different categories of people, and to use these values in design.

As stated earlier, the author believes that intrinsic speed of a disabled person depends principally on two factors: the person's specific disability and his/her mobility aid. Other factors such as assistance provided to the person or the structural layout of the building alter this intrinsic value. However, taken in isolation, each of the two factors, that is, disability or mobility aid, are insufficient in themselves to determine intrinsic speed, since for instance, there is a wide range of speed values for wheelchair users with different disabilities. Some classification of disability and mobility aids is essential to assign appropriate movement speeds to various occupants. This call for a classification system based on disability and mobility aids is not entirely new, but echoes that of Shields [5], although Shields does not emphasise the effects of mobility aids, except in situations whereby an occupant may hinder the movement of others due to larger spatial requirements of his/her mobility aid in a restricted section along an evacuation route. Hallberg [65] classifies occupants according to their movement behaviour and studies the inter-dependencies between movement behaviour and other characteristics e.g., spatial requirements in a building from an architect's perspective. She uses an inventory of movement descriptions consisting of technical, graphical and verbal systems. Different dimensions of movement behaviour are described using two types of adjective group formations. The dimensions described in the first of the two types of formation are pace, quantity and nature of movement. The second type of adjective is comprised of additional variables which specify the movement behaviour of an individual, for example, 'decisive' or 'efficient'. In each dimension a 20-degree scale is used. This is a useful system of classification of actual movement of occupants but does not appear to provide data that can be readily incorporated into design.

4.1.3 Basic categories of disabilities and mobility aids

Having defined the notion of strength in terms of intrinsic speed of an occupant and suggested that speed is primarily influenced by the disability of an occupant and the mobility aid used, it would be useful to briefly analyse these factors. Disabilities can be roughly categorised into two basic groups: those that directly impair movement and those that only indirectly do so. Disabilities that directly impair movement range from impaired muscular co-ordination, through to loss of muscular action, to loss of all four limbs. One would expect the speeds of disabled people using the same mobility aid to decrease down this range, they would be faster when only the co-ordination of movement is impaired, and slower when the use of all four limbs has been lost. Of course, this actually depends on the mobility aid used, since for instance, if electric wheelchairs are being used, the speeds would probably be more or less the same.

Those disabilities that only indirectly impair movement, include conditions such as blindness which demands substantial mental effort in order to maintain direction; deafness which may cause an increase in response times due to a longer information gathering period or 'recognition phase' [29] when aural emergency alarms are used; mental retardedness, including the full range of drug- and alcohol-induced retardedness, as well as medical conditions such as senility, which similarly to deafness may increase response times and in addition, also impair muscular co-ordination.

Mobility aids can also be classed into two groups, those that by their nature define a maximum speed that can be achieved by the user of the appliance, for example, electric wheelchairs; and those whose maximum speeds are determined by the user of the appliance, for example, manual wheelchairs, walking sticks, guide dogs and crutches.

4.2 Evacuation Performance Index

The Evacuation Performance Index of a disabled person is defined as the relative ease of evacuating the disabled person compared to evacuating an able-bodied person.

The EPI of a disabled person can be viewed as being primarily dependant on three factors, the individual characteristics of the person, the amount and type of assistance provided to the person, and building design and environmental factors. Fig. 4.1 summarises in schematic form a view of the inter-relationships between the three factors.

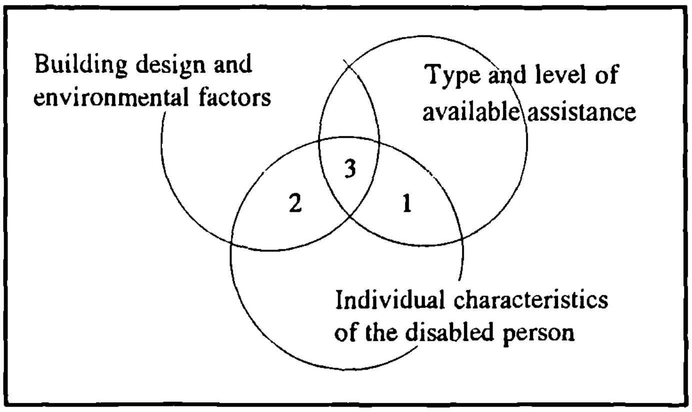

Fig. 4.1: Inter-relationship between factors affecting basic and effective EPIs

Region 1 of the diagram represents the assistance that may affect the evacuation performance of an evacuee, but which is independent of building design and environmental factors, for example, the assistance provided by pushing a wheelchair user in an empty foyer of a building. Region 2 denotes the building design and environmental factors which may affect evacuation performance independently of possible assistance that may be made available to the evacuee, for example, the unassisted movement of a blind occupant moving independently down a narrow crowded stairwell. In Region 3, there is full interaction between all three factors, and it seems that in most cases, design for safe evacuation of disabled people falls in this region [64].

There are various dimensions of EPI: basic, elemental, effective and total effective EPI. The basic EPI is a ratio of the unassisted speed of a disabled person compared to that of an able-bodied person along a straight and obstacle-free route of a pre-specified distance, represented by 'EPI'. The elemental EPI is the EPI at a given section of an escape route, such as an exit, represented by I_i. The three primary factors mentioned earlier impose constraints which might modify an occupant's basic EPI into an effective EPI, represented by I_M. The effective EPI provides a measure of evacuation performance which will be experienced in an actual emergency. The total effective EPI is a summation of effective EPIs over an entire escape route, represented by I_C.

4.3 Experimental Determination of Elemental EPIs for a Typical Evacuation Route

4.3.1 A brief description of the evacuation exercises

The occupants participating in the exercises were disabled students attending full-time courses at the University of Central Lancashire. They were volunteers from a group of students who were contacted by letter and invited to assist in the research programme. Although only six students responded, their contribution to the research programme provided invaluable insight into the design of experimental exercises that could be carried out with a larger population. The students, named participants (P1 - P6), took part in the experiments at particular intervals of the research programme when they were available. The author recorded their individual characteristics which included their gender, age groups, disabilities and mobility aids shown in Table 4.1. A briefing was given by the author, on the requirements of the exercises and the precautions that would be taken to ensure the safety of the participants.

Apart from these participants (P1 - P6), two others participated in later evacuations at different venues. Participant (P7) was an able-bodied person in a wheelchair and participant (P8) was an *EVAC* chair user suffering from multiple sclerosis (refer to section 4.3.2.5).

Table 4.1: Details of participants in the evacuation exercises

Person	Gender	Age	Disability	Mobility aid
P1[1]	Male	21-25	Blindness from birth	Stick
P2	Female	31-35	Damage to the part of the brain controlling muscular actions — requires considerable mental effort to co-ordinate movement. Impaired functioning of all four limbs, and retinal damage. (Cerebral palsy, quadriplegic and retro-entero fibroplasia)	Manual wheelchair
P3	Male	21-25	Brittle-bone syndrome (Osteogenesis imperfecta)	Electric wheelchair
P4	Female	15-20	Disabled lower limbs from birth	Manual wheelchair
P5	Female	25-30	Partially-sighted and profound deafness (use of an electrical ear implant)	None
P6	Female	31-35	Able-bodied	None

The evacuation route chosen for the author's study was in Harris Building (Fig. 4.2). It is the normal circulation route around the building used by staff and students attending lectures. The route was divided into discrete sections at which it was anticipated that EPI values would change significantly, namely: a room where the evacuation commenced, different types of exits (FD1 - FD3), a straight corridor (marked with letters U, V, W, X, Y and Z at 6m intervals) and a corridor with a 90° bend or corner. It must be noted that the terms 'exit' and 'door' are used interchangeably, in this exercise in the author's reference to fire doors, ordinary doors and other types of doors. However, in all the figures of the evacuation route, the exits are marked 'FD' for 'Fire Door'.

In an alternative venue, also an office building, evacuation of occupants down a stairwell was investigated.

[1]Participant (P1) took part in most of the evacuation exercises, but was unable to continue his participation for the rest of the programme since he left the University on completion of his course. An alternative occupant, who was blind and had a partial hearing impairment, participated in the remaining exercises in his place.

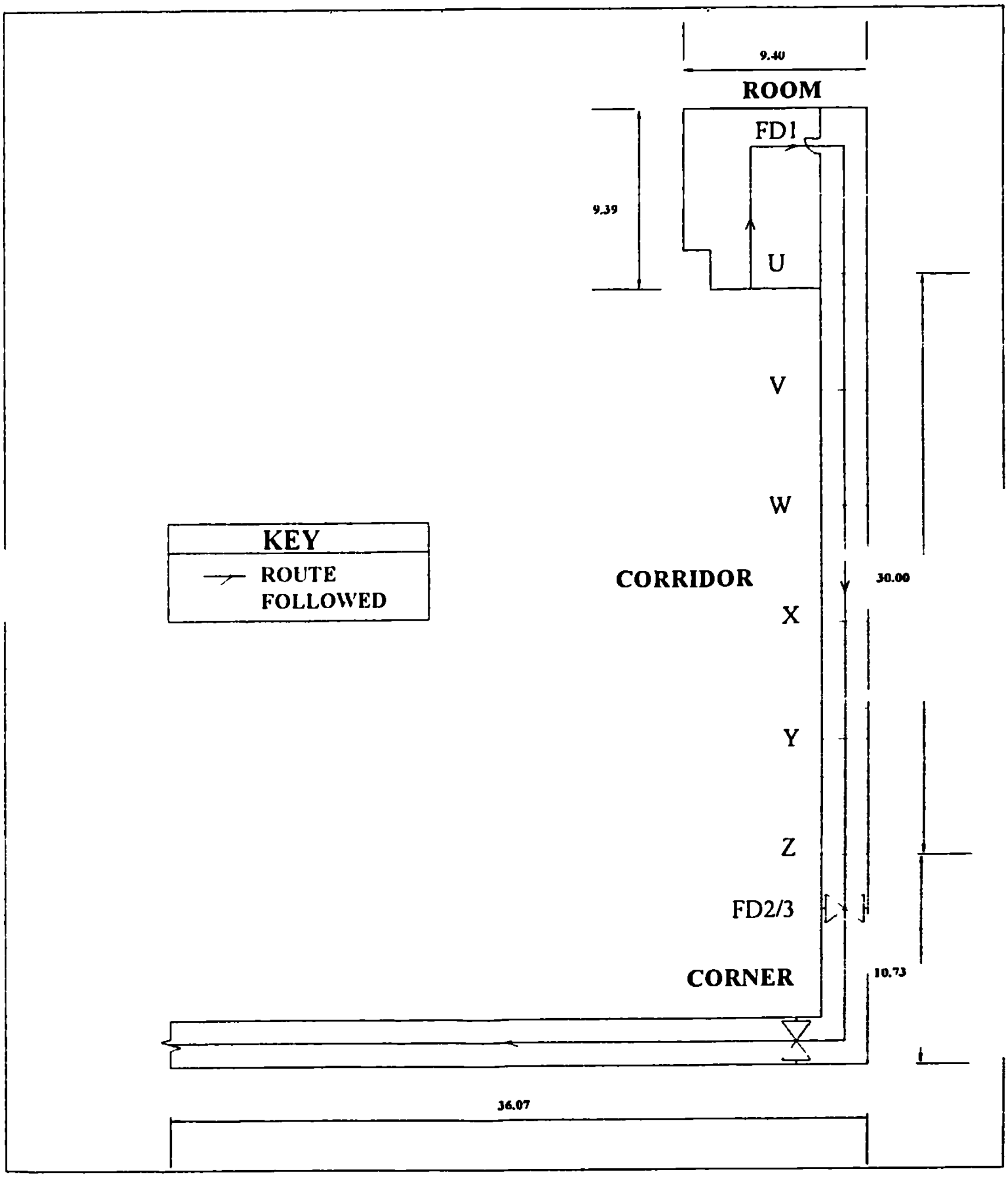

Fig. 4.2: Harris Building: The route followed by participants in the evacuation exercises

4.3.2 Methodology

Each participant in the exercise was required to move along the defined evacuation route while being monitored by a group of observers recording their times at pre-defined positions. The observers consisted of technician staff from the Department of Built Environment and volunteer students. A briefing was carried out regarding the required method of recording time values and measuring distances. The times were recorded using stopwatches some of which were Balmaster (sports-industry-research) 15-minute stopwatches and others were quartz digital stopwatches with minutes, seconds and mini-seconds. A video-tracking procedure for each participant was carried out in order to confirm time values recorded. Whereas fixed cameras would have been an ideal alternative at every corner of the route where there was a directional change, it was not possible to use these due to the restrictions in the number of cameras and the types of mounting frames available. However, the video-tracking method provided results that were adequate for the purpose of the experiment. The type of camera used was a Ferguson video camcorder using a conventional three-hour video tape. A 30m measuring tape was used to measure distances greater than 3m, while a 3m Rabone Chesterman BS 4484 measuring tape was used for the shorter distances.

The basis of the evacuation procedure was partially adopted from a study by Pearson and Joost [17] who compared the evacuation speeds of blind occupants, wheelchair users and able-bodied occupants in a residential setting. In their study, more sophisticated equipment was used, such as micro-switches located throughout the test facility and pressure sensitive mats for detecting occupant movement. Closed-circuit television cameras and a video recorder were also used to record movement. Both micro-switches and mats were connected through relay circuitry to an event (chart) recorder as well as to a timing circuitry. Coulbourn logic circuitry was used to time events to 0.01 second accuracy. This level of accuracy was unnecessarily high for the purposes of the experiment. The data required in this author's research programme did not require such accuracy and her time recordings which were within ±0.5 seconds of measurement which was considered reasonable. Distance measurements were taken to the nearest 1cm.

Over the 30m distance covered during the exercise, the maximum expected error or uncertainty in measuring distance and time was estimated to be about 3%. Time measurements recorded over the shortest distance of 6m resulted in errors of up to 18%. It was unlikely, however, that the uncertainty in speed would be in error by this amount in most of the cases, since these large errors were obtained from the worst combination of individual errors in time and distance measurements. In addition, comparatively large errors in time and distance would be expected during the participants' passage through each individual exit along the route. However, since these actions take a much shorter time than the time spent travelling down a long corridor it would be reasonable to assume that the overall error would be very much less. It is essential to note that because a small sample was used in the experimental procedure the results are not statistically significant but may be taken as indicative.

Other errors could have resulted from the alteration of the position of observers at the various points at which time recordings were taken. As the exercises were not all carried out on the same day, their positions during each individual session could have differed slightly. However, such errors could be considered minimal since the points at which readings were taken were clearly visible from the observer positions. As many precautions were taken as possible to ensure that all the ambient conditions remained the same for each participant.

The signals to start each evacuation session were given verbally and with the motion of a hand. It could be argued that any resulting delay, from the time the signal was given to the actual movement time, could have caused some errors. This time lapse was considered to be a fraction of the response time of each participant relating to their behaviour and initial gain in momentum.

The following discussion narrows down the experimental observation to each specific section of the evacuation route. It is at these sections that elemental EPIs are calculated for each participant. All EPIs were calculated relative to the able-bodied participant (P6). In Appendix A, a typical sample calculation is provided. The author begins the experimental description with the corridor at which basic EPIs of participants were measured. It seemed logical to start with basic EPIs along a straight obstacle-free route along which each participant would travel unassisted and uninhibited. In so doing it was possible to compare the basic EPIs with the elemental EPIs at the other sections of the route in order to realistically appreciate any variations in evacuation capability resulting from changes in the design features of the route. Therefore, the order of experiments described began with those carried out in the corridor followed by those at the 90° turn, followed by the room in which the evacuation started, the exits and finally the stairwell.

The main hypothesis to be tested were as follows:

Hypothesis (1): During the evacuation exercises, at each section of the route, significant differences in EPI will be exhibited across each disability-mobility aid combination.
Hypothesis (2): The elemental EPIs along the route will be significantly different for each disability-mobility aid combination represented.

4.3.2.1 The effects of corridors along the evacuation route

Corridors are a principal section of an evacuation route. The effects of their dimensions are felt in the presence of large populations because they tend to restrict the movement of occupants passing along them and cause bottlenecks during evacuations. The dimensions in question include: the width, length and configuration of corridors. Corridor width, in particular, determines the rate of flow of occupants. The normal capacity of a corridor is about 1.5 persons/m width /s [66].

In this section the parameter of interest is that of travel distances along corridors, selected because of their significance in the design of means of escape. According to building regulations [67], 'actual travel distance' is defined as the distance around any obstacles along a path that an occupant must travel between any point in a building and the nearest exit. On the other hand, 'direct travel distance' is defined as the shortest distance from a given point to the nearest exit. As a typical example of direct travel distances prescribed in the codes of practice, Tables 4.2 and 4.3 provide a range of direct travel distances for hotels and board care homes [67]. In the text, 'escape in one direction' implies that there is only one escape route from a given point a building while 'escape in more than one direction' means that there are alternative routes.

Table 4.2: Travel distances (m) for escape in more than one direction [67]

Category	From any point	Travel distance (Within room)	Travel distance (Total distance)
1	Sleeping area	15	32
2	Area of high fire risk	12	25
3	All other situations	18	35

Table 4.3: Travel distances (m) for escape in one direction only [67]

Category	From any point	Travel distance (Within room)	Travel distance (Total distance)
1	Sleeping area	8	16
2	Area of high fire risk	6	12
3	All other situations	9	18

Maximum direct travel distances in dwellings are 7.5m for escape in one direction and 30m for escape in more than one direction [55]. The travel distances investigated in this study are within the above mentioned ranges.

The author investigated travel along a corridor 30m long marked at 6m intervals in order to monitor EPI changes with variations in travel distance.

Experimental procedure used to investigate the effects of travel distances on EPI

The 6m intervals along the route were marked with white tape of 1cm width at positions U, V, W, X, Y and Z (Fig. 4.2). The six participants in the exercise were required to move along this route while an observer recorded the time taken to cross each demarcation using a digital quartz stopwatch. A video-tracking procedure using a video camera was carried out to trace each participant's movement. The journey was continuous and uninterrupted over the 30m distance. Average times of each participant were calculated over three sessions and their EPIs were obtained. The author expected no significant change in the EPI of each participant over the distances covered. The results obtained were averaged over the three sessions (Fig. 4.3):

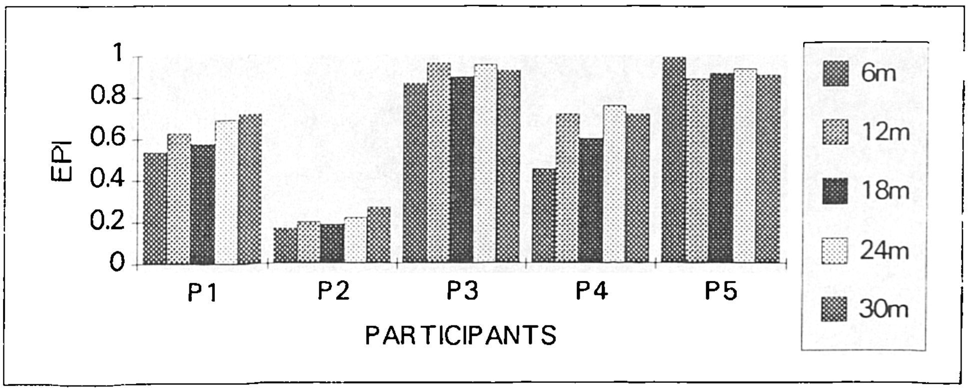

Fig 4.3: EPIs of participants over a range of travel distances

The mean EPIs, the standard deviation and variances of each participant's EPIs are shown in Table 4.4.

Table 4.4: Means, standard deviations and variances of EPIs of participants over range of travel distances

Participants	Mean	Standard deviation	Variance
P1	0.63	0.07	0.006
P2	0.21	0.04	0.001
P3	0.93	0.04	0.002
P4	0.65	0.13	0.016
P5	0.93	0.04	0.002

This exercise verifies the first hypothesis, stated earlier, concerning the significant variation in EPIs across most combinations. The differences in EPI across the range of disability-mobility aid combinations represented were quite significant and the standard deviation of mean EPIs of all the participants was 0.30. As the author anticipated, there were no significant changes in EPI for each participant over the range of distances travelled which was confirmed by the relatively small standard deviations obtained (Table 4.4). These results show that the distances at which EPIs might have began to show some notable change for each combination are probably much greater than maximum distances prescribed in the Building Regulations [67]. EPIs could be thus be assumed to be independent of typical travel distances alone along conventional corridors although they would be expected to differ for each disability-mobility aid combination.

The results reveal that the disabled participants with the highest mean EPIs were participant (P5), the partially-sighted participant and participant (P3), the electric wheelchair user. The EPI of the latter was significantly higher than those of the manual wheelchair users, participants (P2) and (P4). The motorised wheelchair which he used did not require much manoeuvring along a straight route and therefore he could move relatively quickly on his own. Participant (P4) also had a higher EPI than participant (P2). This could be attributed to the fact that quadriplegia and cerebral palsy, from which participant (P2) suffered, result in reduced muscle development and muscular co-ordination, both making movement for this participant very difficult. Participant (P4) on the other hand suffered from a limb impairment. These differences in EPIs emphasise the fact that considered alone, mobility aids are only partial indicators of evacuation capability. This strengthens the case for the evident need of a classification system that does not rashly classify occupants according to the mobility aids they use but also considers the effects of their respective disabilities.

The maximum expected error in EPI was 18% in this exercise. This was because of the 6m distance covered during certain sessions of the exercise. This indicates the need to use a range of sufficiently large distances when carrying out exercises to determine EPIs in order to reduce likely errors.

The following experiments demonstrate notable changes in EPI when the design of the evacuation route changes.

4.3.2.2 The effects of bends and corners along the evacuation route on EPI

The presence of bends and corners that dictate the angles around which occupants must turn when travelling along an evacuation route may have an effect on EPI. However, Togawa argues [44] that slight projections along corridors and corners or bends have little or no effect on flow rates in crowded situations. The only changes experienced are reductions in occupant speed and occupant density increases on the inside of the bend, and a decrease in occupant speed and reduction in crowd density on the outside of the bend. This implies that in densely populated situations EPIs are likely to differ along a 'cross section' of a crowd at a bend or corner. Average EPIs, however, would not be expected to change.

A simple example of a situation that would warrant a change in direction, and therefore require some deviation from the direction of travel, is the discovery of an impassable route by an occupant during a fire emergency. The occupant could take a turn to move in the opposite direction and in so doing transcribe a 180° angle of turn. In more specific terms, the angle of turn is defined as the angle through which a person turns relative to his/her original direction of motion (Fig. 4.4).

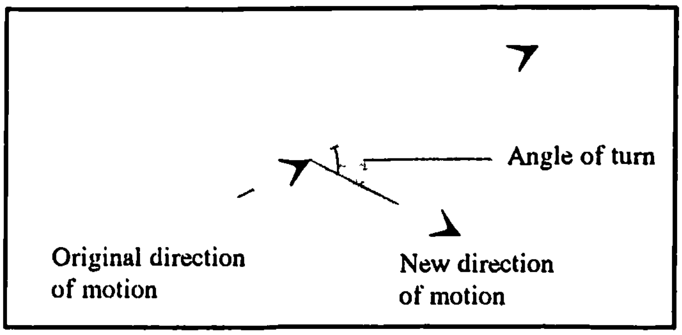

Fig. 4.4: Definition of angle of turn

Experimental procedure used to investigate the effects of a 90° angle of turn on EPI

The author investigated the evacuation capability of the six participants transcribing an angle of turn of 90° along the corridor of the evacuation route described previously (Fig. 4.3). The reason for choosing the 90° angle of turn or corner in this exercise is that it is the most frequent turn made along a corridor whenever there is a change in direction. The distance covered by the participants moving around the corner was about 18m. A sufficiently large distance was used to ensure that any errors in measurement were minimised.

The timed movement of each of the six participants was recorded by an observer as the participants moved along the pre-defined route. The observer recorded the time at which each participant to crossed a white tape of 1cm thickness marking the start and finish point. All doors along the route were propped open to guarantee unhindered movement along the route. The results obtained are shown in Table 4.5

Table 4.5: Comparison of EPIs of participants along straight corridor and around the 90° angle of turn

Participants	EPI (Basic)	EPI (90° turn)	% Δ EPI
P1	0.63	0.39	38
P2	0.21	0.11	48
P3	0.93	0.87	6
P4	0.65	0.41	37
P5	0.93	0.89	4

where, % Δ EPI = percentage difference in EPI

Again there is evidence of significantly different EPIs across the disability-mobility aid combinations represented, in agreement with the first hypothesis. The standard deviation of EPIs was 0.34 and the range was 0.78. The second hypothesis is also verified from the distinct difference in EPIs experienced by most of the participants as a result of the design change from a straight corridor to a corner.

The comparison between the basic EPIs, along the straight unobstructed route in the previous exercise and the effective EPI resulting from a corner along the route, showed significant drops at the corner in the case of participants (P1), (P2) and (P4). This would be expected given the change in direction and the activity associated with moving around a corner particularly with the help of a mobility aid. This would not apply to the partially-sighted participant (P5) who did not use a mobility aid and whose movement around the corner did not require much manoeuvring. The largest drop in EPI of nearly 50% was experienced by participant (P2). This change in the evacuation route was significant for her and she required greater mental concentration as well as greater muscular effort in making the turn. The comparatively smaller drop experienced by the electric wheelchair user, participant (P3), could be explained by the easy operation of the motorised mechanism used to travel around corners. The operation of a lever to make right-angled turns is an easier manoeuvre than moving a manual wheelchair which requires an irregular transmission of forces to the wheels.

It is reasonable to suggest that the number of corners or bends along a route are likely to influence the frequency of changes in EPI. This information could be useful to building designers planning configurations of evacuation routes at the drawing board stage. In existing buildings, the changes in EPI with angle of turn could assess the efficiency of suggested escape routes, particularly in situations where there is a wide choice of routes. The above results suggest that from a given point in a building the direction of escape chosen by an occupant may lower or increase his/her escape potential. An additional design factor is highlighted here, that of giving extra consideration to the positioning of call points, telephones, door handles, lift buttons and all other appliances that need to be used during evacuations. Certain angles of turn would be transcribed to reach these appliances from any given point and any resulting changes in EPI could provide an indication of the ideal positions to place them. As a result, during emergencies an arrangement that encourages maximal speeds and efficient evacuation procedures could be adopted.

The maximum expected error in speed measurement, 12%, was calculated from the data of the fastest moving participants (P3) and (P5), which was much lower than the maximum likely error in the previous exercise.

4.3.2.3 The effects of room arrangements where occupants commence evacuation

The positioning of furniture in a room is particularly important from the point of view of evacuation planning. Furniture arrangements depend primarily on the purpose of a given room. According to Shields [5], "..creation of hostile environments in many residential buildings by the injudious location of room doors and arrangement of furniture will significantly influence the escape potential of disabled people in an emergency". Sime [68] adds that inaccessible or 'handicapping' environments are not necessarily related to the disability an occupant has. He contends that, ".. in a sense we are all handicapped if a building is designed in such a way that we cannot use it in an optimum fashion....".

As a result of different furniture arrangements, two patterns of approach to an exit are discussed in a movement model developed by Takahashi, Tanaka and Kose [41]: the L-shaped and the centripetal approaches. These were briefly introduced in Chapter 3. The patterns of approach resulted from two different styles of furniture arrangements. The L-shaped approach is a result of tiered seating, for example, as in a typical theatre setting. It is likely that an occupant furthest away from the exit would avoid the obstacles in his path when approaching the exit and would therefore make his/her way around the room, and in so doing, trace an L-shape as shown in Fig. 4.5(a). The top half of the figure shows a room with two exits that is divided into two parts. A room is divided into parts, which are treated independently, when there are multiple exits in order to simplify the analysis. The width and length of each part are represented by a and b respectively. Initially, there is a uniform distribution of occupants in each part. All occupants start to move towards the exit simultaneously during an emergency Travelling in 'L' stages each person must cover a distance vt in approaching an exit given that the average velocity of all occupants is v at time t. In the time lapse considered any occupant within the locus vt will reach the exit. This is the shaded area in the figure.

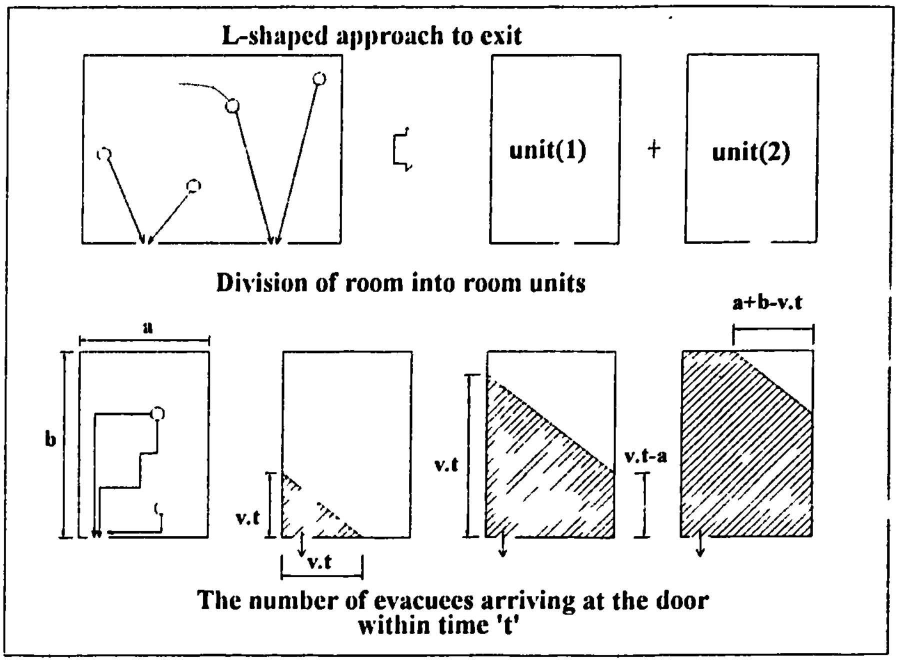

Fig. 4.5(a): L-shaped approach of occupants to exit (adopted from Takahashi et al. [41])

The number of occupants reaching the exit in time t is derived by using geometric relationships shown in the equation below:

$$P = \begin{cases} \rho\{\frac{(vt)^2}{2}\}, \dots\dots\dots\dots (0 < vt \le a) \\ \rho\{\frac{a^2}{2} + a(vt - a)\}, \dots\dots\dots\dots (a < vt \le b) \\ \rho\{ab - \frac{(a+b-vt)^2}{2}\}, \dots\dots\dots\dots (b < vt \le a+b) \end{cases}$$

where,

a = width of the unit (m)

b = length of the unit (m)

t = lapse time from the start to the time to reach the exit (s)

v = average walking speed (normally assumed to be 1.3 m/s [6])

ρ = density of evacuees (persons/m²)

P = number of occupants arriving at the door of the room by time t (persons)

The parameter of interest is v which is the average occupant speed. Takahashi et al. assume that v remains constant throughout the scenario.

The second pattern of movement, the centripetal approach, results from a furniture arrangement in which there are a few or no obstacles in the path of movement, for example, in a gymnasium. The centripetal approach of occupants to the door is shown in Fig. 4.5(b) in which a given room is also divided into two parts, with each part treated independently. In this case, the exit of the room is not at a corner. The room can therefore be regarded as a combination of the two parts with an exit at the corner of each part. The absence of obstacles along the route means that a locus, the shape of a sector, is covered by occupants who reach an exit in time t. The centre of the sector is the exit of a given part.

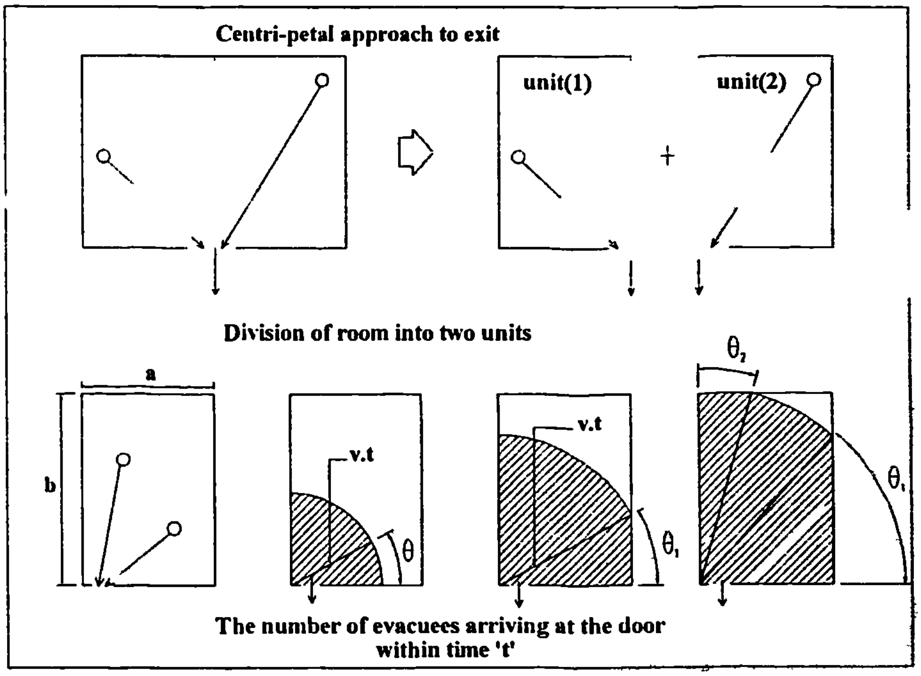

Fig. 4.5(b): Centripetal approach of occupants to exit (adopted from Takahashi et al. [41])

The number of occupants arriving at the exit at time t for each unit is given in the following equation:

$$
P = \begin{cases}
\rho\left\{\dfrac{\pi(vt)^2}{4}\right\}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (0 < vt \le a) \\
\rho\left\{\dfrac{(avt)\sin\theta_1}{2} + (vt)^2\dfrac{(\frac{\pi}{2} - \theta_1)}{2}\right\}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (a < vt \le b) \\
\rho\left\{\dfrac{(avt)\sin\theta_1}{2} + (vt)^2\dfrac{\left(\frac{\pi}{2} - \theta_1 - \theta_2\right)}{2} + \dfrac{(bvt)\sin\theta_2}{2}\right\}, \ldots\ldots \left(b < vt \le \sqrt{a^2 + b^2}\right)
\end{cases}
$$

$$
\theta_1 = \cos^{-1}\left(\frac{a}{vt}\right),
$$

$$
\theta_2 = \cos^{-1}\left(\frac{b}{vt}\right)
$$

Similar to the L-shaped approach, v is again the critical parameter and is assumed to be constant. As occupants with various disability-mobility aid combinations will have different speeds, it is essential to determine the nominal speeds for each combination. With such values, more accurate evacuation time predictions would be obtained for a given scenario.

For small rooms it is possible to relate EPI values to the arrangement of obstacles in a room by explicitly defining patterns of movement around various furniture arrangements and monitoring resulting occupant movement. The following section describes an experimental setting in which the movement of occupants around various arrangements in a room was observed and recorded. The author used three different arrangements around which occupants were required to find their way from a given starting point. The purpose of the exercise was to demonstrate the variations in EPIs with different arrangements.

The difficulties anticipated in planning this experiment included the attempt to accurately trace each occupant's path of movement. It was unlikely that every occupant would follow an identical path from the starting point to the exit. For example, wheelchair users moving around corners or bends tend to follow an arc-shaped path whereas an able-bodied occupant, without a mobility aid, is likely to make a sharper turn more easily. The overall distance covered by the able-bodied occupant is therefore likely to be less than the distance covered by the wheelchair user. However, in this exercise the differences in distance were considered to be negligible

Experimental procedure used to investigate the effects of different furniture arrangements on EPI

The room layouts in Figs. 4.6, 4.7 and 4.8 show the three different arrangements used in the exercise. The first is typical of a cafeteria with round tables placed in a staggered fashion (Fig 4.6). The second and third arrangements represent a simple assembly room and a classroom layout respectively (Figs. 4.6 and 4.7). Each participant in the exercise was required to move from the starting point (SP) to the exit and the time for each one to cover this distance was recorded by observers whose positions are shown in the figures, for example, (OB1). The participants were required to carry out the exercise three times for each arrangement. The EPIs of each participant for each furniture arrangement were measured from the starting point (SP) to the exit of the room (Table 4.6). A graphic pattern of EPIs for all the arrangements is shown in Fig 4.9.

Table 4.6: EPIs of participants for each furniture arrangement

	Arrangement 1	Arrangement 2	Arrangement 3
Blind participant (P1)	0.32	0.45	0.28
Manual wheelchair user (P2)	0.10	0.23	0.12
Electric w/chair user (P3)	0.60	0.83	0.71
Manual wheelchair user (P4)	0.50	0.77	0.71
Partially-sighted and deaf part.(P5)	0.75	0.77	0.83

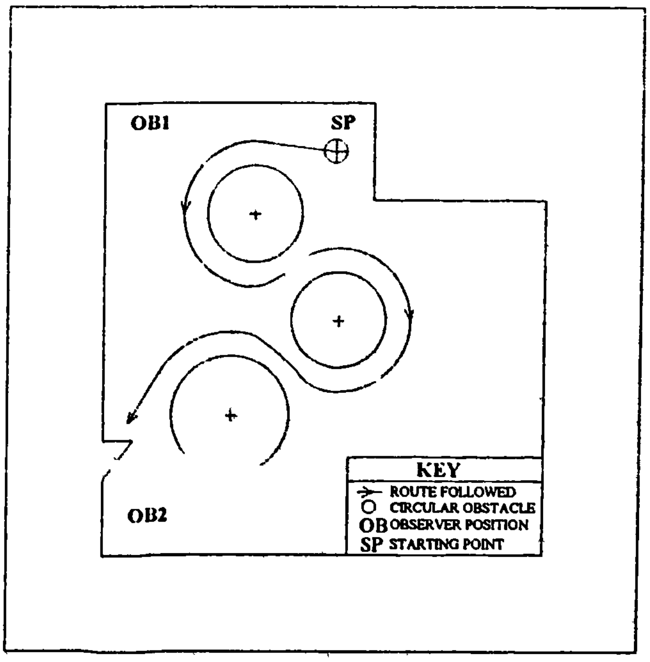

Fig. 4.6: Arrangement 1 of furniture in the room where evacuation commenced

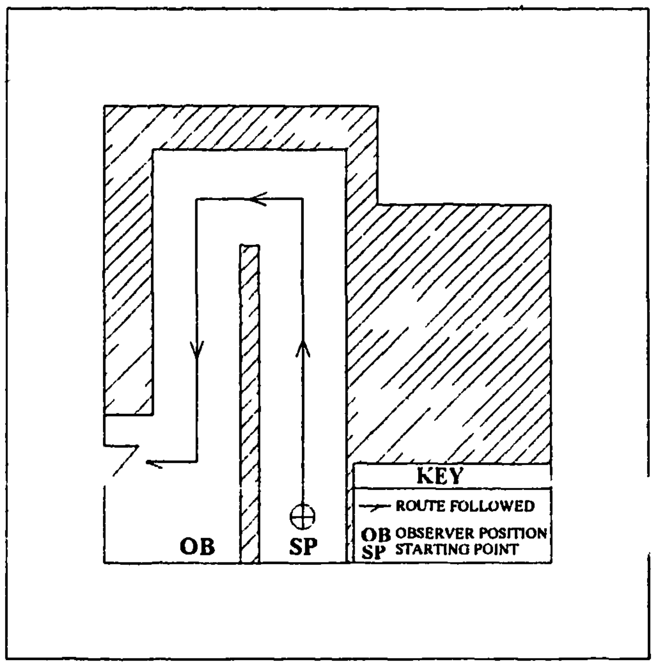

Fig. 4.7: Arrangement 2 of furniture in the room where evacuation commenced

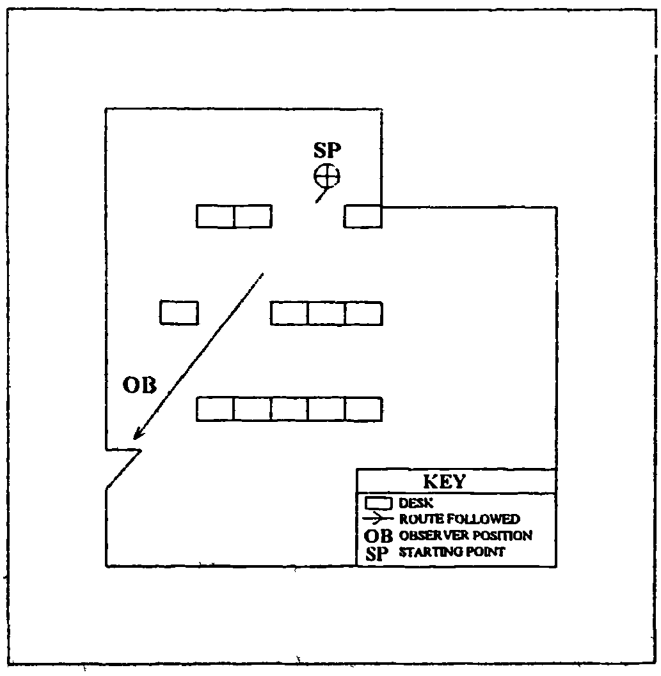

Fig. 4.8: Arrangement 3 of furniture in the room where evacuation commenced

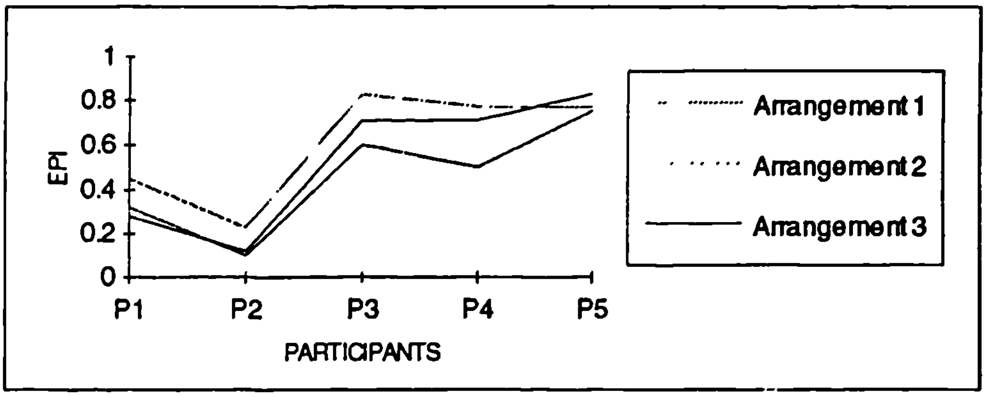

Fig. 4.9: Pattern of EPIs of participants for each furniture arrangement

Once again there was a distinct difference in EPIs represented across each disability-mobility aid combination and the previously observed difference in EPIs of the two manual wheelchair users was evident. This is in agreement with the first hypothesis The evident modification of basic EPIs as a result of the variation in building design resulting from a given furniture arrangement reinforces the point that disability-mobility aid combinations are not sole determinants of evacuation capability. The effects of building design in modifying EPIs is so far evident and in agreement with the second hypothesis.

An interesting observation from the results showed that the patterns of EPIs across the disability-mobility aid combinations represented were similar for all the arrangements (Fig. 4.9). Variations in each participant's EPI for the different arrangements were evident but were not very large. The largest range and variance observed was 0.21 and 0 02 respectively. This result has design implications in that for any arrangement desired in a building, a mean EPI ± a certain percentage could be used for each disability-mobility aid combination represented unless, of course, the EPIs for the specific arrangement are available.

Lowest EPI of 0.10 was obtained by participant (P2), a manual wheelchair user, during the evacuation in which Arrangement 1, was used. This arrangement had several circular turns requiring much effort to manoeuvre. All the other occupants obtained the lowest EPI, with the exception of participant (P1), for this same arrangement. The blind participant (P1) experienced difficulty in moving around the arrangement as his walking cane would occasionally get caught in the legs of the chairs or other protruding parts of the furniture. It was also difficult for him to construct a mental layout of the arrangement during the exercise. This is an indication of the difficulty that is sometimes experienced by totally blind occupants in moving around an unfamiliar environment with a complex arrangement. The EPI concept highlights specific problems experienced by occupants with different disabilities and indirectly provides a measure of their difficulties

The maximum possible error in this experiment was 4%. Much lower errors were evident in the calculations of EPI with Arrangements 1 and 2.

4.3.2.4 The effects of exits along the evacuation route on EPI

Four main factors influence occupant movement through exits: the time spent passing through the exit when unobstructed, the width, the position and the type of exit. Although the action of passing through an exit is of a relatively short duration, the design of an exit is important because, like corridors, in crowded situations bottlenecks often occur and change the pattern of movement of occupants. The resulting effect is that longer evacuation times are experienced

Exit width is an important dimensional parameter affecting occupant movement. A range of exit dimensions is suggested in the British Standards [69] which are generally adequate for an able-bodied population. At the present time there are no standard methods for determining appropriate exit widths that have been borne out of empirical studies of occupant movement through exits, that is, occupants with various disabilities. Needless to say the spatial requirements of those using various mobility aids differ significantly, with evident difficulty experienced by wheelchair users passing through narrow exits, for instance. Manual wheelchair users utilising their own efforts to propel themselves forward generally require additional 'elbow space' when passing through an exit.

The positioning of an exit is likely to influence occupants' evacuation route choice. There are two main orientations of exits: centrally-placed and remotely-placed exits. Centrally-placed exits are generally directly visible to occupants who are more likely to use them during an emergency. Remotely-placed exits may not be used for normal entry into or exit from a building and are likely to be used only by occupants who are very familiar with the building layout.

In theory the easiest exit for all occupants to use is an automatic door since no muscular or mental activity is required by a user. Therefore, if an occupant moves along a corridor with such an exit or door in the path of movement, the occupant's EPI may not change significantly during movement through the exit since no extra time-consuming activity is required. This condition applies providing that the mechanism used to open the door does not fail. If it does fail, the EPI is zero for all occupants attempting to use the door unless it can be opened manually. However, one would expect that the slowing down action experienced on approaching an ordinary exit would reduce EPIs slightly, particularly if some action is required to open the door, for example, twisting, turning, pushing or pulling of a handle.

The mechanical effort required to open a door is also an important consideration Some occupants have disabilities that hinder their ability to comfortably open doors. The reaching, turning and twisting action may be difficult for an occupant with poor muscular co-ordination, for example. In such a case, if the disabled person is not assisted with opening a door, their EPI at that point is zero. An analysis of actions required to move through different types of doors is discussed in the following section. The author discusses three different exit types and proposes a method for calculating EPIs of occupants using them

Experimental procedure used to investigate the effects of exit types on EPI

Certain primary actions are required when passing through exits. The main actions identified by the author include·

- approaching the exit from a 2m distance, the estimated distance at which an occupant would normally begin to slow down to open a door,

- making contact with the handle,

- moving through the door past the line defining its position, and

- accelerating up to 2m away from the door having passed through the door.

The 2m distance suggested for the approach to and the acceleration from an exit was obtained from the observation of occupant movement through exits filmed on video camera. The author observed occupant movement through three different exit types and recorded the time taken for the six participants to carry out the four primary actions described above. The exit types considered included a door with a turning handle at 0.88m height, one that required a pulling action and another that required a pushing action, both with handles at 1.17m height. The above mentioned 2m distances were measured using a 3m measuring tape and were marked across the width of the floor on either side of the exit using white tape of 1cm width. Each participant was required to cross the first 2m line, make contact with the door and after opening it move through it to cross the final 2m mark. An observer (OB) in Fig. 4.8 recorded the time for each participant to cross each pre-determined point marked A, B and C. The time recorded in each case was the actual time at which a participant first crossed the tape. In order to obtain accurate time values, video recordings were taken of each participant in the exercise. The key time values were the starting time when each participant received a verbal and hand signal to move and the time at which the final 2m mark was crossed. The EPIs for each participant were obtained as shown in Table 4.7

Table 4.7: EPIs of participants for each exit type

	Exit 1	Exit 2	Exit 3
Blind participant (P1)	0.75	1	-
Manual wheelchair user (P2)	0.17	0.28	0.19
Electric w/chair user (P3)	0	0	0
Manual wheelchair user (P4)	0.40	0.67	-
Partially-sighted and deaf part.(P5)	0.96	0.86	0.88

The exit types were as described below:

Exit 1 = twisting/turning action to open door

Exit 2 = pushing action to open door

Exit 3 = pulling action to open door

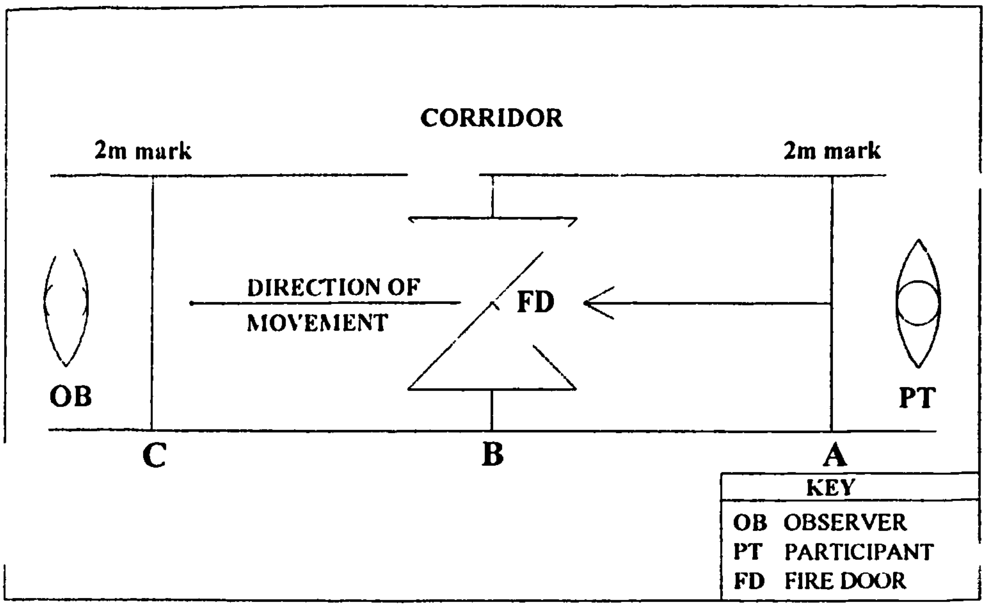

Fig. 4.10: Experimental layout for observation of occupant movement through exits

Notable variations in EPI were obtained across the different disability-mobility aid combinations represented in agreement with the first hypothesis. As the results demonstrate, the type of exit used as part of an evacuation route is an important design consideration because of evident changes in EPI when different exits are used. On average the EPIs obtained for the push or pull doors were higher than the those obtained for the door with a twist mechanism. Most conventional fire doors along corridors appear to be 'push' and/or 'pull' doors, which is ideal. As suggested in the previous experiment with the furniture arrangement, an average EPI ± a certain percentage could be used as a design value for each exit since the variation in EPI for each combination was small.

The maximum error in EPI calculation was 2%. This error was obtained from the shortest time taken by participant (P6) during the evacuation involving the use of a door with a pushing action. Due to unavoidable circumstances the author was unable to record data at Exit 3 for participants (P1) and (P4). This was because during this part of the research study the co-ordination of times when participants could attend the evacuation sessions and the availability of the premises was rather difficult. Thus the data for Exit 3 could not be obtained for the mentioned participants.

4.3.2.5 The effects of stairwells along the evacuation route on EPI

Stairwells are an important section of an evacuation route because they are a starting point for vertical evacuation which may be a barrier for occupants with mobility problems. Wherever a stairwell begins, EPIs are likely to alter considerably for various classes of disabled people. Even among groups of occupants who do not use mobility aids there may be difficulties experienced in moving down stairwells for psychological reasons. Canadian studies [12] in high-rise office buildings have shown that at least 3% of the building population cannot or should not evacuate unassisted down stairwells due to apparent and non-apparent disabilities.

The design parameters of stairwells that are believed to significantly influence occupant movement include· the width of the stairwell, tread and riser dimensions, handrail heights and the length and configuration of a stairwell. It is interesting to note that a stairwell comprises a combination of a sloping section along the treads and a level surface on the landings and at the corners. It also has a series of points at which occupants are compelled to change their direction of travel. It is inevitable that occupant speed would change at each of these sections.

Strictly speaking, only when occupants are unassisted in their movement down stairwells will their EPIs in the stairwells be considered valid. However, occupants using mobility aids, such as wheelchairs, would require assistance in moving down a stairwell in the first place and so their EPIs would be zero if no assistance was provided.

The author designed different evacuation exercises to analyse the movement of occupants down stairwells. In the first exercise the movement of participant (P5), the partially-sighted occupant with an auditory impairment, was observed. The second exercise involved the evacuation of a wheelchair user down a stairwell assisted by two fire marshals, participant (P7). This participant was a staff member at Bolton Health Authority office building where the exercise was carried out [70]. Sime [71] carried out a similar evacuation study prior to the author's in which he participated as a wheelchair user being assisted down a stairwell. The EPIs obtained along the stairwells in the above three studies is shown in Figs. 4.12 - 4.14. The author compared these exercises to the evacuation of an occupant in an *EVAC* chair, participant (P8) who was a member of staff, at Palatine House in Preston [72]. The exercise was monitored in order to observe any major differences in the evacuation procedures used. An *EVAC* chair is a device used primarily to assist disabled people down a stairwell (Fig. 4.11). It is composed of a premium flame-resistant, vinyl-coated nylon seat with a safety belt. Its operating principle briefly entails the interface of continuous belting to rear carriages which contain a smooth, continuously working braking system allowing controlled descent down a stairwell. At each landing it can be moved on two six-inch diameter polyurethane moulded wheels at the base [73]. An occupant placed in an *EVAC* chair would be seated upright and would be supported by one or two assistants behind the chair.

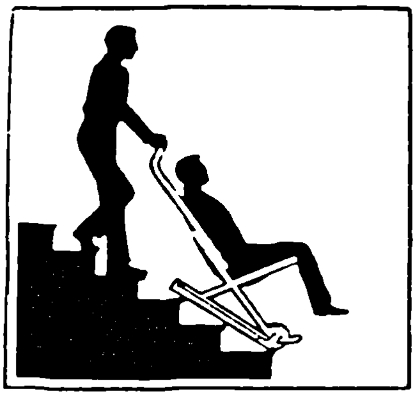

Fig. 4.11: Diagram of *EVAC* chair in use (adopted from PARAID [73])

Experimental procedure used to monitor occupant movement down a stairwell

The method of determining EPIs involved the observation and timing of occupant movement at pre-determined points in the stairwell. These points included the starting point at the top of the stairwell and then, the first and last step on each landing and finally the base of the stairwell. The reason for selecting these points was the anticipated variation in EPIs due to changes in the gradient and direction of the route.

In the first exercise participant (P5) was required to evacuate down a stairwell of a four-storey building. The stairwell had a width of 0.985m width between the handrails. As the participant descended the stairwell, the author followed and recorded times at each pre-determined point using a quartz digital stopwatch. The evacuation exercise was repeated and the average times were calculated (Fig. 4.12).

In the second exercise a wheelchair user, participant (P7), was evacuated down a stairwell of 0.975m width between the handrails, assisted by two fire marshals. The given scenario was a fire drill in an office building during which all able-bodied occupants evacuated first and were followed by the assisted wheelchair user (Fig. 4.13). In Sime's study, he acted as a wheelchair who was evacuated down the main stairwell of a six-storey office building (Fig. 4.14).

In the final exercise the author observed the *EVAC* chair user, participant (P8), being evacuated down a section of a ten-storey building via the main stairwell. She recorded the times taken at the landings and floors over two storeys and calculated the occupant's EPI over this distance In this scenario the author was present purely for observational purposes during a routine fire drill and therefore had no control over the running of the exercise and the distances covered during the evacuation. Due to the fact that the evacuation was only two storeys, a figure showing the EPIs along each section of the route is not included

The EPIs of participant (P5) were calculated at each pre-determined point and a profile of the variations in EPI was derived (Fig 4.12) The values on the x-axis ranging from 1 to 9 corresponded to EPIs on the y-axis, beginning with the 1st EPI value having been calculated over the distance from the top of the stairwell to the first landing. This same method of calculation progressed in obtaining the EPIs for all the remaining positions shown on the x-axis.

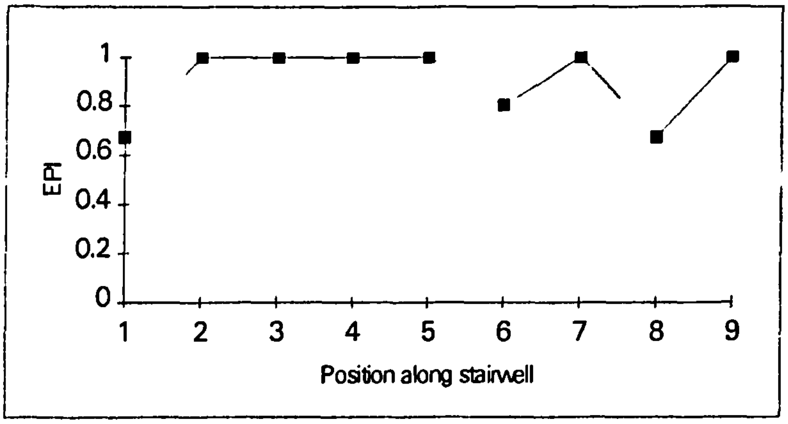

Fig 4.12: EPIs of partially-sighted participant (P5) along stairwell

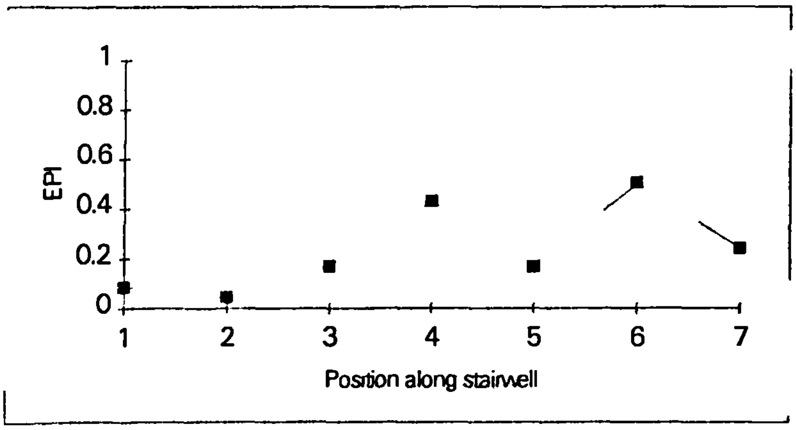

Fig 4.13: EPIs of wheelchair user (P7) evacuated down stairwell (Author's study [70])

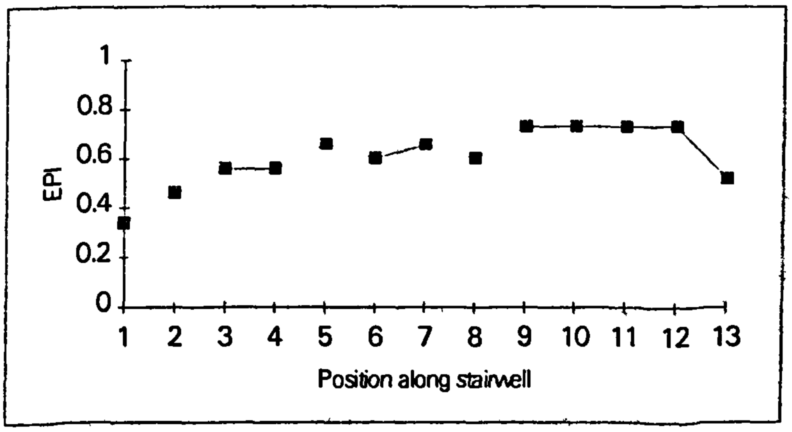

Fig 4.14: EPIs of wheelchair user evacuated down stairwell (Sime's study [71])

No conclusive result could be drawn from the profiles (Fig. 4.12 - 4.14). The general observation made, however, was that a regular pattern of change in EPIs developed at some point during the evacuation in all three cases.

Rather than sub-dividing each section of a stairwell and recording speeds at specific sections, the EPIs of the occupants could be calculated over the entire stairwell. The EPI of the partially-sighted participant (P5) in this case would be 0.92, using average speed values. In comparison, the wheelchair user (P7) had an EPI of 0.30 and the *EVAC* chair user (P8) had an EPI of 0.62, calculated over two storeys not including transfer time of the user into the chair. This strengthens the case for the use of an *EVAC* chair to evacuate down stairwells because of the higher EPI. However, not all wheelchair users appreciate being transferred from their chairs to an alternative device. Comparing these to previous results the evacuation capability of participant (P5) did not change significantly at the stairwell. Overall, the EPIs in this exercise were significantly different for the classes of disability represented.

In situations where there are adverse changes in EPI along a stairwell, the design of the stairwell should be scrutinised more carefully. For example, the amount of space available to turn comfortably at a corner on a landing while carrying a wheelchair user is usually rather limited and creates difficulty for those assisting. Various solutions could be sought to avoid this negative effect on evacuation procedure, such as, changing the carrying technique at a given point along the route or by using a different carrying device. Otherwise, at the drawing board stage the dimensions of the landing could be altered. The latter solution would be more suitable if there was a large percentage of wheelchair users who would need to be evacuated using a stairwell in a given building.

Summary of experimental section

The results from the experimental exercises described in this section demonstrate the value of the EPI concept by emphasising the following crucial points:

1. The 'intrinsic speed' and therefore the EPI of an occupant is primarily though not entirely dependent on his/her disability-mobility aid combination. There were notable differences in EPI represented across the different combinations for all the

activities carried out in the evacuations. This was in agreement with the first hypothesis and was evident in the experimental findings.

2 In agreement with the second hypothesis, it is evident that modifications in building design bring about notable changes in EPIs across the various disability-mobility aid combinations. The largest range in EPIs for a given combination was 0.93, exhibited by participant (P3). Thus by deconstructing a given evacuation route, the measured elemental EPIs of occupants at each section demonstrate the influence of building design on EPIs.

3. Hinks [61] encourages a hierarchical classification of parameters affecting evacuation capability and an assessment of their effects The EPI concept has this capability and can be used as a tool to prioritise the parameters.

4 With regard to travel distances and EPIs, there was no significant change in EPI with distance travelled by each participant.

5 For a given section of the evacuation route, for example, in the room where the evacuation commenced, although the EPI values for each combination varied over the three arrangements considered, the <u>patterns</u> of EPIs did not change significantly Moreover, the changes in EPI were not very large. The largest variation obtained was 0.02. This implied that a mean EPI ± a certain percentage, perhaps 2% obtained from the largest variation, could be used as a design value for furniture arrangements

6. Handicapping environments have been defined qualitatively as those environments which are difficult for disabled people to move around. The EPI concept is capable of providing a measure for deciding acceptable levels of accessibility in building layouts.

The following section discusses the combinations of elemental EPIs to obtain a total effective EPI of occupants moving along an entire evacuation route.

4.4 Application of Elemental EPIs in Determining Total Evacuation Times

Having computed all the elemental EPIs of the participants in the exercise along a typical evacuation route, the next logical step is to obtain a total effective EPI. These values will enable the total evacuation time of a given participant moving along a given escape route to be determined. The total evacuation time for each occupant, in this research study, can be briefly defined as the total time taken by individuals representing a given disability-mobility aid combination to evacuate along a given route. Alternatively a profile of these elemental EPIs could be obtained in order to emphasis the variations in EPI along the route An EPI profile is a graphical representation of the variations in evacuation capability experienced by an occupant travelling along a given route Both concepts of an EPI profile and a total effective EPI are explained more fully in the next section and their implications on total evacuation times are discussed

4 4 1 Description of profiles of elemental EPIs

A profile provides a vivid picture of the changes in evacuation capability experienced by occupants in progressive stages along a route. Two primary methods of deriving profiles are evident and are described briefly, referencing five of the six participants (P1 - P5) in the evacuation exercises carried out in this chapter.

1 The first method shows all the elemental EPIs of the participants along the route travelled These elemental EPIs are obtained from section 4.3 and are combined for each participant (Fig 4.15)

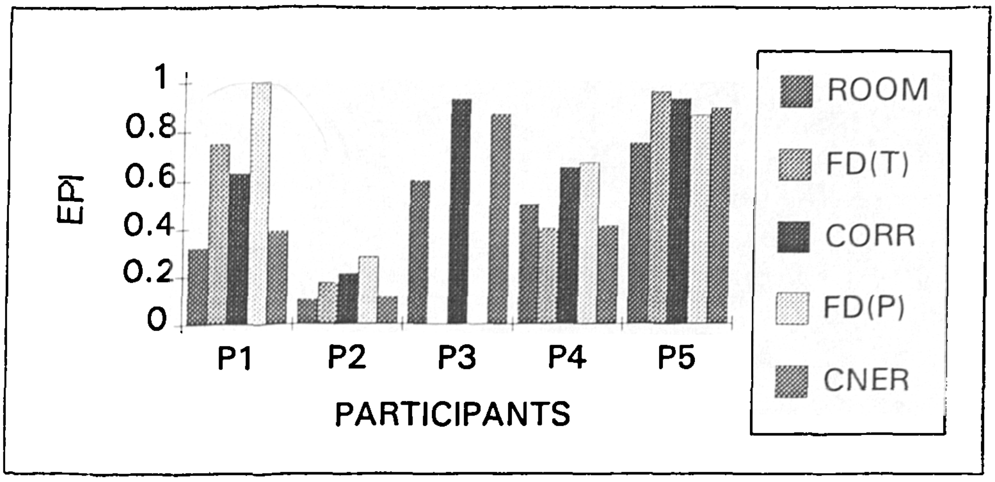

Fig. 4.15: EPI profiles of participants along evacuation route

Earlier on, Fig. 4.2 gave a diagrammatic representation of all the sections of the route travelled and in the above Fig. 4.15 these sections are identified in the key, where 'ROOM' represents the room where the evacuation began (using cafeteria-styled furniture arrangement), 'FD (T)' is a door with a twistable handle leading out of the room (marked as FD1 in Fig. 4.2), 'CORR' is the straight corridor, 'FD (P)' is a fire door with a push handle (marked as FD2/3 in Fig. 4.2) and 'CNER' is the 90° corner.

From Fig. 4.15, the EPI profile that attracts much attention is that of participant (P2). The considerably lower range of EPIs, compared to the other participants, highlights the need to either provide assistance to such occupants or make appropriate changes in building design to enable safe egress. In existing buildings, assigning of fire marshals to specific occupants is the main method of providing assistance.

In most cases it was in the room where the evacuation began that EPIs were lowest compared to the other sections of the route. This could indicate the need to pay closer attention to the starting point of an evacuation. This touches on the issues that researchers such as Sime [30] have been investigating more intently, that of, analysing methods of reducing response times of occupants when they are given a cue to evacuate. For example, the types of warning systems other than the conventional fire bell have been known to increase occupant response times [74].

The EPI profile of participant (P5) was very similar to that of an able-bodied participant whose elemental EPIs would all be unity. This would suggest that such an occupant could move relatively independently during an evacuation. It is essential though, to recognise that there are several measures of partial-sightedness and these are often difficult to categorise. It would be reasonable to assume, however, that an increase in the severity of a visual impairment could result in a distinct change in the EPI profile of an occupant. The EPI profile of the non-sighted participant, for example, demonstrates a significantly different EPI profile.

2. Alternatively a profile could be constructed using the lowest EPI profile overall. This would be a lower bound solution and could, in fact, be used to design for the worst possible case. Thus the profile exhibited by participant (P2) would be used (Fig 4.16).

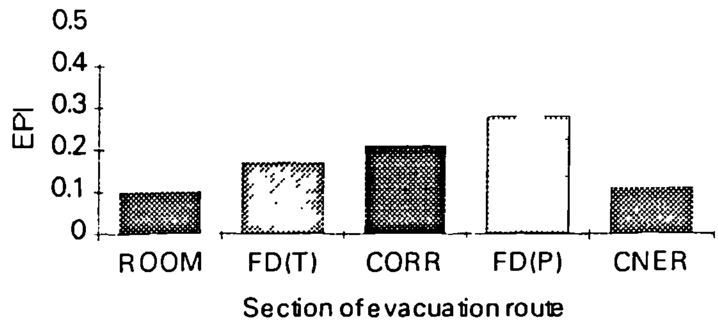

Fig. 4.16: EPI profile derived using lower bound elemental EPIs

The profile obtained using the lower bound solution (Fig. 4.16) shows a rather grim picture of elemental EPIs along the route. Designing for this condition would be difficult and it would be considered more economical to upgrade the managerial arrangements to ensure the safety of all occupants in a given building particularly those exhibiting such EPI profiles. On the other hand, the peculiarity of the EPI profile of participant (P3) stands out with the elemental EPIs of zero at the exit. This could be considered to be the worst case unless assistance at exits can always be guaranteed.

One consideration that has not been sufficiently addressed is the multiple interaction of external factors affecting EPIs. Earlier Fig. 4.1, provided a schematic representation of the condition where individual characteristics, provision of assistance and building design and environmental factors were shown to interact simultaneously. It may well be that subsets of these categories interact similarly. However, the question is raised as to which EPIs to use for design purposes. For example, there could be a section of a route where the effects of width, gradient or bends individually lead to different elemental EPIs. One option would be to isolate all the elemental EPIs resulting from these factors. Their combined effects could then be measured. Either the lowest elemental EPI, for example, caused by the bend could be used for design purposes, or the combined elemental EPI caused by the effects of width, slope and bend acting simultaneously could be used depending on the designer's preference.

4 4.2 Calculation of Total Effective EPIs

The option of using total effective EPIs in predicting evacuation times can be employed in a number of ways. The first two methods are simple but have a primary disadvantage in that they do not recognise that some elemental EPIs are more important than others and therefore they do not include weighting factors. The third method is appears to be the most appropriate because it acknowledges the differences in importance of the elemental EPIs as discussed below.

1. In the first instance the arithmetic mean of elemental EPIs of each disability-mobility aid combination represented in the population can be determined as follows:

$$I_C = \sum_{i=1}^{n} \frac{EPI_i}{n}$$

where, $i, \ldots, n$ represent sections of the evacuation route and n is the total number of sections.

This provides a rather general measure of EPI and has the effect of nullifying the important differences in elemental EPIs along a typical route, as was mentioned earlier. Notwithstanding this is a prevalent approach in current research, only in rare and isolated cases have researchers attempted to deconstruct an evacuation route in order to analyse the specific effects of building design on evacuation capability. Togawa was one such example [44] but, as mentioned earlier, the populations he considered were all able-bodied.

2. In the second instance total effective EPIs can be determined by calculating average speeds of occupants over the total length of the route so that EPIs of each class of occupants are calculated using the equation below:

$$I_C = \frac{t_{AB}}{t_D}$$

where, t_{AB} is the average time taken by an able-bodied occupant and t_D the time taken by a disabled occupant to travel along the entire route.

3. In the third instance, the superiority of some of the elemental EPIs over others is recognised. Therefore, instead of calculating the total effective EPI by finding the average of all the elemental EPIs along a given route, the elemental EPIs along the most significant part of the route are acknowledged as most important. For example, considering a long corridor 1000m in length with two fire doors, one with a push and the other with a pull handle. The EPI of the corridor would be most significant assuming that the EPIs at the doors for the given class of occupants is not zero.

   To sum up elemental EPIs a method similar to summing up pressure drops down ducts or pipes can be used. Just as each element in a pipe or duct has a particular weighting factor, in the same way, each element of an evacuation route has a factor which is the inverse of the time taken for an able-bodied person to perform a particular function. For example, for a straight corridor the weighting factor is the length of the corridor divided by the average velocity of a typical able-bodied person along the corridor. An example of this calculation is given in the following section in which the total evacuation time of participant (P4) is determined and compared to a typical value of t_{TL}.

4.4.3 Calculation of Total Evacuation Times

In this section the method of determining the total evacuation time for a class of occupants is described. Defined more explicitly, this is the time taken by occupants of a particular disability-mobility aid combination to evacuate along a given route, and is expressed as follows:

$$t = \sum_{i=1}^{n} \frac{d_i}{I_i \times v_i}$$

where,

t the total evacuation time (s)

d_i = the travel distance of a given section of an escape route (m)

v_i = the average speed of an able-bodied occupant at a given section of the route (m/s)

I_i the *evacuation performance index* (EPI) at each section of the route for the class of occupants of a particular disability-mobility aid combination

n_i number of evacuation route sections

Alternatively using the total effective EPI, I_C, to calculate the total evacuation time means that the equation used will be expressed as follows:

$$t = \frac{d}{I_C \times v_O}$$

The times in both methods should give similar results as will be demonstrated in Chapter 5, section 5.2. Although the second method is simpler to use, the first is more ideal as the actual sub-components of time taken to travel along a given route are calculated.

The significance of the relationship between the total evacuation time t and the time for tenability limits to exceed their allowable limits t_{TL}, is demonstrated in an example. In the relation $t_{TL} \geq t$, t_{TL} is usually a fixed value and it would be desirable to reduce t as much as possible to guarantee sufficient time for safe evacuation. To give an idea of typical t_{TL} values, a look at Shields' analysis of t_{TL} [5] showed that a typical threshold limit for safe evacuation is based on the time for the smoke layer of a fire to develop to a height of 2m above floor level. During a fire the smoke layer develops from the ceiling downwards to this height at some point, just above the head height of a tall adult. Using a multi-compartment zone model FAST [75] which models the transportation and movement of the smoke and toxic products of combustion, Shields predicts this time to be typically about 70 seconds.

The fire modelled in the above scenario originated in a bedroom with dimensions: $3.6 \times 3.9 \times 2.5\text{m}$. There was an adjoining corridor from the bedroom 18.5m in length. The fire was considered to be a rapidly growing one assumed to have started in the middle of the bedroom, with the door open. As stated earlier tenability limits were deemed to occur when the smoke layer developed down to 2m and a further 0.5m more would have been the height at which hazardous conditions would develop for a wheelchair user with a head height of 1.5m The corresponding time would be 90 seconds in this case. A 20-second time allowance for detecting the fire is required [76].

The author selected one of the wheelchair users, participant (P2), from the previous set of exercises and calculated her total evacuation time using her elemental EPIs over the route described in the above paragraph (see Fig. 4.17).

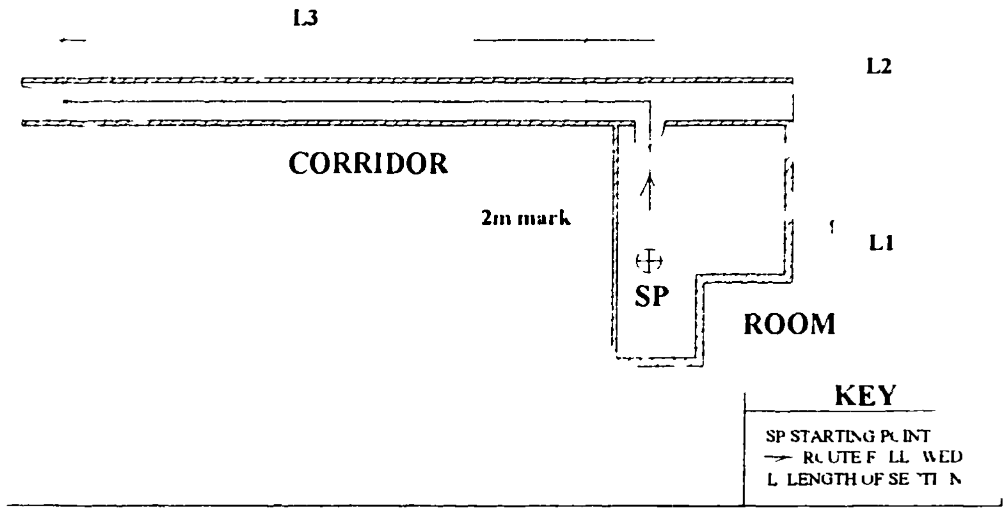

Fig 4.17: Evacuation route followed in Shields' study [5]

The setting of the evacuation route was such that the participant began her evacuation in a bedroom with the same dimensions. She needed to cover a distance of 1.9m to reach the 2m mark positioned before the exit of the room where she would decelerate down before opening the door. Having passed through the exit, she would make a 90° turn after which she would be expected to accelerate at a point 2m from the door and travel along a corridor a further distance of 16.5m. Note that the 4m distance travelled while passing through an exit also included the 90° turn. Therefore there had to be a choice of the elemental EPI to use at this point; that of the exit which was 0.17 or the elemental EPI at the 90° turn, 0.11. The author decided to use the latter lower value. The total evacuation time was then calculated as follows:

The critical time values include,

t_R = time for an able-bodied occupant to travel across the room (s)
t_{CN} = time for an able-bodied occupant to travel around a corner (s)
t_C = time per metre for an able-bodied occupant to travel along a corridor (s)

while, l_C = the length of the corridor (m)

Given that the average walking speed of an able-bodied person is 1.3m/s along all the sections considered and the elemental EPIs of participant (P2) from the previous exercise (Fig. 4.16), the following equation gives the total effective EPI, I_C, based on the pressure drop analogy mentioned in section 4 4 2:

$$I_c = \frac{(t_R + t_{CN} + l_C t_C)}{(\frac{t_R}{0.1} + \frac{t_{CN}}{0.11} + l_C \frac{t_C}{0.21})}$$

The total effective EPI, I_C was calculated to be 0.17 and the corresponding total evacuation time was 101 seconds. Assuming the 20-second detection time for the fire [76], this time is increased to 121 seconds The time would be outside the safe limit of 90 seconds and therefore the occupant would be in a dangerous situation, requiring assistance during evacuation. Previous experiments [64] revealed drastic increases in EPI when the wheelchair user was pushed by an able-bodied person. During one evacuation session her EPI increased to an unusual 2 8, well above that of an able-bodied person along a corridor. The implications of such assistance on evacuation time in this example means that the time taken to traverse the length of the corridor would then be 5 seconds. The total evacuation time in this case would therefore be reduced to 48 seconds which is within the acceptable range.

Further comparisons using empirical data from Shields' study [5] are made in the next chapter in order to assess the reliability of the EPI concept.

4.5 Elements of a Design Procedure based on EPI

Having looked at some of the factors that can affect the evacuation performance of a person, the elements of a fire safety design procedure are presented [64] based on (i) classifying evacuees according to their disability and mobility aid, (ii) experimentally determining evacuation performance indices for each class, and (iii) devising quantitative relationships that describe the effects of assistance available to evacuees and building design and environmental factors on the EPIs.

Assume, for example, that the governing design standards specify:

1. disability-mobility aid distributions for different occupancy types, that is, the range of disability and mobility aid combinations present in each occupancy type, and the proportion of occupants which have each combination,
2. a total effective EPI for each disability-mobility aid combination, and
3. expressions defining quantitatively the effects of assistance and building design and environmental factors on the EPI of each disability-mobility aid combination.

Design in such a case may proceed along the following lines, for each evacuation route out of the building:

(a) First, the designer computes the time t_{TL} for tenability levels to exceed their allowable levels, and the travel distance d through the escape route.

(b) Second, the total effective EPI of each disability-mobility aid combination along the evacuation route is calculated. This calculation will utilise the expressions defined in '3' above to take into account any assistance which will be available to disabled evacuees, and any building design and environmental factors of the evacuation route that might modify the EPIs of the evacuees.

(c) Next, the worst case evacuation time t_W is computed from the equation

$$t_W = \frac{d}{I_M \times v_O}$$

where I_M is the smallest effective EPI computed from Step (b) above, and v_O is the average evacuation speed of an able-bodied person. Note that v_O itself varies with building design and environmental factors, although not with level and type of assistance.

(d) Finally, the designer ensures that $t_{TL} \geq t_W \times SF$, where SF is a factor of safety.

If the inequality $t_{TL} \geq t_W \times SF$ cannot be satisfied, the designer has to modify the assistance to be made available to disabled evacuees and the building environmental factors such that Step (b) returns a high enough I_M. However, if the fire safety evaluation is being performed at the architectural design stage, then the layout of the building may be modified, for example, by providing fire-fighting lifts so that Step (a) returns a higher value for t_{TL} or a smaller value for d. Note that once the inequality has been satisfied for a particular combination of level and type of assistance to be made available to evacuees and building environmental factors, then managerial steps have to be taken to ensure that these conditions prevail in an emergency.

The design procedure described above computes a lower bound or ultra-safe evacuation time since t_W is calculated using I_M, the smallest effective EPI over the range of disability-mobility aid combinations. An alternative procedure which is perhaps more realistic and which returns an upper bound value of t_W is that which uses the sub-component times given by:

$$t_W^P = \sum_{i=1}^{n} \frac{d_i}{I_i^P \times v_i}$$

and,

$$t_W = \max(t_W^P)$$

where, $i = 1, \ldots, n$ sub-divides the evacuation route into elemental sections for which elemental EPIs represented by I_i^P are known The individual expressions are as described in section 4.4.3. The parameter t_W^P is the worst evacuation time exhibited by a class of occupants with a particular disability-mobility aid combination represented by P The range of disability-mobility aid combinations can be represented by $P = 1, \ldots, m$

4.6 Alternative Factors affecting EPI from other Empirical Studies

Apart from building design effects on EPI, it was stated earlier that the effects of providing assistance and environmental factors were also important. In this section, the effects of the former are discussed from the author's observation of a London Underground evacuation of a wheelchair user from a train, across the tracks of the Bakerloo line and down a slope to a place of safety [77]. The scenario represented in the exercise was an accident caused by the collision between a London Underground (LU) train and a British Rail (BR) one. This section is included solely to demonstrate the possible extreme variability in EPI. It does not incorporate the use of EPI for design purposes.

In the exercise, London Underground Ltd (LUL) staff, with the assistance of fire, police and ambulance services, and volunteers from the public participated in the scenario and the rescue operation. The measure of performance in this exercise was based on the speed, efficiency and treatment of casualties by the police, fire and ambulance services. The exercise took place on a Sunday, 30th of January 1994, when most engineering works are carried out on railway lines and therefore there was likely to be minimal disruption of normal services. Bakerloo line, south of Stonebridge station was the selected venue where both British Rail (BR) and London Underground trains travel along railway lines that are close to each other. The 'accident' occurred as a result of a head-on collision between a BR train and an LUL train which had, for some unknown reason, been derailed. The rescue operation and evacuation lasted two and a half hours.

The author monitored this 'accident scenario' and observed the procedure used to evacuate a wheelchair user from the LUL train across the railway track and finally down a slope to a place of safety. Initially, the wheelchair user was positioned near one of the train doors and was evacuated by four assisting policemen who first lifted him from a height of about a meter and a half out of the train. They then carried him in his wheelchair a few metres along the track after which he was transferred to a stretcher, and then taken down the slope to the place of safety. Guide ropes were placed on one side of the path leading down the slope which made the route much safer to walk on.

A descriptive profile of the changes in EPI primarily resulting from the provision of assistance is as follows: Initially the occupant was positioned in one of the aisles near a doorway of the train at which point his EPI value was zero since he was unable to evacuate unassisted. He was then assisted out of the train by the policemen and carried in his wheelchair a few meters along the track, after which he was transferred to a stretcher. While he was on a stretcher, his weight was more evenly distributed compared to his weight distribution in the wheelchair which meant that the stretcher was therefore much easier to carry. His evacuation capability or EPI could be said to have increased as a result of the transfer from the wheelchair. Along the sloping surface to the place of safety the EPI of the occupant was reduced as the people assisting the disabled person had to use guide ropes to descend while supporting the occupant, making the carrying exercise difficult. The EPI value could be assumed to have dropped considerably at this point due to the precarious act of carrying the disabled person while attempting to descend the slope. Although this is an extraordinary and extreme example of the use of the EPI concept in that it is an outdoor evacuation, the philosophy of the changes in the ease of evacuation or in evacuation capability is still valid It appears that provision of assistance is the simplest way of increasing evacuation capability of occupants. However, it must be recognised that assistance is dependant on availability and reliability of those providing assistance. The quality of assistance is also important since there are conditions whereby unnecessary assistance reduces EPIs [64].

4.7 Idiosyncrasies of the EPI concept

There are certain idiosyncrasies or irregularities that arise through the use of the EPI concept as a measure of evacuation capability. These are outlined below:

a) EPI values greater than one

There are cases in which EPI values are greater than one, which implies that the evacuation potential of a disabled person is greater than that of an able-bodied occupant. From the iterative design procedure introduced in section 4.5 earlier this would mean that the worst evacuation time calculated t_{w} would be less than the calculated time if the EPI value in the expression was 1, the EPI of an able-bodied person Although a building designer would not use the EPI of the disabled person in the design of the evacuation route he could use this information to plan efficient evacuation strategies that would recognise the ability of some disabled people to move independently along a significant potion of the route.

b) EPI value equal to zero

There are some conditions in which it is impossible for a disabled person to evacuate unassisted through a section of an evacuation route. Theoretically their EPI value would therefore be zero This would result in a value of infinity for t_{w} the worst evacuation time calculated under these conditions A building designer or management personnel would need to make provisions for the disabled person to ensure safe egress either by providing extra assistance or an accessible section of an evacuation route at this point. For example, he could suggest the installation of a ramp alongside steps. These would be key sections of the route that would warrant thorough analysis at the design stage.

c) Combinations of EPI values

The complex question of the multiple interaction of external factors on the EPI of an occupant was discussed earlier, in section 4.4.2. There appears to be a need to prioritise the effects of particular factors in a given category, for example, environmental factors. The example given in section 4.4.2 describes this condition in more detail.

d) Deconstruction of an evacuation route
The process of deconstructing an evacuation route in a complex building is monotonous and tidious. Even though a solution can be found to speed up the procedure, the primary difficulty arises in actually defining the criteria used to sub-divide the route into sections. The criteria used could differ from one designer to another.

e) Transient changes in EPI
Although elemental EPIs may have been used in calculating the worst evacuation time during the design stage, there are times when there may be changes in the elemental EPI itself at a particular section of a route For example, if stacks of boxes are placed along a corridor significantly reducing the width and hindering occupant movement, there may be a considerable reduction in EPI followed by an increase in the value of t_{ii}. Such changes may occur only temporarily but in several locations in the building at a given time. Estimated evacuation times would therefore fluctuate considerably. It is the duty of fire marshals, fire safety officers and other management personnel to ensure that this does not happen

f) Differences in the configuration of elements of an evacuation route
From Pauls' studies [12] it is evident that there are differences in occupant flow rates down stairwells when the configuration of a stairwell is changed. The tread and riser dimensions have been observed to cause significant variations in flow rates. This implies that there may be a significant number of EPIs for stairwells alone. It may be impractical to determine all these values and therefore some mean value for stairwells would probably have to be used for each disability-mobility aid combination.

4.8 Conclusions
This chapter has shown the practical value of the EPI concept and provides a simplified mechanism for predicting evacuation times when designing for fire safe conditions and planning of evacuation procedures. The foundations for structuring a classification system for disabled people have been touched on, based on the disability-mobility aid combination of an occupant. This combination has been shown to influence evacuation capability although not independently. Changes in building design have been observed

to create variations in EPI which can be represented clearly by using a profile. The final section of the chapter discusses some of the idiosyncrasies of the concept.

The next chapter compares predicted evacuation times using the EPI concept with measured times from Shields' empirical studies [5]

CHAPTER 5

A Brief Comparison of Results From Empirical Studies and EPI Predictions

In this chapter, measured evacuation times from empirical studies involving mixed-ability populations are compared to total evacuation times predicted using the EPI concept. The empirical studies analysed were the most recent ones on evacuation movement and behaviour of mixed-ability populations carried out by Shields' [5]. This author has chosen to analyse, in particular, three of Shields' hotel evacuation studies in which he recorded the individual speeds of the occupants who participated. The reason for selecting these exercises is that the data recorded was of sufficient detail to calculate total evacuation times along the chosen escape route. There was a total of sixty-two participants in the exercises, six of whom had disabilities. Of these six, four were manual wheelchair users, one required the use of a walking frame and the other used a walking stick Shields does not mention in his study the criteria he used for selecting the participants and he does not provide background information on the nature of the participants' disabilities. He adopted certain elements of the evacuation study carried out by Pearson and Joost [17] mentioned in Chapter 4. A detailed description of his experimental study is provided in subsequent sections.

The main objective of Shields' study was to investigate the behaviour of and interactions of a mixed-ability population engaged in the process of evacuating hotel bedroom accommodation under emergency conditions. His measurement of evacuation capability of the participants entailed the use of an Evacuation Time Ratio (ETR) which is defined as the ratio of the <u>mean</u> evacuation time of wheelchair users to the <u>mean</u> evacuation time of able-bodied occupants. While sharing some similarities with the EPI in that the ETR is a comparative ratio of speeds of disabled and able-bodied occupants, the EPI is significantly different. The primary difference between the two ratios lies in the fact that the ETR is based on average evacuation times along a given route while the EPI is based on individual times at specific sections of the route. In addition, the ETR does not consider the effects of external influences, which have been shown by this author to be significantly influence evacuation capability

Nevertheless, the emphasis in this chapter is on the comparison of measured evacuation times of the four wheelchair users in Shields' studies and the predicted times of these participants using the EPI concept. This comparison is somewhat similar to the example given in section 4.4.3 in the previous chapter in which a predicted time from the FAST model [75] was compared to the total evacuation time of a wheelchair user, participant (P2). The only difference here is that rather than using predicted times from a fire model such as FAST, total evacuation times are compared to actual measured time values. The same evacuation route is considered in this study (Fig. 4.17).

5.1 A Description of the Hotel Evacuations

The hotel where the evacuations were carried out was originally constructed in 1871 and extended in the early 1970's. It contained a total of sixty-three bedrooms A layout of a typical bedroom is shown in Fig. 5.1.

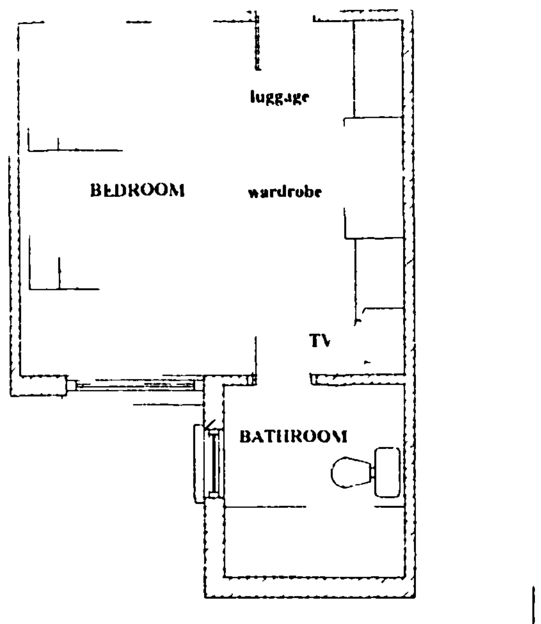

Fig. 5.1: Typical layout of bedroom (adapted from Shields [5])

According to the hotel management, on average, four wheelchair users per week made use of the bedroom accommodation. Access to bedroom accommodation was separate to that of the dining and function rooms. A central circulation space linked the bedroom blocks and provided a means of escape via an exit at ground-floor level, discharging to the front of the building. Alternative means of escape from the first-floor was provided via an external steel stairwell.

Three evacuations were organised, two of which represented day-time scenarios and one which represented a night-time scenario. The participants in the exercise were located in different bedrooms for each of the evacuations. The evacuations were recorded using twenty-one strategically placed video cameras which captured the movement and behaviour of each participant. In the first evacuation (EVAC1) and the second evacuation (EVAC2) a fire was deemed to have occurred in the entrance foyer at one end of the building making the doors leading to it unavailable for the purpose of egress. In the third evacuation (EVAC3) the fire was considered to have started in the central stairwell.

Each participant in the day-time scenario was prescribed a series of tasks which began with the participant sitting in a room watching television. On hearing the alarm s/he would retrieve a personal belonging from a dressing table drawer and after this leave the bedroom and finally evacuate the building. In the night-time scenario the tasks for each occupant began with the participant lying on a bed with the room in darkness. At the sound of the alarm, the participant would turn on the bedside lamp. S/he would then retrieve a personal belonging from a drawer in the dressing table and leave the room and evacuate to a place of relative safety.

The evacuation times of each participant from a room, along the protected corridor to the place of relative safety were obtained from the video recordings taken during the exercise. The place of relative safety was considered to be adjacent to the escape route and was accessed through self-closing fire-resisting doors. The primary sections of the escape route considered in the author's analysis included: the room where the evacuation began, a door with a twistable handle leading out of the room, a 90° turn, a straight protected corridor and a single fire door with a push handle leading to the place of relative safety.

5.2 Calculation of Total Evacuation Times of the Wheelchair Users

The prediction of total evacuation times was made possible by using Shields' records of speeds, times and distances travelled by the participants in the three evacuations. The video recordings which he made were ideal for sifting out the required information on occupant movement. Together with this information and knowledge of EPIs of the manual wheelchair users, referring to the data in Chapter 4, it was possible to calculate the total evacuation times of each wheelchair user with reasonable accuracy. The average speeds of the able-bodied population along the sections of route considered were obtained from Shields' data and from alternative research studies [3], at least for the speed of movement through the exits.

Due to the fact that occupant movement was essentially unhindered along the route and that no assistance was provided to the wheelchair users, the author maintained that it was reasonable to assume that only the effects of building design were active during the evacuation.

As stated earlier, the underlying objective of the exercise was to compare the measured times of the four wheelchair users from Shields' studies with the predicted times of the same participants using the EPI concept. The percentage differences in the measured and predicted times were calculated and analysed The purpose of the analysis was to assess the reliability of the EPI concept in predicting evacuation times.

The following tables 5.1 and 5.2 provide a summary of the measured and predicted times of wheelchair users (W1 - W4) obtained from EVAC1, EVAC2 and EVAC3. Table 5.1 shows the predicted times using sub-components of time and elemental EPIs along each section of the escape route. This method is described in section 4.4.3 of the previous chapter. Table 5.2 shows the predicted times using the total effective EPI calculation, also described in section 4.4.2. The details of the data used in the prediction of total evacuation times using the former method can be found in Appendix B (Tables B1 - B10) as an example.

Table 5.1:Comparison between measured times and predicted times (s) for all three evacuations (sub-component method)

	M(1)	P(1)	M(2)	P(2)	M(3)	P(3)
W1	51.0	49.4	79.0	48.1	46.0	53.4
W2	56.9	49.4	63.0	48.1	37.0	35.2
W3	174.0	161.3	150.9	169.1	131.0	222.1
W4	187.0	161.3	140.0	169.1	135.0	222.1

where, M(1), M(2) and M(3) refer to the measured times and P(1), P(2) and P(3) refer to the predicted times using EPIs.

Table 5.2:Comparison between measured times and predicted times (s) for all three evacuations (total effective EPI method)

	M(1)	P(1)	M(2)	P(2)	M(3)	P(3)
W1	51.0	44.0	79.0	42.4	46.0	33.3
W2	56.9	44.0	63.0	42.4	37.0	18 5
W3	174.0	148.0	150.9	153.8	131.0	163.8
W4	187 0	148.0	140.0	153.8	135.0	163.8

Table 5 3 below shows the percentage differences between the measured and predicted times using the first method (sub-component method).

Table 5.3:Percentage differences between measured and predicted times (sub-component method)

	EVAC1	EVAC2	EVAC3
W1	3	39	16
W2	13	24	5
W3	7	12	70
W4	14	21	65

Apart from the two unusually large percentage differences of 65% and 70 °o in which predicted times were over-estimated, most of the remaining differences were below 25%. On the whole, three-quarters of the differences ranged between 3 and 25°o which is a reasonable result.

A small population was used to determine EPIs in the author's study described in Chapter 4, in specific circumstances. Shield's study also involved a small number of occupants in specific circumstances, in this case a hotel evacuation. In spite of this, the comparison of results obtained from the two studies were very promising. It would therefore be reasonable to say that the adoption of the EPI concept in predicting evacuation times has considerable potential value.

In his study, Shields found that the wheelchair users took 1.9 times longer in EVAC1 and 1.6 times longer in EVAC3 than able-bodied occupants to leave their bedrooms during the day-time scenarios. In Pearson and Joost's study [17] it took 1.6 times longer EPI predictions for a manual wheelchair user in a similar arrangement revealed that it took 1 4 times longer for the wheelchair user. The EPI predictions in this case are also in agreement with empirical results

There was a distinct difference between the evacuation times of the wheelchair users (W1) and (W2) and the other two wheelchair users. This demonstrates how occupants using the same mobility aids may exhibit different evacuation capabilities and highlights the fact that it is insufficient to classify disabled people solely by the mobility aids they use This point has been evident throughout the author's research study From Pearson and Joost's study [17] this observation was also evident in that considerable individual differences were observed in all the subject groups participating in their exercises, namely the blind participants and wheelchair users. The standard deviations and ranges for the total egress times of these occupants were consistently large for all the scenarios.

The pipe and duct theory described in section 4.4.2 is being continually used in traditional engineering applications and fits well in the calculation of total effective EPIs for a specific class of occupants. For several years databases and software packages using the pipe theory have been used to calculate pressure drops and fluid flow-related parameters. In the same way it would be possible to build up a database using the same principle with evacuation parameters including EPIs in different environmental settings. It should be noted that the author is not advocating the use of general fluid flow principles to simulate occupant movement but is rather using a mathematical principle to link evacuation parameters based on observed occupant movement and behaviour.

The signs of a positive agreement of EPI predictions with measured results is evident in this small but not insignificant study. Further validation studies would be useful with a larger and more representative population.

CHAPTER 6

Conclusions and Recommendations

6.1 Contribution to Research in Fire Safety Engineering

The main factor that prompted this research was the revelation from national statistics of the significant percentage of fatalities in fires in the UK who are known to have had some kind of disability. Such disabilities include those that were physically or mentally-related and impinged on occupants' ability to comprehend or react promptly to an emergency. Moreover, there is a problem in the approaches adopted in current research investigating the movement and behaviour of mixed-ability populations during fire emergencies. The limitations in these approaches include:

- the broad and rather vague delineations of the categories of disabled people that lead to a shallow appreciation of the reality of the specific problems associated with their movement during emergencies,

- the various assumptions being made about movement speeds of disabled people which are not confirmed from empirical studies,

- the actual studies carried out to analyse occupant movement, with a view to predicting their likely evacuation times, tend to be isolated in their approaches. This was observed by the author's review of research material on the subject in which she categorised models into groups in accordance with their underlying principles and identified their strengths and weaknesses.

In attempting to resolve to above mentioned problems the author defined a basic safety criterion for Fire Safety Engineering based on an analogy with traditional engineering principles. This safety criterion not only defined relationships between different classes of fire emergencies and time to safely evacuate, but also provided a basis for defining a quantitative attribute of occupant movement relating to their intrinsic speeds. She found that two basic factors influenced occupant speeds, namely their disabilities and their mobility aids. This notion of disability-mobility aid combination provided a foundation for a classification system for mixed-ability populations. While it was recognised that the disability-mobility aid combination was not a sole determinant of speed and that external factors tended to modify occupant speed, the effects of these factors were measured through the use of an *evacuation performance index* (EPI). This was defined as the relative ease of evacuating a disabled person compared to evacuating an able-bodied person. The index was viewed as being primarily dependant on three factors: individual characteristics, amount and type of assistance made available to occupants and building design and environmental factors. The concept of the EPI allowed changes in evacuation capability brought about by the above three factors to be measured. This meant that actual variations of evacuation capability along a typical evacuation route could be appreciated because of the flexible nature of EPIs. The author carried out some exercises to demonstrate the changes in EPIs of a group of disabled students along a route of an office building in the University of Central Lancashire.

A procedure for design based on this notion of EPI was suggested by the author through which the likely evacuation times of different disability-mobility aid combinations represented in a population could be calculated. The predicted times took into account all the changes in EPI along the route. This was a major step forward from current research methods that do not demonstrate this flexibility. The total evacuation times calculated from the author's data were compared to measured times from empirical data from an alternative source. The results obtained were encouraging bearing in mind the limited data that was available for comparison.

In summary the benefits of the EPI concept include its ability to measure evacuation capability and its flexibility in measuring the changes in evacuation capability along a given route, as was mentioned earlier. The resources required to carry out experiments to measure EPIs are comparatively more economical than the equipment used in current evacuation studies. All that is required is ordinary equipment for measuring distances and times and the assistance of a few observers. The concept is easily comprehensible and does not require specialised expertise in its application. It is also serves as a useful tool for assessing the reliability of escape routes. The EPI concept could also be used as an indicator of the presence of a 'handicapping environment'. Earlier on in Chapter 4 of the thesis, the notion of 'handicapping environments' was briefly introduced. It pointed to the fact that it would be valuable to have some quantitative measure of accessibility of a building having had prior knowledge of the likely percentage of disabled occupants expected to use the building. Codes of practice could adopt this measure to speed up the process of assessing various building layouts. Finally, its application is not limited to a particular building type but rather to any range of buildings.

6.2 Prospects for Further Work

The development of this new concept requires a significant amount of work to be done particularly in deriving quantitative expressions that take into account changes in: the assistance provided to occupants, any building design and environmental factors of an evacuation route that might modify nominal EPIs. Further work on the subject could also include an investigation of the effects on EPIs of alternative factors other than those considered in this thesis. Methods could be sought to channel the findings in this research programme, and those to follow, into a format usable in the codes of practice on means of escape. The design procedure suggested, for example, could simplify the work of architects and building designers in their planning of acceptable means of escape Further development of this procedure could incorporate various structural aspects apart from escape route dimensions

One major weakness in the EPI concept is the requirement for a large amount of data on each disability-mobility aid combination represented in a population. The approach adopted in the author's data collection laid the foundation for work that could be carried out on a larger scale. The author was constrained by limitation of time, personnel and participants A more rigorous method would be the measurement of mean, maximum and minimum EPIs for a large group of occupants of each disability-mobility aid combination.

All in all there is encouraging potential in the use of the EPI concept in deriving fire-safe design solutions for mixed-ability populations.

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APPENDIX A

Sample: Typical Example of EPI Calculation from Data in Chapter 4

Sample: Typical Example of EPI Calculation from Data in Chapter 4

This section provides an example of an EPI calculation using data from the furniture arrangement, 'Arrangement 1' described in Section 4.3.2. Participants (P1 - P5) were all disabled and participant (P6) was able-bodied. The time data collected from the experiment is shown in Table A1.

Table A1: Time values (s) of participants (P1 - P6) obtained from experiment using Arrangement 1

	Arrangement 1	Arrangement 2	Arrangement 3	Average
P1	45	38	29	37
P2	113	114	121	116
P3	20	20	19	20
P4	26	23	23	24
P5	16	16	16	16
P6	13	12	11	12

Identical distances were travelled in all cases, from the starting point (SP) and the exit. Thus the EPI, of any of the disabled occupants (P1 - P5) could be determined using the following equation:

$$I_i = \frac{t_{AB}}{t_D}$$

where,

t_{AB} = time for the able-bodied participant (P6) to travel from the starting point (SP) to the exit (s)

t_D = time for a disabled participant (P1 - P5) to travel from the starting point (SP) to the exit (s)

I_i = the elemental EPI of a disabled participant in a given section of an evacuation route, in this case, a room with furniture 'Arrangement 1'.

In this case the EPI, I_i, of participant (P2), for example, was 0.10.

APPENDIX B

Data from Measured and Predicted Evacuation Times in Chapter 5

Data from Measured and Predicted Evacuation Times in Chapter 5

The data used in the calculation of total evacuation times in section 5.2 of Chapter 5, are shown below, where v_A is the average speed of an able-bodied person and v_D is the speed of a disabled person in (m/s), in this case, a manual wheelchair user. The time sub-components are represented by t in seconds. The sections of the route are represented as follows: the room where the evacuation began 'ROOM', the corner (90° turn) made when leaving the room 'CNER', the corridor, 'CORR', and the fire door, FD(P).

Total Evacuation Times for EVAC1

Table B1.: Total evacuation times for wheelchair users (W1) and (W2) - EVAC1

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.71	1.65	0.3	0.2	8.3
CNER	0.41	4 00	1.5	0.6	6.7
CORR	0.65	26.35	1.5	1.0	26.4
FD (P)	0.67	4.00	0.8	0.5	8.0
					49 4

Table B2.: Total evacuation times for wheelchair users (W3) and (W4) - EVAC1

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.12	1.65	0.3	0.04	41.3
CNER	0.11	4.00	1.5	0.17	23.5
CORR	0.21	25.05	1.5	0.32	78.3
FD (P)	0.28	4 00	0.8	0.22	18 2
					161.3

Table B3.: Comparisons between measured and predicted times (EVAC1)

	MEASURED TIME (s)	PREDICTED TIME (s)
W1	51.0	49.4
W2	56.9	49.4
W3	174.0	161.3
W4	187.0	161.3

Total Evacuation Times for EVAC2

Table B4.: Total evacuation times for wheelchair users (W1) and (W2) - EVAC2

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.71	1 65	0.3	0.2	8.3
CNER	0.41	4.00	1.5	0.6	6.7
CORR	0.65	25.05	1.5	1.0	25.1
FD (P)	0.67	4.00	0.8	0.5	8.0
					48 1

Table B5.: Total evacuation times for wheelchair users (W3) and (W4) - EVAC2

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0 12	1 65	0.3	0.04	41.3
CNER	0.11	4 00	1.5	0.2	20.0
CORR	0.21	26.35	1.5	0.3	87.8
FD (P)	0.28	4 00	0 8	0.2	20.0
					169 1

Table B6.: Comparisons between measured and predicted times (EVAC2)

	MEASURED TIME (s)	PREDICTED TIME (s)
W1	79 0	48.1
W2	63.0	48.1
W3	150.9	169.1
W4	140.0	169.1

Total Evacuation Times for EVAC3

Table B7.: Total evacuation time for wheelchair user (W1) - EVAC3

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.71	1.65	0.3	0.2	8 3
CNER	0.41	4.00	1.0	0.4	10.0
CORR	0.65	17.6	1.0	0.7	25.1
FD (P)	0.67	4.00	0.8	0.4	10.0
					53.4

Table B8.: Total evacuation time for wheelchair user (W2) - EVAC3

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.71	1 65	0.3	0.2	8.3
CNER	0 41	4 00	1.0	0.4	10 0
CORR	0.65	4 85	1.0	0.7	6.9
FD (P)	0.67	4 00	0 8	0.4	10 0
					35 2

Table B9.: Total evacuation times for wheelchair users (W3) and (W4) - EVAC3

SECTION	EPI	DIST (m)	v_A (m/s)	v_D (m/s)	t (s)
ROOM	0.12	1.65	0.3	0.2	8 3
CNER	0.11	4 00	1.0	0.1	40.0
CORR	0.21	30 75	1 0	0.2	153 8
FD (P)	0.28	4 00	0.6	0.2	20 0
					222 1

Table B10.: Comparisons between measured and predicted times (EVAC3)

	MEASURED TIME (s)	PREDICTED TIME (s)
W1	46.0	53.4
W2	37 0	35.2
W3	131.0	222.1
W4	135 0	222 1

APPENDIX C

Author's Publications

EURO-Facilities Management Conference: World Trade Centre, Netherlands,
September 12th - 17th 1992.

Towards the Extension of an Evacuation Model to Ensure the Safety of Disabled People in Fire Emergencies in Buildings

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TOWARDS THE EXTENSION OF AN EVACUATION MODEL TO ENSURE THE SAFETY OF DISABLED PEOPLE IN FIRE EMERGENCIES IN BUILDINGS.

Over decades researchers in various fields have sought to analyse the subject of fire safety in their respective disciplines. As a result the parameters involved are emphasized more in some models, less in others and omitted and replaced in several cases. However, there is some degree of overlapping and a number of parameters are common to most.

The object of the poster presentation is to give some indication of the categories of evacuation models ranging from purely behavioural, psychological models to mathematical models focusing on fire physics and chemistry. The category of models chosen for research is based on legislative rules and models. The issue of building safety particularly for disabled people has recently been given greater importance in Building Regulations and British Standards. With the current changes in 1992 in the approach of the Building Regulations which seek now to give guidance, within given limits allowing experts in the field to exercise their own skill and judgement, this presents an ideal opportunity to further develop regulations and guidelines focusing on building and fire safety for disabled people.

It is hoped that in the coming years, with more emphasis on equal opportunities as far as issues such as building access are concerned, there will be guaranteed safety for all building users without unnecessary strain being experienced by the building owner financially or otherwise. By developing a simple but effective code of practice that borrows the strengths of models already developed (many that are sofisticated in nature) and attempts to reduce the weaknesses, the objective of the research will be within reach. The simplicity of a model offers numerous advantages, one of them being the ease of application of the principles introduced to a greater segment of the population thus lessening the continual need to seek professional advice.

TOWARDS THE EXTENSION OF AN EVACUATION MODEL TO ENSURE THE SAFETY OF DISABLED PEOPLE IN FIRE EMERGENCIES IN BUILDINGS

INTRODUCTION

Facilities management is concerned with the interaction of people with buildings, ensuring the smooth-running existence of the two. Where buildings are involved, structural aspects are analysed and where people are concerned psychological aspects among many other factors, are important. The area f Fire Safety is a broad subject that resea chers in various disciplines have sought to analyse evacuation of buildings is an issue of particular interest. Numerous models have been designed to quantify this aspect of Fire Safety to give tangible information on time data, building dimensions and other related parameters that would ensure safety for evacuating occupants.

The analysis of currently available models shows that the importance of the parameters involved in evacuation are all very relative. Psychologists tend to emphasize the behavioural aspects of people while the engineer tends to focus more on the technical and structural aspects of means of escape. It would be ideal to combine the various approaches and so develop a model that combines as many fields as possible. The different assumptions made are not always compatible from model to model and often conditions apply for only certain building types and not others. Thus there is considerable difficulty in standardizing fire evacuation system. However, there are ideas and concepts that will always apply. For example, factors such as the design of staircases will always be important whether in existing and new buildings, in offices or in hospitals, or when considering mobility aspects of the population.

It is hoped that as more emphasis is being laid on the subject of evacuation of disabled people in the UK Regulations and Standards, there will be more people able to have access into a building and safe egress in the event of a fire emergency will be assured. The gradual but definete emphasis on the design aspects and evacuation procedures suitable to disabled people is commendable.

Presently the documents dealing with disabled people are the British Standards BS 5588 part 8 and Building Regulations - Approved Document Part M. These give guidelines for evacuation procedures a d design aspects. Unfortunately there is no easy solution to building design that caters for all categories of the population using the building. The professionals involved in the construction of buildings need to come to some agreement in satisfying the requirements and this is not an easy task as opinions differ and there is no single set of rules on which all the professionals can base their judgement.

The objective of this project is thus to take a brief look at some model categories and analyse their relative strengths and weaknesses. The research focuses on the mobility aspects of an egressing population. Many of the models assume that each occupant will be able to move along the evacuation route in a uniform manner but it is known that people have different mobility abilities and different reactions to emergency situations with a consequent effect on evacuation times. People with various kinds of disabilities will require aid in different ways and may need to follow alternative evacuation procedures.

By analysing the models that have been developed the parameters requiring more emphasis can be identified. The strengths of the models can be adopted to develope a code of practice or an extension of a model that would in some way enable all building users to be assured of safe access and egress in emergency.

BRIEF ANALYSIS OF MODELS THAT HAVE BEEN DEVELOPED

If an imaginary line is drawn and at one extreme end represents purely behavioural aspects and the other are mathematical and technical aspects of evacuation (see Figure 1), it can be seen that the ideal objective would be to tend towards the mid-point where a reasonable balance in their focus is achieved. The question arises though, as to whether this is possible in reality. The various categories of models each has its focus somewhere along the line and it is the purpose of this paper to look into the advantages and disadvantages of each approach.

Differences in methodology of models

Four different methods of analysis of fire scenarios; some being real-life fires and others imaginary (as in the form of a fire drill) are described (1):

(a) Laboratory experiments;

(b) Carrying capacity and evacuation (pedestrian movement) research;

(c) Computer and environmental simulations;

(d) Field research (questionnaire surveys and case studies based primarily on interviews)

There are advantages of using each of the above and when all are incorporated into one study, the validity of the results obtained holds more weight. There is no arrangement or experimental setup that can replace a real-life fire situation thus the strength of statistical analysis based on interviews with people involved in real fires is recognized. However, sometimes people are not able to give detailed and accurate accounts of their experience. Video-disc simulation places people in a "real-life" situation created, where real choices have to be made. It is a method that has been favoured by researchers in various fields. Fire drills are, strictly speaking, practices and training sessions. Although fire scenarios are unpredictable, they give an idea of what is likely to happen in a real situation.

"Because of the difficulties associated with any one research procedure it is necessary to develop a system of research whereby the various difficulties in studying human behaviour in fires may be cancelled out by the variety of procedures .. The most productive strategy would appear to be one in which a number of research streams were continued more or less in parallel so that the results from them could be fed into each other" (2). The streams include the examination of actual fires (case studies), simultaneous field and lab experiments, interviews with firemen and other informants, reviews, consultation and attitude surveys (See Figure 2).

As it is unethical to involve people in real fires for testing purposes one has to settle for methods or procedures specially created and comparable to a fire emergency environment. There are however increasing attempts to create situations that are as realistic as possible such as the use of artificial smoke to study behaviour in smoke-filled environments.

<u>Categories of the models</u>

Models can be separated into different categories to emphasize the differences in approach to prediction of evacuation parameters such as time and speed values. There is no hard and fast rule for separation of models into various categories. There will be some degree of overlapping in a number of cases and thus the following models may fit under alternative categories.

1) Behavioural models

Behavioural models have been divided into conceptual and computer models. (3):

a) Computer models

Stahls' computer model BFires (4) is an example of a model that is suitable to a broad range of building occupancies. It is also commendable for the range of parameters included. Occupant mobility is considered. The information given by BFires is useful to the building designer in issues such as ideal positioning of exits for safer and faster egress etc.

Sc e of the findings of the BFires program include the positive correlation of the occupants' familiarity with the building layout, with the speed and directness of their escape. The studies also revealed that indecision and mobility impairments act to increase egress time of occupants during BFires simulated fire events.

Limitations associated with this model as in other behavioural computer models include the limited range of the number of people in the simulation. The model focuses on actual evacuation time assuming the decision by the occupants to move has already been made.

b) Conceptual models

Conceptual models attempt to include a theoretical design in the model providing some understanding of the decision-making and alternative choice processes of the individuals involved with the fire incident situation. There is a whole range of mental adaptive processes that are spelled out by these models and they are generally based on the concept of the individual as an information processing, decision-making participant initially involved in a fire incident.

Breaux, Canter and Sime's model described in Wood's report (3) is an example of a conceptual model based on taped interviews of participants involved in fire incidents in three types of occupancies. Although Wood's report dates twenty years back, the detailed description of the cognitive processes experienced by an occupant in a fire emergency gives a very useful foundation for development of an arbitrary model with a conceptual basis. A total of 1189 actions carried out by the participants was tabulated into an "act" dictionary and the acts were compared in a transition matrix to identify and evaluate the sequence of actions.

Conceptual models recognize the indivi ıality of the occupant and recognize the fact that the occupants are decision-making beings, a factor ignored by models of other categories. Emphasis is laid on the human behavioural aspects rather than the technical aspects such as building planning. A suitable balance between the behavioural and technical aspects in the design of an evacuation model is important.

2) Network Analysis models

The objective of network flow optimization models is primarily to identify "bottlenecks" (areas where there is likely to be crowding of people); an issue of interest in emergency evacuations. There are non-behavioural in nature and tend to have a "global view" of the building population. They give optimal time for building evacuation, in the sense that they minimize the time to evacuate people and gives the quickest route possible.

Evacnet+ developed by Kisko,. Francis and Noble (5) is a powerful network model in terms of movement and it has a relatively wide scope . It is flexible enough to model the evacuation of almost any structure representable as a network. It able to deal with large numbers of people as well as with complex buildings. It is also described as a powerful tool that will allow fire safety engineers to make objective decisions about the evacuability of buildings.

However, as mentioned before, the network models are not behavioural in nature and they regard the flow of the egressing occupants as a whole, assuming constant flow rates in stairwells for a given number of people. The mobility aspect of the occupants is ignored.

3) Models based on the carrying-capacity of egress routes

The models in this category are generally found in legislative literature. Many are based on tests carried out several years ago, some which would need to carried out in a wider scope of conditions. In most of the tests for speed determinations etc, fit ambulant people participate in ideal experimental conditions. Building regulations and standards are rigidly based on the results obtained.

A critical look at the United Kingdom Building Regulations and Standards reveals that models presently used have been based on results of tests or findings going back as far as six decades ago. The Post War Building Studies 1952 is an important base to which many codes refer and analyses numerous parameters associated with evacuation and their correlations. There are limiting assumptions in the calculation of stairwell capacities, for example, such as the set flowrate figures, uniform distribution on each storey, no obstruction of flow of people (ideal case), etc.

The strength in the new approach of the Building Regulations 1992 is the guidance aspect. The basic limits and data are provided for determining adequate means of escape and from that step the Building Control officer is required to use his knowledge and skill; also being free to apply alternative legislative codes such as the British Standards that apply in the case concerned.

4) Mathematical models

Mathematical models tend to lay their emphasis on the physics and chemistry of fire in order to measure parameters that provide a form of quantification to determine the available time for occupant egress. One such model is Cooper's (6) ASET (Available Safe Egress Time) model. According to Cooper "..for fires in buildings , the ability of occupants to safely egress from all threatened spaces is equivalent to a condition of life safety". The application of this equivalence principle l ads to the concept that safe egress and thus life safety, can be achieved in buildings designed to have a balance between the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET). The relationship between the two parameters is:

$$ASET = t_{HAZ} - t_{DET} > RSET$$

where t_{DET} and t_{HAZ} are the time of fire detection and time of onset of hazardous conditions. Various criteria can be used to provide the basis for determination of egress time.

The mathematical model, while giving a wide choice of criteria on which to base egress time values, is limited in its application. Generally in an evacuation procedure one requires information on the entire evacuation route. ASET focuses on the fuel assemblies of a given space. Cooper concentrates on the egress movement following the alarm; a common occurrence with other models.

5) Models based on empirical studies of crowd movement

In order to study crowd movement along corridors or down stairwells it is useful to have access to high-rise buildings where the travel distances down the stairs and along the corridors will be quite considerable. The two most important aspects of building evacuation are the relationship between rates of flow of people leaving a building and the width of the stairs down which they walk and, secondly, the total evacuation time. These two aspects form the corner-stone for the NFPA rules regarding means of escape. His calculation method has been adopted by NFPA Life Safety Code, 1985 edition.

The "effective width" model developed by Pauls has been widely used in calculating flowrates and other related parameters. Some of his findings in the evacuation studies he carried out (1971), included the mean flow of 1.24 people/second/meter of effective stair width on the best-used stairs. The peak flows achieved were among the highest ie, 1.60 persons/second metre of effective stair width. Numerous parameters were tested to obtain their relationship to flowrates. The optimum conditions obtained from the studies were: density (persons/m^2) of 2.0, speed (along the slope of the stair) of 0.5m/s and flow of 1.18 persons/second/metre of effective width. In developing calculations concerning evacuation time Pauls takes into consideration sub-components overlooked in a number of other models. The first two subcomponents of evacuation time are relatively simple and they are usually the only components that directly affect the means of escape requirements found in the codes and related documents. The third and fourth subcomponents are the pre-movement time between the onset of the cue supposed to initiate evacuation and the decision to begin moving and the time component due to any behaviour that diverts an individual from the most direct egress route once that persons's egress movement is initiated. If the latter time components are ignored in a prediction then that prediction should be stated as the <u>minimum</u> possible evacuation time.

Pauls warns that the use of flowrates obtained from observation should not be used indiscriminately or used in handbooks for design. He states that the flows that are actually briefly sustained maxima have been used as a basis of design or for performance prediction. Models based on crowd movement such as Pauls' can be complex as there are numerous parameters for which correlations can be found and many of these parameters are constantly changing with time.

6) Models based on informative fire warning systems

Informative fire warning systems seek to reduce the time component named by Sime as the "gathering phase" when people require more information about the cues given in the emergency situation. The clarity of the information given is a significant factor. There are still differences in the way people interpret information and it cannot be assumed that they will all process it in a similar manner. According to Tong and Canter (7) have shown that there are three areas of failure with the traditional alarm systems namely:

(a) A failure of people to differentiate alarms from other types of alarms.
(b) A failure of people to regard fire alarms as authentic warnings of a genuine fire.
(c) A failure of fire alarms to present information which will assist fire victims in their attempts to deal with the fire.

Thus the value of the IFW systems can be appreciated.

Studies done by Pigott (8) and further work carried out with the Fire Research Station (9) quantified the effectiveness in the motivation of escape using coloured graphic displays , computer-generated voice, text displays and alarm bells. The computer-based systems also have the capacity to control false alarms and have a high degree of credibility. On the issue of cost Pigott states that, " ..the provision of a remote "big brother" computer to watch over a computer-based active system is now very cheap". The power, speed , graphics and voice capabilities of the more imaginative personal computers are within the economic reach for ordinary or professional purposes.

Estimates derived from the studies by Canter, Powell and Booker (10) suggest that time saving of the order of one or two minutes could be achieved through the appropriate use of IFW systems in large complex occupancies. The report also states that apart from reducing delays at the critical stage these systems may have an even greater impact on increasing the effectiveness of the overall evacuation response.

The strengths in the IFW systems, as briefly discussed above, are their reliability in giving clear information regarding the evacuation procedure and in dealing with false alarms. However there are a few problems encountered in these area. False alarms are not totally eliminated and clarity of information is relative as people have different interpretation capabilities and reactions to information received. The cost effectiveness is an advantage. Constraint on the provision of the information is necessary though. Occupants may desire more relevant information than they perhaps receive and cannot always use it to the best advantage particularly if the message is ambiguous. Studies have been done on making the messages more comprehensive. The "debate" concerning the use of voice messages only or both the voice and visual messages is discussed in the Fire Research Report (9). The credibility of the system depends not only on its technical reliability but also the effectiveness of the training procedures associated with its use. In the report (10) the authors state that ".. should training procedures be less than adequate or fail to compensate for the perceived disadvantages , occupants may well come to distrust or even disregard the system". The system has the advantage of aiding care staff of hospital establishments who are responsible for moving patients who have difficulties in moving.

7) Models based on the capability of disabled people to egress

Most models in this category are related specifically to institutions where disabled people are cared for such as hospitals or elderly peoples homes. In order to quantify the degree of disability or the amount of help required, generally a ranking system is used. The effect of various difficulties on factors such as speed or ease of movement has been studied although much more research work is required in this area. It must not always be assumed that egress-related actions carried out by disabled people will always be performed at a slower pace. It has been observed that people with hearing impairments respond quicker to a fire alarm in the form of flashing strobe lights than many cases where there are occupants without disabilities. The "gathering phase" is significantly shorter although there are instances were the response to the alarm may be quick but the actual reaction hinders the evacuation procedure.

The hydraulic model with its perfectly ideal conditions, is challenged by models under the above category. The hydraulic model assumes that the building occupants are alert , able-bodied and ambulatory. The model defines the building evacuation as a "two-phase" process. The first phase, the "start-up phase" consists of an immediate, appropriate, self-initiated decision to evacuate. "Self-initiated" movement means that no assistance is required from others to initiate evacuation. The second phase, the "egress phase", consists of a deliberate progression towards an exit; each occupant moving under his or her own power in tight formation with the other evacuees.

A few of the factors drawn up in Archea's framework of a model include the the observation that the single wheelchair patient may be moved as fast as an able-bodied assistant can move but the assistant plus the wheel chair takes up more of the available space in the exit route than does the single fully ambulatory evacuee. The overall speed reduction, increased demand for space and decreased flexibility from attempting to move cumbersome objects through constricted channels can seriously disrupt the overall continuity of the outward flow. Substantial queuing can be expected to occur as temporary blockage develops while wheelchairs, for example, are guided around corners or through fire doors. Another concept that is introduced is that of "counter-flow" which describes the return of assistants helping patients to evacuate. It is important to determine whether the shuffling between the "safe-end" and the "threatened-end" of the evacuation route reduces the carrying capacity of the channel and if the counterflow actually provides supplementary manpower when it is needed.

The importance of considering the occupant mobility quantitatively is stressed in the models in this category. The present Building Regulations and Standards are beginning to recognize the need to acknowledge the presence of disabled people when planning means of escape and in the development of mathematical calculations to determine time and speed -related data.

TOWARDS DEVELOPING A CODE OF PRACTICE FOR THE EGRESS OF DISABLED PEOPLE

The present codes of practice in the United Kingdom that are specifically designed for disabled people such as BS 5588 part 8: 1988 "Code of practice for means of escape for disabled people" , Approved document - Part M " Access and facilities for disabled people" etc, need to allow the safe egress of disabled people at the design stage of the building involved. The regulations that are given tend to be based on the assumption that the buildings will be properly managed, particularly in overseeing the evacuation procedure laid out by the organisations using the building. Each organisation needs to adopt the Regulations for fire safety to their specific environment so that the evacuation procedure involving both the disabled and non-disabled people will be reliable and adequate.

What are the strengths and weaknesses of the present UK codes of practice ? There is a wide range of answers to this question , a few of which shall be discussed. The strengths include the recognition of the need for separate procedures in evacuating disabled and non-disabled people knowing that in certain conditions such as in high-rise buildings it is difficult to involve disabled people into a stream of moving building occupants, for example, in a total evacuation. Suggestions for the dimensioning of staircases and other building dimensions are given in Approved Document M acknowledging the presence of disabled people in the building thus making the buildings much more easily accessible. Various modes of evacuation are suggested such as the use of wheelchair lifts, fire-fighting lifts in British Standard BS 5588 - part 8 which shows an increase in the awareness that modes of evacuation of disabled people are important at the design stage.

There are some weaknesses in the codes of practice and the evacuation models that have been developed. There is still no standard that has quantified the classified varieties of disabilities and there is a shortage of time-based data that would give a helpful indication of how much time is required to safely evacuate a group of people with mobility difficulties. Work has been done by Pearson and Joost (11), Archea (12) and Sime (13) based on a more quantitative approach which if adopted in the codes would help towards the development of a more standardized procedure of evacuation with more 'tangible' data available. The buildings that existed before most of the present codes were written have the task of implementing more reliable procedures of evacuation in many cases, as many of the new regulations would not be easily met by virtue of that fact that these regulations have come much later. Some building are poorly managed and thus even with an ideal evacuation procedure, problems would be encountered in a real emergency.

In analysing the above points, one needs to test and investigate the following parameters:

(a) Quantifiable parameters such as the time-related data (the average time it takes for people with certain disabilities to move).

(b) Clarification of definition of disability in the context of evacuation as not all disabilities will result in mobility difficulties.

(c) Classification of the disabilities observed with a view to quantifying them by a ranking system for example. This presents some problems due to the diversity of disabilities and the fact that numerous other issues need to be considered such as the individual's determination to be in control of his circumstances.

(d) Training material for Fire Safety needs to be re-examined and in some cases revised.

(e) Management aspects need to be analysed in more detail.

Having categorized the models, touched on their strengths and weaknesses and introduced a few important factors, testing and collection of data from which conclusions can be drawn and recommendations can be made, is the next step. Hopefully with more data available, there will be a more valid base on which models or codes of practice involving disabled people will be founded.

CONCLUSION

One of the ultimate goals in the study of Fire Safety in buildings is to have all buildings accessible to all people, ensuring safe access and egress. This will not be achieved only by emphasizing the need to have buildings comply with the codes of practice but by analysing how the occupants relate to their environments and from the drawing board stage formulating designs that will be suited to the various categories of building users.

Sime, in a study of "Handicapping environments" (14) introduces the idea that the term "handicapped person", "...misleadingly suggests that the difficulty a person may have , in entering and moving around a building, is a consequence primarily of a physical or sensory "disability" which a person has, rather than a handicap caused by architectural design". As long as the assumption is made that the handicapped have a problem independent of the building itself being a handicap, the responsibility for barriers and of impoverished architectural environment offered to the handicapped person will be avoided. He continues to state that, "..in sense we are all handicapped if a building has not been designed in such a way that we can use it in an optimum fashion". Thus in dealing with the issue of safe evacuation of all building occupants the architectural layout is an important consideration from the beginning. The building design has the capacity to create a "handicap"; thus the problems in access and egress and the resulting delay in the total evacuation times.

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FIGURE ONE

SIMPLE DIAGRAM TO REPRESENT THE TENDANCY TOWARDS THE IDEAL MODEL

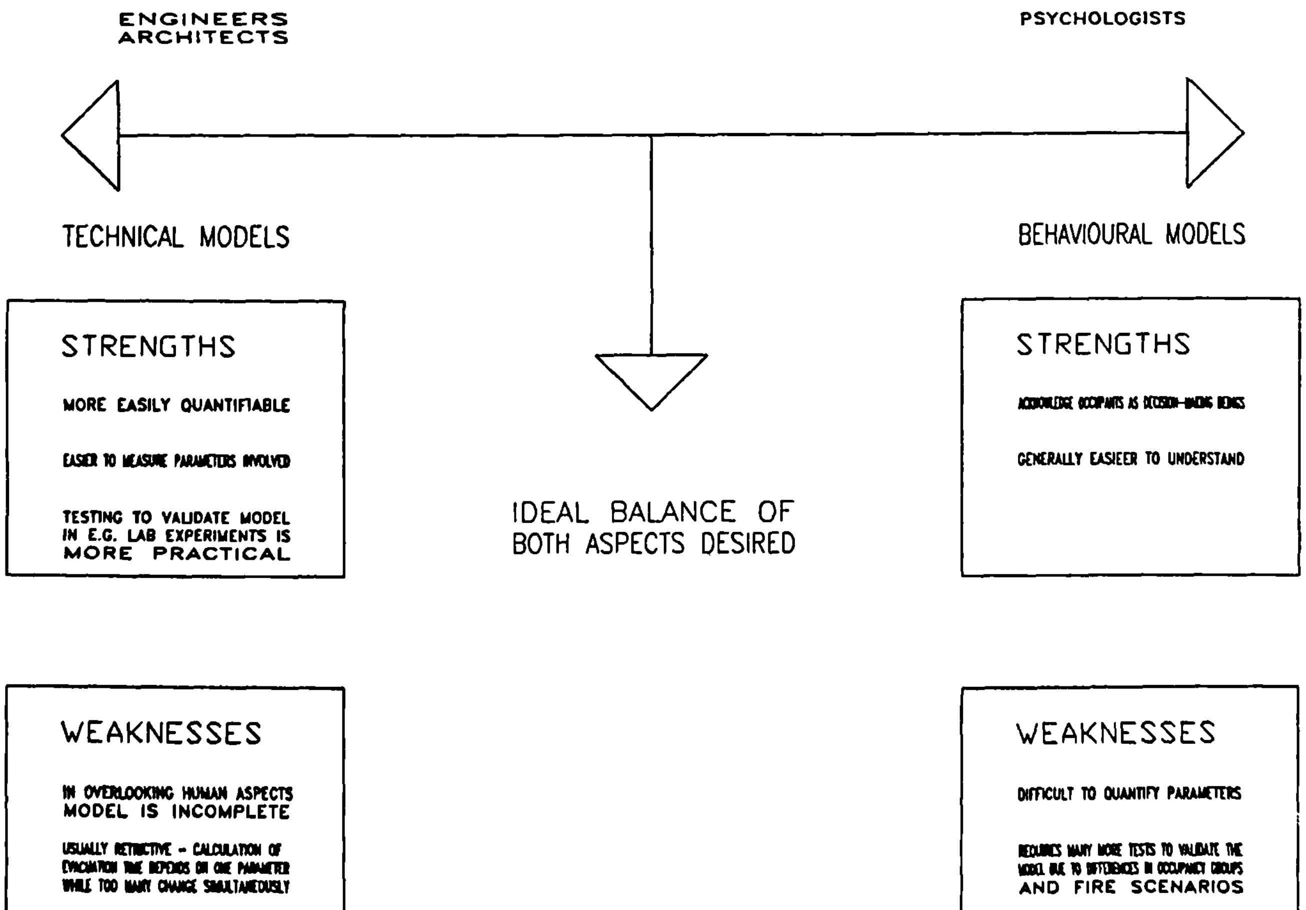
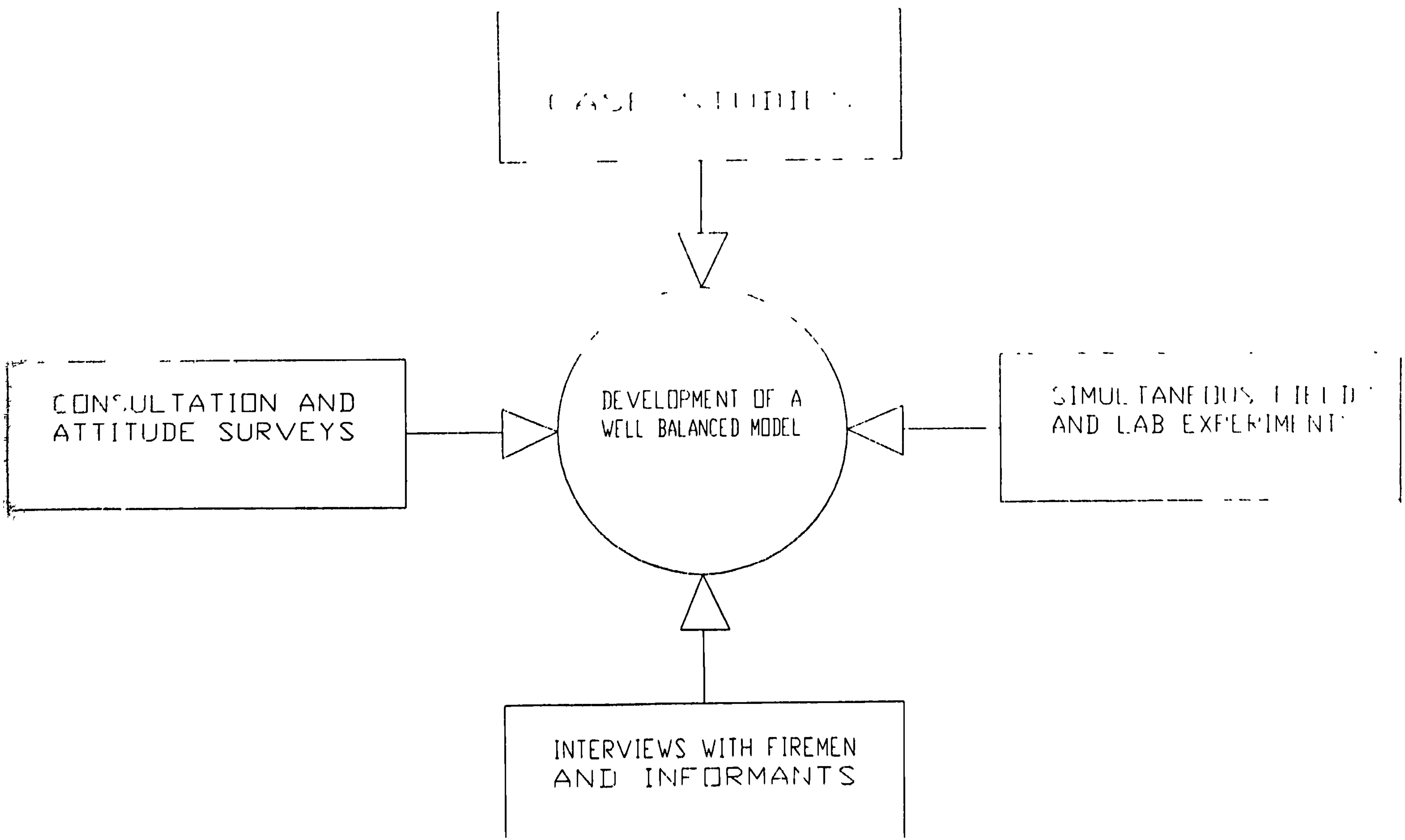


FIGURE ONE

FIGURE TWO ADAPTED FROM [illegible]
IN FIRES EMPIRI[illegible]
EDU[illegible]



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Office Evacuation Observation Covers Levels of Familiarity with Building

Rubadiri, L. and Roberts, J.P.

Office Evacuation Observation Covers Levels of Familiarity with Building

Modelling to predict evacuation times in fire emergencies, with particular reference to disabled people, is the research area chosen by LINDIWE RUBADIRI for her doctorate at the University of Central Lancashire. In this article, Ms. Rubadiri and her supervisor, PROF. JOHN ROBERTS, describe a study of an evacuation exercise at Bolton Health Authority.

My observation of an evacuation carried out at Bolton Health Authority's building, Lancashire, emphasised the fact that behavioural aspects and capability to move are strong influences on evacuation behaviour and the total evacuation time.

The behavioural aspects investigated included the effect of familiarity on choice of exit and evacuation time. Sime and Kimura [1] state: "Peoples' exit choice behaviour is closely related to the normal patterns of circulation and configuration of exits". In the study the Level of Familiarity (LOF) was defined on an objective scale from 1 - 5 ranging from very unfamiliar to very familiar with the building layout. The LOF was represented on a questionnaire. The relationship between the LOF and evacuation time for a specified mean travel distance (to the final exit) and the relationship between LOF and travel distance within a given time was investigated.

Capability to move

Previous studies [2] have raised certain questions:

- Is the stairway width sufficient for a person to be carried in a wheelchair, or should arrangements be made for people to be transferred to a special carrying device?
- What arrangement should be made for member of staff to locate people who require assistance and guide them towards a place of safety?
- If a refuge is used as a temporary waiting area for people requiring assistance, to whom is the situation reported and at what stage is vertical evacuation initiated?
- By what means can someone with a mobility impairment indicate their presence in a refuge and their requirement for assistance?

In attempting to investigate the above issues the observation of a wheelchair user was one of the main focuses of this study. The purpose of the exercise was to provide a general response to the questions raised based on the Bolton Health Authority exercise.

Objectives of the exercise

1) To monitor the evacuation of the building and to determine quantitatively the extent to which familiarity with the building layout influences exit choice behaviour,

2) To determine the relationship between the LOF and evacuation time for a given distance and the relationship between the LOF and travel distance for a given time,

3) To monitor the evacuation of a wheelchair user from the 3rd floor of the building, identifying the strengths and weaknesses of the evacuation exercise.

Evacuation exercise

At 11:00 a.m. on Thursday the 11th of March, an evacuation was carried out at Bolton Health Authority which is a seven-storey office building (including the basement) with two stairwells and three exits on the ground floor.

A group of selected staff were given prior information of the drill. Six observers from the University of Central Lancashire assisted in data collection.

Observers positioned

Observers were positioned at the three exits leading out of the building. Two observers were positioned at the main entrance and two at one of the back exits. The other back exit leading from one stairwell was monitored by one observer. The sixth observer monitored the evacuation of the wheelchair user from inside the building to the final exit.

It was anticipated that the main entrance would be the used by a major percentage of the population. Questionnaires were handed out to evacuating occupants as they were counted and timed.

RESULTS AND ANALYSIS

Familiarity aspect: The result of the questionnaire survey revealed that the majority of occupants considered themselves familiar (LOF = 4) with the building layout. The range of LOF scores extended from 2 (unfamiliar) to 5 (very familiar).

The three most frequent reasons indicated for exit choice (in order of priority) were:

1) It was the nearest route;
2) Followed others;
3) Most familiar route.

For those with the lowest LOF scores, the signs showing 'FIRE' or 'EMERGENCY EXIT' seemed to assist with the evacuation of the building.

Familiarity with the route was a primary influence on exit choice. The highest LOF scores represented revealed that instruction to use that route was an important reason for exit choice.

The range of travel distances of occupants from their initial positions to the final exit were grouped. The mean distance in each group was determined. For each of the specified mean distances the change in evacuation time was investigated with the variation of LOF. For significant distances (in this case mean distance of 36m (199.5 ft) and above) it was found that the more familiar an occupant was, as measured by the LOF score, the more quickly they travelled a given distance in three of the four cases analysed. Change in travel distance with the variation in LOF for a given time revealed that occupants with the highest LOF travelled greater distances in a given time.

Capability to move

The average speed of movement three storeys down the stairwell with a width of 0.975m between the handrails was measured as 0.21 m/s. This was significantly lower than the speed obtained by Sime and Gartshore [3, 4], 0.41 m/s (stairwell width of 1.345m) and the Canadian studies, 0.5m/s. Stairwell widths were significantly larger in the latter studies.

Analysis and application

Proximity to an exit plays a significant role in the exit choice behaviour provided the occupants are familiar with the position of emergency exits. This can be achieved by training and encouraging staff/occupants to use all the available exits during fire drills.

None of the occupants used the 'back exit' which was nearer to them from the base of the stairwell on the ground floor than the main entrance. Although occupants selected the 'nearer route' option as a reason for exit route choice they actually passed the nearer exit to go to the familiar exit (main entrance). It can be argued that the assembly point outside the building was nearer the main entrance and more directly accessible than from the back exit; thus an additional reason to believe the main entrance was the nearest and most 'direct' route.

Building layout

Familiarity with the building layout is a significant element of evacuation behaviour There is an evident relationship between LOF and evacuation time in that increased familiarity may lead to quicker evacuation times and also shorter times to cover longer distances to get to the final exit. Further investigation is required in determining what actually increases flow velocity at higher LOF. It is likely that increased knowledge of the building layout is a motivating factor resulting in increased speed.

One consequence of the above finding is that it is worthwhile to encourage staff in office buildings to familiarise themselves more thoroughly with the building layout as part of the fire safety training plan.

The 'group behaviour' element was evident and confirmed that occupants do not respond to evacuation cues in isolation but tend to follow a 'leader' when leaving the building. This principle can be applied in a beneficial way by having marshals direct people out of a building during emergencies - a method applied by a number of organisations.

At BHA marshals ensure that every floor is cleared and report to the Fire Safety Officer. Rather than adopting a 'direct' leadership role they appear to have a more indirect authoritative role.

Evacuation of the wheelchair user

Regarding the arrangements made for staff to find disabled people, the BHA evacuation procedure [5] states that fire marshals in charge of the floors delegated to them should be informed whenever disabled people are present on the floor.

It states further that, " At THIS POINT it should be decided who in the event of an emergency, should take responsibility for the disabled person...". This worked quite effectively during the evacuation in so far as the marshal in charge of the wheelchair user responded promptly when the alarm sounded. However, she required extra assistance in carrying the wheelchair user down the stairwell. A delay was experienced as occupants leaving the building did not offer assistance.

From the previous studies carried out (4) the stairwell width between the centre-lines of 1.405m is equivalent to the maximum quoted in the *US Life Safety Code Handbook (Lathrop)*. Sime suggests that it would seem to be a minimum in terms of carrying a wheelchair user to safety.

The stairwell used by the group carrying the wheelchair user was just less than 1m wide between handrails. Two marshals assisted in carrying down the wheelchair user. A third fire marshal was slightly injured hitting his foot against the base of the wheelchair in attempting to provide further assistance. Manoeuvring corners at various stages proved time-consuming.

In most high-rise buildings rather than increase stairwell widths in buildings to allow for easier evacuation of disabled people refuges are provided in the stairwell lobbies. It is in these refuges that disabled people wait until the main flow of occupants has evacuated.

The evacuation procedure at Bolton Health Authority was efficient. The strengths and weaknesses experienced in the evacuation exercises are discussed on a regular basis and attempts are made to make changes in the training program where required.

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Towards a Coherent Approach to Engineering Fire Safety for Disabled People

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Towards a Coherent Approach to Engineering Fire Safety for Disabled People

In this paper, we suggest a coherent approach to engineering fire safety for disabled people based on a concept of the evacuation performance index *of classes of disabled people. This index is taken as the relative ease with respect to an able-bodied person of evacuating a disabled-person, and is founded on a consideration of the effects of disabilities and mobility aids on evacuation times. We show how this concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. We argue that the evacuation performance index of a class of individuals is primarily dependent on these three categories. Use of the index should enable assessment of the relative effects on the evacuation capability of an evacuee of changes to the amount and type of assistance provided to the evacuee, and changes to the building design and environmental factors.*

1 INTRODUCTION

1.1 Preamble

There has been increasing concern for improvement of the design and accessibility of adequate means of escape for disabled people, with a range of studies being carried out on the problem [1-4]. These, and similar studies in fire safety in general, have led to various formulations of quantitative and qualitative relationships between the numerous parameters in the field. Although information gathered from such studies is widely available in the form of research reports and fire safety legislation involving disabled people, the information is in general disjoint, in the sense that it focuses on a few critical parameters, and fails to relate them to one another in a coherent fashion. For example, the Building Regulations Approved Documents M [5] and K [6] define bounds on building dimensions such as appropriate door and stairwell widths, while BS 5588 Part 8 [7] emphasises procedural guidelines for evacuation that can be adopted by fire safety officers. However, both documents leave the burden of effective integration of their stipulations on fire safety officers and designers. Such flexibility is desirable since it allows engineering solutions to fire safety problems to be designed, as opposed to prescriptive and over-constrained approaches taken directly from codes of practices. However, there are currently no well-established fire safety design philosophies or methodologies which can be used as basis for coherently integrating the different applicable codes of practices in less traditional and less obvious fashions.

1.2 Background

Typical fire safety studies involving disabled people have adopted a comparative, dimensional, guidelines and ranking of priority parameters approaches.
The comparative approach: Studies involving disabled and able-bodied people performing egress-related activities have provided a reasonable basis for comparisons based on speed and time [1]. Such data has provided an indication of the amount of assistance required by disabled people to reduce their evacuation time. Marchant and Finucane [2] developed an alternative approach based on a concept of *patient mobility factor* in order to compare the difficulty of handling different types of patients in hospitals. This factor is dependant on the number of staff available to assist patients, the number of staff actions required to assist each patient, and the number of patients requiring assistance. In the comparative approach, emphasis is on computing ratios between parameters such as speed and level of assistance required, but little is done to develop more fundamental relationships.

The dimensional approach: The Building Regulations [5,6] focus on dimensional aspects of building design for fire safety, such as acceptable door and stairwell widths, handrail heights etc. However, there is limited information relating these parameters to procedural and behavioural aspects of occupants during evacuations.

The guidelines approach: The British Standard 5588 Part 8 [7] provides details on the procedure and order of evacuation of disabled people. The guidelines are particularly useful to management personnel of multi-storey buildings planning for emergencies. The standard introduces, along with other design considerations, the concept of refuges or protected areas in which disabled people on floors above ground level can wait for assistance. It provides a general and practical approach to design, which however, fails to recognise the quantitative relationships between parameters operating during emergency evacuations. In addition, Shields [4] notes that this standard offers no guidance on appropriate data for use in the design of, for example, means of escape.

The ranking of priority parameters approach: Hallberg [3] devised a rating system approach to determine an individual's highest risk element in the evacuation of elderly residents during fire emergencies. The system is founded on observation of the behaviour of elderly residents, and has been tested by observing their performance in fire drills. It consists of two steps, in the first, each resident is rated on the basis of daily observation by staff. In the second, scores on particular risk factors such as response to instructions or impaired consciousness are analysed. The overall need of a resident is taken as the single highest score on all factors. One advantage of Hallberg's system is that there is an adequate balance of emphasis on fire safety parameters particularly those relating to the amount of assistance required by residents in board and care homes. A disadvantage however, is the need to significantly modify the system in order to adapt it to venues of a different category under a different set of building regulations.

On the whole, whilst providing valuable insights to some of the factors involved in fire safety, the preceding approaches fail to define a general framework for designing solutions to fire safety engineering problems. Each approach is presented in isolation with no mechanism for integration with others. What is lacking is some common unifying thread, for instance, a design philosophy embodying a clear safety criterion, such that the approaches can be understood as elaborations of different aspects of the safety criterion, or techniques for computing some of its components.

1.3 Objectives

In this paper, we suggest a framework for devising engineering solutions to fire safety problems involving disabled people, based on an analogy with traditional engineering design. Through this analogy, we establish the need for a fire safety design philosophy founded on explicit notions of a *safety criterion*, *imposed loading* and *strength.* We suggest appropriate definitions of these concepts in fire safety engineering, but concentrate on the concept of "the strength of a class of disabled people". We investigate this notion of strength through the concept of *evacuation performance index*, which we define as the relative ease compared to an able-bodied person of evacuating a disabled-person, and which is founded on a consideration of the effects of disabilities and mobility aids on evacuation times. We show how this concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. We argue that the evacuation performance index of a class of individuals is primarily dependent on these three categories. Use of the index should enable assessment of the relative effects on the evacuation capability of an evacuee of changes to the amount and type of assistance provided to the evacuee, and changes to the building design and environmental factors.

By providing fire safety engineering a logical design philosophy, we increase understanding of evacuation of disabled people, and provide a simplified mechanism for fire safety design and planning of evacuation procedures.

2 FIRE SAFETY ENGINEERING DESIGN

In order to better appreciate the limitations of current fire safety techniques, it may prove worthwhile to review the underlying assumptions and philosophy on which design in some traditional engineering fields, for example civil engineering, is based. Design in civil engineering can be grossly defined as *the creation of a structure that safely performs some pre-specified functions;* whereas in fire safety engineering, it could be viewed as *the creation of structural and managerial arrangements which in the event of a fire emergency ensure that some pre-specified proportion of the*

occupants of a building can safely evacuate. Concentrating for the moment on the civil engineering definition, and ignoring its reference to functions and structure, we are left with the concept of safety. For each class of civil engineering design problem, there is an explicitly defined safety criterion which must be satisfied by all solutions to the problem. These criteria generally state that the intrinsic strength of structural elements must be capable of withstanding the loads imposed on them, or $f_S \geq f_L$, where f_S denotes the strength of a structural element, and f_L its imposed loading. Thus, civil engineering design is dominated by the computation of the strength of structural elements, and the loads imposed on them; and ensuring that the combination of imposed loading and strength satisfies the safety criterion. In the same vein, civil engineering design research is dominated by derivation of safety criteria for different types of structures, and formulation of techniques for computing the strength of structural elements and their imposed loading.
If one were to transpose traditional design to fire safety engineering, we would require a clear understanding of the equivalents of (i) safety criteria (ii) loading, (iii) strength, and (iv) how different structural and managerial arrangements impact on loading and strength. With these concepts in mind, in subsequent subsections we present our first approximations of fire safety engineering equivalents of these terms.

2.1 Safety criterion

In order to devise an acceptable safety criterion for fire safety engineering, it is necessary to revisit the goal of fire safety design problems. Roughly stated, this goal is too ensure that in the event of a fire emergency, occupants have sufficient time to evacuate the building without becoming incapacitated. Essentially therefore, the safety criterion should define relationships between different classes of fire emergencies and time to safely evacuate, or in other words, should embody the notion of tenability limits. In mathematical terms, we can state this criterion simply as $t_{TL} \geq t$, where t_{TL} specifies the time for tenability levels to exceed their allowable limits for different classes of fires, and t specifies the total evacuation time of the occupants of the building. Comparing this equation with that presented earlier from the civil engineering field, and noting that because the fire engineering criterion is expressed in terms of time we have to correlate terms on its left hand side to those on the right hand side of the civil engineering criterion, we see that t_{TL} correlates to f_L and should embody the notion of loading, while t correlates to f_S and should embody the notion of strength.

2.2 Loading

The time for tenability levels to exceed their safe limits depends on a number of factors, but primarily on the size and type of the fire source. The fire size determines the volume of effluents produced and its type determines the chemical nature of these effluents. Further, the fire itself can directly cause injury. Tenability levels are influenced significantly by structural measures such as sprinklers, compartmentation and pressurisation. Essentially, the fire and any factors affecting its growth, types of effluents produced and movement of these effluents determines the imposed loading.

Since our research is not on this topic, we can only urge for research into the effects of measures such as sprinkler design and compartmentation on the growth of tenability levels. We see one of the goals of such research being that of providing methods for computing t_{TL} for any given building and design fire.

2.3 Strength

The civil engineering concept of strength, the built-in resistance of structural elements to imposed loading, will in fire safety engineering correspond to the intrinsic capacity of occupants to evacuate a building. Thus, what we seek is some quantitative attribute of a person, for which given a building layout and the amount and type of assistance available to the person, we can predict the person's evacuation time. Such an attribute is basically that person's 'movement speed'; however, it would be unrealistic to expect that for a building occupied by a hundred people, for example, exact values of all their speeds are known in advance to enable design to proceed. Furthermore, utilising a single nominal speed is inappropriate, since this fails to consider the wide range of speeds of disabled people. A reasonable compromise is to experimentally determine nominal speed values for different classes of people, and to use these values in design.

We believe that the intrinsic speed of a disabled person depends principally on two factors: the person's disability and his/her mobility aid. Other factors such as assistance provided to the person or the structural layout of the building simply serve to modify this intrinsic value. Evacuation exercises performed by us, which are described later, suggest that taken in isolation, each of the two factors, that is, disability or mobility aid, is insufficient to determine intrinsic speed, since for instance, there is a wide range of speed values for wheelchair users with different disabilities. Our call for a classification system based on disability and mobility aids is not entirely new, but echoes that of Shields [4], although Shields does not note the effects of mobility aids.

Our arguments that classification of the evacuation potential of disabled people should be based on their disability and mobility aids expedites at least a cursory look at these two factors. Disabilities can be roughly categorised into those that directly impair movement and those that only indirectly do so. Of the former category, we have from impaired muscular co-ordination, through to loss of muscular action, to loss of all four limbs. One would expect the speeds of disabled people using the same mobility aid to decrease down this range, fastest when only the co-ordination of movement is impaired, and slowest when all four limbs have been lost. Of course, this actually depends on the mobility aid used, since for instance, if electric wheelchairs are being used, the speeds would probably be more or less the same. Of those disabilities that only indirectly impair movement, we have conditions such as blindness which demands a lot of mental effort in order to maintain direction; deafness which may cause an increase in response times due to a longer information gathering period or 'recognition phase' [8] when aural emergency alarms are used; mental retardedness, including the full range of drug- and alcohol-induced retardedness, as well as medical conditions such as senility, which similarly to deafness may increase response times and in addition, also impair muscular co-ordination. Again, one expects speeds to vary with each class of disability.

Mobility aids can also be classed into two groups, those that by their nature define a maximum speed that can be achieved by the user of the appliance, for example, electric wheelchairs; and those whose maximum speeds are determined by the user of the appliance, for example, manual wheelchairs, walking sticks, guide dogs and crutches.

In the next section, we analyse some of the effects of providing necessary assistance to disabled people and building design and environmental factors on their basic evacuation speeds. We perform this analysis by use of the concept of the evacuation performance index (EPI) of a disabled person. We define this index as the ratio of the unassisted speed of the disabled person compared to that of an able-bodied person along a straight and obstacle-free route. The index is intended to correlate with our notion of strength, and thereby evacuation potential, with a higher index indicating a higher evacuation potential. The concept of evacuation performance index shares similar philosophical origins as Marchant and Finucane's patient mobility factor [2] and Hallberg's concept of *evacuation capability* [3] which he uses to describe, among other things, the ability to understand and follow instructions, the ability to use the evacuation route and demonstrated performance during fire drills. However, EPI is the much more precisely defined and some of the factors implicit in patient mobility factor and evacuation capability such as staff assistance or the ability to understand instructions are considered to have secondary, though not unimportant, effects on the EPI of a person.

In the penultimate section, we discuss elements of a design procedure based on the concept of EPI.

3 EVACUATION PERFORMANCE INDEX

We view the evacuation potential of a disabled person as primarily dependant on three factors, the individual characteristics of the person, the amount and type of assistance provided to the person, and building design and environmental factors. Central to this is the individual characteristics of the person which is dominated by his/her disability and mobility aid, and thus determines his/her basic escape potential or evacuation performance index. The other two factors, assistance and building design and environmental factors impose constraints which might modify this basic EPI into an effective EPI. By effective EPI, we mean the evacuation performance which will actually be manifest in an emergency. Fig. 1 summarises in diagrammatic form our view of the inter-relationships between the three factors.

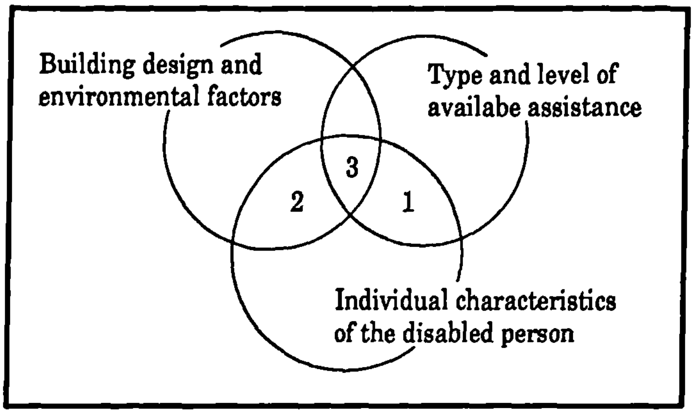

Fig. 1: Factors affecting basic and effective EPIs

Region 1 of the diagram represents the assistance that may affect the evacuation performance of an evacuee, but which is independent of building design and environmental factors. Region 2 denotes the building design and environmental factors which may affect evacuation performance independently of possible assistance that may be made available to the evacuee. In Region 3, there is full interaction between all three factors, and it seems to us that in most cases, design for safe evacuation of disabled-people falls in this region. With the aid of results from evacuation exercises, the balance of this section investigates some of the factors that affect the evacuation performance of evacuees.

The bulk of quantitative data used to study some of the factors influencing the evacuation performance evacuees was obtained from fifteen evacuation exercises involving five participants with different types of disabilities, and utilising different mobility aids. Table 1 summarises the details of the participants. The exercises involved each participant starting at a particular position (SP in Fig. 2) representing the point of discovery of a fire. From this point they proceeded to a call point (CP) and 'sounded' an alarm, and moved to a telephone (TP) to make an emergency call. They then left the room and proceeded to the final place of refuge (RP) by going through two corridors. Fig. 2 shows the route followed.

Person	Gender	Age	Disability	Mobility aid
P1	Male	21-25	Blindness from birth	Stick
P2	Female	31-35	Damage of the part of the brain controlling muscular actions — requires a lot of mental effort to co-ordinate movement. Impaired functioning of all four limbs, and retinal damage. (Cerebral palsy, quadriplegic and retro-entero fibroplasia)	Manual wheelchair
P3	Male	21-25	Brittle-bone syndrome (Osteogenesis imperfecta)	Electric wheelchair
P4	Female	15-20	Disabled lower limbs from birth	Manual wheelchair
P5	Female	31-35	Able-bodied	None

Table 1: Range of disabilities represented in the exercises

From the data obtained in the exercises, we computed each participant's average speed along two straight sections of the evacuation route (AA-BB and CC-DD of Fig. 2), and calculated the ratio of this speed to that of the able-bodied participant (P5), to obtain their EPIs (Table 2).

Participant	Average speed (m/s)	EPI
P1 (Blind)	1.18	0.63
P2 (Manual wheelchair user)	0.37	0.20
P3 (Electric wheelchair user)	1.92	1.03
P4 (Manual wheelchair user)	1.34	0.72
P5 (Able-bodied)	1.86	1.00

Table 2: Average unassisted speed of participants along straight routes

The results reveal, perhaps surprisingly, that the participant with the highest EPI was P3, the electric wheelchair user. This EPI was also significantly higher than those of the manual wheelchair users (P2 and P4). Note also, that the EPI of the quadriplegic manual

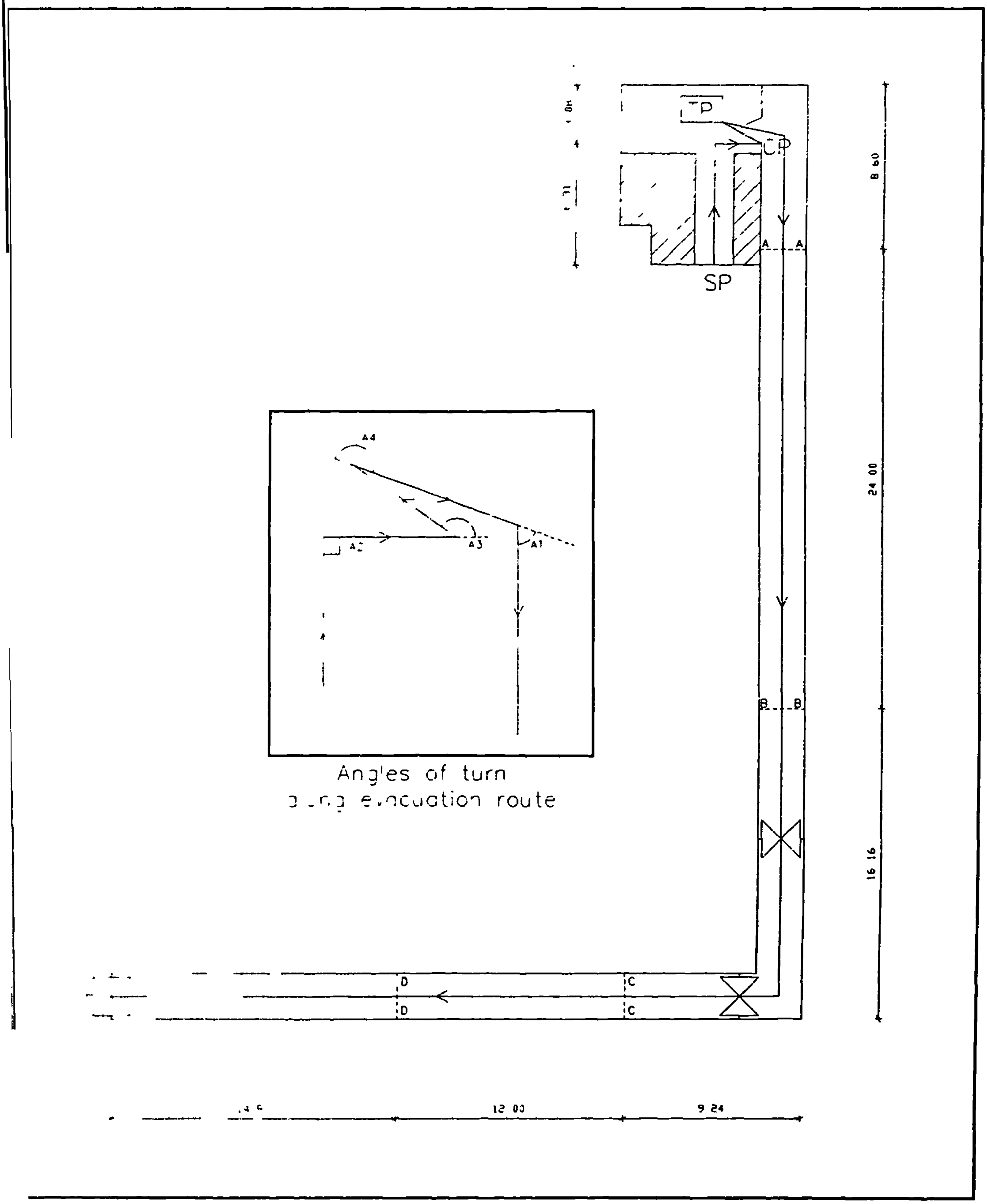

Fig. 2: Evacuation exercises: building layout and route followed

wheelchair user (P2) was significantly lower than that of the other manual wheelchair user. This could be attributed to the fact that quadriplegia and cerebral palsy result in reduced muscle development and muscular co-ordination, both making movement very difficult. These differences in EPIs does emphasise the fact that considered alone, mobility aids are only partial indicators of evacuation potential. Evidence in support of the fact that disabilities alone are also at best only partial indicators of evacuation potential is provided by results of exercises described in [9, 10] involving vertical evacuation of disabled people using a wheelchair and an *EVAC* chair. In this first exercise, a manual wheelchair user was evacuated from the third to the ground floor [9]. In the second exercise, a disabled person was evacuated one floor down using an *EVAC* chair [10]. In the case of the wheelchair, an average speed of 0.21 m/s was obtained compared to 0.62 m/s for the *EVAC* chair.

3.1 Assistance given to disabled people

Evacuation performance indices provide a quantitative method of easily evaluating the amount of assistance required by disabled people. Whenever necessary assistance is provided to evacuating disabled people, this has the general effect of increasing their speeds or EPIs. Unnecessary assistance typically leaves the EPI unchanged or may even reduce it. The effects of providing necessary assistance was displayed when the quadriplegic wheelchair user (P2) was pushed along the route by the able-bodied participant (P5), resulting in an increase in her EPI from 0.20 to 2.80. It is interesting to note that the EPI of the able-bodied participant whilst assisting the wheelchair user was also 2.80, that is, increased from 1.00, indicating that an able-bodied person can move at a greater speed when pushing a wheelchair or a similar appliance.

3.2 Building design and environmental factors

3.2.1 Environmental factors

The internal environment of a building, independent of those factors directly created by an emergency, may affect the evacuation times of people from the building. One such environmental factor which can potentially have severe adverse effects on effective EPIs is crowd densities on escape routes. Studies carried out by Fruin [11] and Ando et al. [12] show that in general speed reductions are inevitable at high crowd densities. We expect this problem to be worse when disabled people are present in an evacuating crowd. In our evacuation exercises, we observed that at low crowd densities, able-bodied occupants make purposeful attempts to avoid being an obstacle to disabled people. In some cases, they may even assist a disabled person by, for example, opening doors. Therefore, at low crowd densities effective EPIs are likely to be much greater than at higher crowd densities, even if only because the actions carried out by able-bodied occupants enhance the movement of disabled people. Further studies are necessary to investigate the variation with respect to crowd densities of EPI values for various disability and mobility aid combinations.

3.2.2 Building design factors

Building design has considerable influence on evacuation time and procedure. This is particularly so in the case of disabled people. According to Sime [13] the expression 'handicapped person' misleadingly suggests that the difficulty that a person may have, in entering and moving around a building is primarily a result of a physical or sensory 'disability' rather than a handicap caused by architectural design. He argues that "... in a sense we are all handicapped if a building has not been designed in such as way that we can use it in an optimum fashion". Architectural layout is an important consideration from the drawing board stage when designing for safe evacuation of occupants from a building.

In our study, the influence of building design on EPIs was investigated from two view points, namely, from the opinions of disabled people who completed a questionnaire, and by studying the effects of turning different corners on the speed of the participants in our exercises.

The questionnaire responses revealed that blind people find wide open areas disorientating, particularly in unfamiliar surroundings. This situation, they claim, worsens when a loud alarm bell sounds and a blind occupant needs to find the way out of a building.

As wheelchair users cannot use stairwells to move from one storey to another, they usually use lifts, although there is a limitation on their use during fire emergencies. In the questionnaire responses, complaints were made about the heights of lift call buttons, that they are generally difficult to reach. Heavy fire doors were also a cause for concern. There has been previous debate about the minimum amount of pressure that should be exerted on fire doors to enable weakened people and people with limited co-ordination to use the doors easily [14]. A compromise has to be reached because reduction in pressure required from reduced weight of fire doors would sharply decrease their ability to self-close and self-latch. Efforts should be made to develop fire doors with opening and closing characteristics that ensure they can be operated by handicapped people but still serve their purpose as fire doors.

We investigated the effects of turning different corners on the speed of participants since in order to traverse the evacuation route in the exercises, participants had to turn through a number of angles of different degrees (64°, 90°, 148° and 172° marked A1-A4 in Fig. 2). In this paper, we take angle of turn to mean the angle through which a person turns relative to his original direction of motion (Fig. 3).

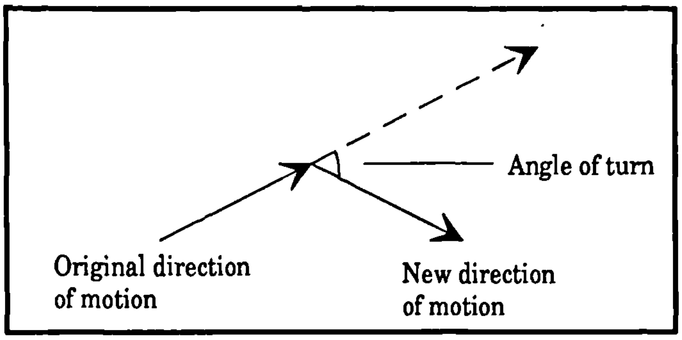

Fig. 3: Definition of angle of turn

Fig. 4 shows in graphical form the variation of angle of turn against angular velocity for each participant over the three sessions. In Session 1 we observed that each participant had a preferred angle of turn at which they were fastest, with the exception of the blind participant (P1). He experienced averagely lower angular velocities than the other participants, and in addition, the flat nature of the curve suggests that all turns posed him roughly the same degree of difficulty. In familiarising themselves to a particular surrounding, blind people normally require a number of 'walks' around the place in order to develop a mental map of the layout. Thus, in unfamiliar surroundings, they experience great difficulty in moving around, especially going round corners. The electric wheelchair user (P3) experienced a reduction in angular velocity with an increased angle of turn from 90° to the range of angles above 90°. This could be explained by the fact that the operation adopted to turn the wheelchair requires greater manoeuvring. The able-bodied occupant experienced the highest range of angular velocities.

In Session 2 the same pattern of preferred peaks is evident, this time in all cases. As the blind participant familiarises himself with the evacuation route the pattern of angular velocities can be likened to that of a sighted person. His range of angular velocities increased and were more compatible with those of the other disabled participants.

In Session 3 the pattern of preferred peaks was evident once again, with the exception of the manual wheelchair user (P4). His angular velocity increased to a constant value from 90° to the range of angles above 90°. Familiarity with the exercise, or perhaps boredom due to repetition, appeared to result in a gradual decrease in the angular velocities of the able-bodied participant over the three sessions.

The above results suggest that there seems to exist a relationship between angle of turn and angular velocity, and their effect on EPI values. Further, at particular ranges of angle of turn there will be a maximum EPI. For different types of disabilities and mobility aids these maximum EPIs may not necessarily occur at the same angle of turn.

From the design point of view, consideration should be made regarding the positioning of call points, telephones, door handles, lift buttons and all other appliances that need to be used during evacuations. EPIs could provide an indication of the ideal positions of these appliances such that during emergencies maximum speeds and efficient evacuation procedures are obtained.

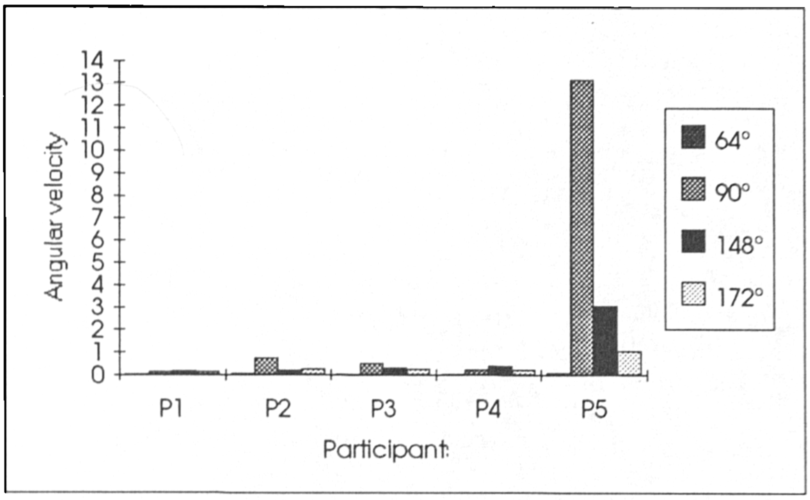

Fig. 4a: Angular velocities of participants in Session 1

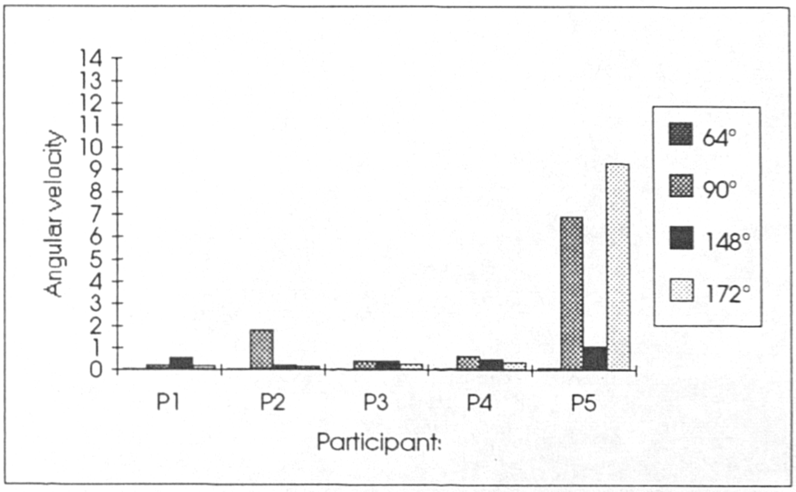

Fig. 4b: Angular velocities of participants in Session 2

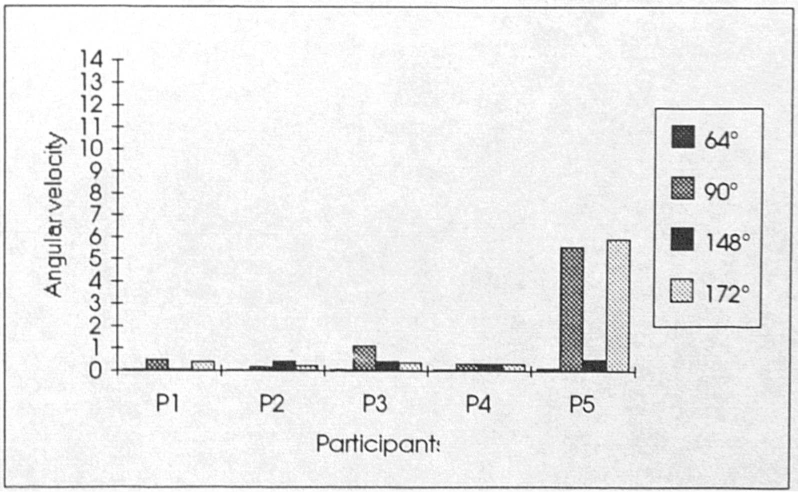

Fig. 4c: Angular velocities of participants in Session 3

4 ELEMENTS OF A DESIGN PROCEDURE BASED ON EPI

Having looked at some of the factors that can affect the evacuation performance of a person, in this section, we present the elements of a fire safety design procedure based on (i) classifying evacuees according to their disability and mobility aid, (ii) experimentally determining nominal evacuation performance indices for each class, and (iii) devising quantitative relationships that describe the effects of assistance available to evacuees and building design and environmental factors on the EPIs.

Assume, for example, that the governing design standards specify:

1. disability-mobility aid distributions for different occupancy types, that is, the range of disability and mobility aid combinations assumed to be present in each occupancy type, and the proportion of occupants which should be assumed to have each combination,
2. a nominal EPI for each disability-mobility aid combination, and
3. expressions defining quantitatively the effects of assistance and building design and environmental factors on the EPI of each disability-mobility aid combination.

Design in such a case may proceed along the lines of, for each evacuation route out of the building:

(a) First, the designer computes the time t_{TL} for tenability levels to exceed their allowable levels, and the travel distance d through the escape route.

(b) Second, the effective EPI of each disability-mobility aid combination along the evacuation route is calculated. This calculation will utilise the expressions defined in Step 3 above to take into account any assistance which will be available to disabled evacuees, and any building design and environmental factors of the evacuation route that might modify the nominal evacuation performance indices of the evacuees.

(c) Next, the worst case evacuation time t_w, is computed from the equation $t_w = \dfrac{d}{I_m \times v_o}$, where I_m is the smallest effective EPI computed from Step (b) above, and v_o is the nominal evacuation speed of an able-bodied person. Note that v_o itself varies with building design and environmental factors, although not with level and type of assistance.

(d) Finally, the designer ensures that $t_{TL} \geq t_w \times SF$, where SF is a factor of safety.

If the inequality $t_{TL} \geq t_w \times SF$ cannot be satisfied, the designer has to modify the assistance to be made available to disabled evacuees and the building environmental factors such that Step (b) returns a high enough I_m. However, if the fire safety evaluation is being performed at the architectural design stage, then the layout of the building may be modified so that Step (a) returns a higher value for t_{TL} or a smaller value for d. Note that once the inequality has been satisfied for a particular combination of level and type of assistance to be made available to evacuees and building environmental factors, then managerial steps have to be taken to ensure that these conditions prevail in an emergency.

5 CONCLUSIONS

In this paper, we have attempted to define the elements of a coherent procedure for fire safety engineering design. We argued that such a procedure should be founded on a classification of people based on their disability and mobility aids. We introduced the concept of the evacuation performance index of disabled people as a quantitative measure of their evacuation potential. Next, we argued the evacuation performance of an evacuee depends primarily on his/her individual characteristics, but also on the amount and type of assistance available to the evacuee and on building design and environmental factors. Finally, we presented a procedure for design based on this notion of evacuation performance indices.

Further work on the subject could include an investigation of the effects on EPIs of more factors other than those considered in this paper.

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Evacuating Workers with Disabilities: A Review of the Effects of Mixed-Ability Populations on Evacuation Model Predictions

Rubadiri, L. and Roberts, J.P.

Evacuating Workers with Disabilities: A Review of the Effects of a Mixed-ability Population on Evacuation Model Predictions

Present-day emphasis on design of buildings that are accessible to disabled people has brought with it a requirement to ensure their safe egress. The increasing pressure to improve fire safety standards by improving designs has warranted the use of modelling techniques to identify some of the critical factors that operate during emergencies. A case study carried out in a 10-storey office building, illustrates the different ways of assessing the time needed to evacuate a mixed-population including some people with disabilities and the author offers advice to those assessing whether their current evacuation methods are adequate.

Introduction

With more than 800 deaths a year in the UK resulting from fire, and many times this number suffering injuries, fire safety is a issue of national concern. In order to reduce the possibility of fire or protect occupants from its inevitable danger, researchers have sought to study the process of fire growth and the behaviour of people exposed to fire and its effluents. Subjecting people to real fires in buildings to observe movement and behaviour is unethical so it has been necessary to use simulation methods to represent human behaviour and movement during emergencies, a concept otherwise termed as evacuation modelling. These are several different approaches to modelling each with their strengths and limitations.

Models have occasionally been categorised into groups in accordance with their underlying principles [1], providing, as a result, a basis for analysis and comparison.

Analysis of current modelling approaches

Some form of measurement is essential for the purpose of identifying and determining relationships between parameters such as speed and travel distances. Modelling is a method of representing the relationships that exist between parameters in a system and is therefore adopted for defining the complex, dynamic and interactive processes in fire emergencies. Models help consolidate existing knowledge and highlight gaps in that knowledge in given areas of research [2]. Modelling is not a simple exercise as numerous assumptions are made during their development. Kendik's opinion [1] on major evacuation models analysed is that, "... all of them appear. to make several assumptions partially to overcome gaps in technical literature which makes their validation against real world events or fire drills necessary". It is important to see the quantitative and qualitative aspects of models in the right context and not to attach an unjustified significance to numbers which result [3].

Most models fail to account for the effect that disabled people have on an evacuating population. The resulting effect is significant because occupants with various disabilities may have mobility problems that may hinder crowd movement or alter patterns of movement, further influencing evacuation times and procedure.

Models that do focus on evacuation capabilities of disabled people are few and tend to be scenario-specific, meaning their predictions cannot be applied on a general basis. There have been some attempts to collect more quantitative data from evacuations involving disabled people, the results are made available in form of isolated research reports. A general framework linking all available data is essential in order to adopt it comprehensively in design procedure.

Categories of models

There are no hard and fast rules for categorising models and in a number of cases there is some degree of overlap in the factors that are considered in each category. The two main categories considered are mathematical and psychological. Mathematical models are sub-divided into empirical, analogue and systemic models. Psychological models can be conceptual or computer models. In each category, model principles are briefly discussed, their assumptions are stated, strengths and limitations analysed. The overall value of each category is judged on the basis of its inclusion or acknowledgement of the presence of disabled people in the evacuating population and the consideration of the implication of their presence on evacuation time and procedure.

Psychological models

Models in this category focus primarily on behaviour of occupants during emergencies. The first category of psychological models, conceptual models [4] include a theoretical design in a model that attempts to provide an understanding to the decision-making processes of an individual involved in a fire incident. Computer models, on the other hand, adopt computer techniques to represent or demonstrate behavioural aspects and to simulate movement.

The most recent conceptual model that simulates behavioural changes in relation to environmental conditions, is Proulx's stress model [5]. This model illustrates the complexity of the interaction of processes an occupant may experience during an emergency and a user's effort to psychologically cope with a fire. Emotional stages of control namely, uncertainty, fear, worry and confusion are defined in relation to changes in emergency conditions around an occupant. Proulx argues that excessive stress can impair cognitive processes and therefore must be reduced in such a way as to allow a person to interpret a situation accurately and execute appropriate decisions. Prompt response to alarm, an easier problem-solving process and a reduction in stress will be attained if precise information concerning an emergency is available to occupants.

Sime's comprehensive collection of human behavioural studies include investigation of the effects of familiarity with a building layout on evacuation behaviour [6], effects of affiliation ties [7] etc. Such studies have shed light on several important aspects of emergency behaviour. He identifies a 'gathering phase' [8] that occurs between the onset of a cue to evacuate and the time to actually move with the intention of evacuating. Many models consider only the time required to move through evacuation elements as a primary measure of total evacuation time, Sime has introduced this time additional time phase as a significant delay factor.

Only a few studies have been carried out with disabled people to examine the conceptual processes they undergo in emergencies. One such study involves the analysis of way-finding techniques of visually impaired occupants. Passini and Proulx's studies [9] on decision-making processes and way-finding techniques of congenitally blind occupants revealed that more decisions were made and more detailed planning done in preparation for a journey to a given destination when compared to a sighted control group. Similar studies on various groups of disabled people are essential to determine their real needs in moving around buildings.

The alternative to conceptual models, the use of computer techniques to simulate human behaviour, has been increasing significantly with advancing technology. Virtual reality simulating techniques appear to have stolen the show in the current arena of behavioural studies in fire emergencies. The VEGAS (Virtual EGress Reality and Analysis Simulation) system [10] is capable of modelling the net effect of fire and human behavioural response under various variable stress conditions. The underlying principles of the system are based on 'order from chaos' or 'anti-chaos' theory which explains behaviour as net effects of complex decision-making processes having a finite probabilistic outcome for an evacuating group of occupants.

One of the strengths of this model is its ability to programme each 'human' character to respond according to one's proximity to fire or smoke, time from initial alarm, proximity to exit and behaviour of one's neighbours. An additional benefit of the system is the interactive and visual nature of its operating environment which allows observers to alter physical parameters within the virtual reality realm while the system is running and to view the resultant effects. As physical parameters can be easily altered, individual characteristics of occupants can be simulated, such as movement patterns of disabled people.

Other contemporary computer models such as BFires [11] include a wide range of occupant characteristics in their analysis.

Mathematical models

Mathematical models have been described as phenomenological models and simulate the actual physical phenomena that affect safety. They can be probabilistic, in that a range of possible occurrences is allowed for, or they may be deterministic which means that they are scenario specific and predict single possible outcomes.

Pauls' effective width model [12] is an example of an empirical model based on knowledge of mean flows and evacuation starting times. It was developed from observation of studies in stairwells of high-rise buildings.

According to his observations one of the most important aspects of building evacuation is the relationship between rates of flow and the width of stairs down which occupants move. The other significant aspect is the total evacuation time of the building.

The effective width model is applicable to high-rise buildings and large populations, a combination of factors that would create difficulties in evacuating disabled people.

From Canadian studies [12], an estimate was made that about 3% of the population of high-rise buildings could not or should not evacuate down stairwells in a crowded situation during an emergency. According to Pauls, participation of disabled people in the fire drills he observed, disabled people had no effect on mean flows. When disabled people reduced the flow in their immediate vicinity it was countered by increased flow later.

Shields [13] analysed more specifically the effects of disabled people with different mobility aids on evacuation times of a mixed ability population. His findings highlighted the differences in occupants' movement abilities depending on their disabilities and mobility aids. His studies are among the most recent on evacuations involving disabled people, with actual quantitative data collected and relationships of critical parameters derived from first principles. Previous studies included work by Pearson and Joost [14], Hallberg [15] and others.

It appears that while empirical studies involving disabled people have provided some valuable quantitative data, this data or methodology is presented in isolation with no mechanism for integration with other data. What is lacking is a common unifying thread or design philosophy that embodies a clear safety criterion such that various approaches can be seen understood as elaborations of different aspects of a basic safety criterion or techniques for computing some of its components [16].

A Case Study - An evacuation at Palatine House (Preston)

In order to demonstrate the effects of a disabled person in an evacuating crowd, a case study was carried out at an office building to observe the pattern of movement of the able-bodied population and the procedure of evacuating a disabled person using an *EVAC* chair. Palatine House, where the evacuation was monitored, is a 10-storey office building served by one main staircase and one emergency staircase on the opposite side of the building.

An evacuation was carried out during the morning of 26th of May 1993 as part of the organisation's campaign for safety awareness in their premises. When the alarm went off, the total evacuation procedure was adopted whereby all occupants evacuate at the same time. It was assumed that the emergency stairwell was blocked off by fire therefore only the main stairwell was used. The authors observed the movement of occupants as they left the building.

The procedure would generally require the able-bodied population to evacuate first while any disabled person requiring assistance would wait in the lobby area so as not to hinder others. This appears to be a reasonable procedure as the appliances that are used to evacuate disabled people, in this case the *EVAC* chair, are usually of a width that would occupy a significant proportion of the stairwell width.

Findings

The 398 occupants present were evacuated in 6 minutes 23 seconds. Two major delays were experienced as evacuation proceeded down the main stairwell, one 126-second delay and one 7-second delay. The average time taken to descend from a floor to a landing was 9 seconds. The first major delay would have been equivalent to descending 7 floors (14 floor to landing intervals) and therefore was a significant delay factor.

The average speed of descent of an able-bodied person, unimpeded, was 0.75m/s just over Fruin's value [17] for the horizontal component for a fast walk down a stairwell of 0.70m/s. The average impeded speed down the stairwell due to crowded conditions was 0.5m/s. The average unimpeded speed of evacuating the occupant on the *EVAC* chair was 0.62m/s.

Conclusions

Evacuation modelling techniques serve as an evaluation tool to assess the effects of these aspects on occupant evacuation time. While these techniques have some theoretical value, they are insufficient in themselves to assess occupant movement and behaviour. Observation of real evacuation exercises or fire drills must also be done to provide a clearer understanding of escape behaviour and to provide an idea of typical evacuation times.

Observations from the Palatine House evacuation described in this paper highlighted the following important points:

- In planning evacuation procedures, management personnel should recognise that evacuation capabilities may vary considerably among mixed-ability populations and must ensure that their escape strategies are adequate for all occupants.

- 'Bottlenecks' usually result from merging between groups of occupants leaving a floor of a building and attempting to join the rest of an evacuating crowd using a stairwell. Queuing and subsequent time-consuming delays occur as a result. The positions of potential bottlenecks could be identified whenever fire drills are carried out and the duration of resulting delays should be recorded. These records would be a useful indication of the success or failure of an evacuation strategy. It may well be that a phased evacuation procedure would be more appropriate than a total evacuation procedure where bottlenecks and delays are more likely to occur. In such a case the building would need to comply with the Building Regulation requirements for phased evacuation [18].

- It is useful to record the number of occupants and their evacuation times in each stairwell during each fire drill. Their average rates of flow through the base of the stairwell could then be calculated. In this way, the measured values could be compared to typical flow rate values (certain sources have suggested a rate of 1.1 persons m^{-1} s^{-1} [19]) so that flow rates that are much higher or much lower than the desired value would be easily identified and the evacuation strategy could be modified accordingly.

- The techniques adopted by management personnel for evacuating disabled occupants should be discussed and agreed with them. Evacuating a disabled person using their mobility aid, for example, carrying an occupant in a wheelchair down a stairwell rather than transferring them to an alternative device, may be a preferable arrangement.

- Frequent and adequate training in safe carrying techniques should be encouraged among staff designated to assist disabled people during emergencies. This would enable management to regularly assess evacuation strategies for disabled people and would provide opportunities for staff to practice the techniques thus instilling greater confidence during emergencies.

- Management personnel have the responsibility to decide whether a separate evacuation procedure for disabled occupants is necessary. If disabled people are likely to hinder the movement of able-bodied occupants in a joint evacuation, it may be necessary to keep the disabled occupants in a refuge area with a fire warden while the rest of the occupants evacuate [20]. However, it should not always be assumed that disabled occupants will hinder the general occupant flow as they may in some cases be able to evacuate with the able-bodied population without any problem.

- The procedure for evacuating a disabled occupant may not necessarily be a slower process than evacuating an able-bodied population. The average speed of the able-bodied population in the evacuation exercise was 0.5 m/s, while that of the occupant in the *EVAC* chair was 0.62m/s. Since disabled occupants are normally the last to be evacuated, the time they spend in a refuge is significantly influenced by the speed at which the able-bodied crowd evacuates. There must be equal emphasis on improving the evacuation strategy of able-bodied occupants as there is on improving procedures for evacuating disabled occupants as the two sometimes have a significant effect on each other.

- The location of occupants requiring assistance must be quickly and easily ascertained during an emergency. The evacuation procedure at Palatine House has adopted the use of an 'evacuation card' which is supplied to all disabled staff. This card, which informs fire safety staff about the need for assistance, is handed over to a member of staff at the start of an evacuation. It is then handed to the fire brigade if the disabled occupant and the persons assisting have not yet evacuated the building by the time they arrive. This is an example of a strategy that can be adopted.

The ongoing observation and monitoring of evacuations involving disabled people has enabled the authors to design a flexible evacuation methodology based on a concept of an Evacuation Performance Index (EPI) of various classes of disabled people. The EPI is defined as the relative ease compared to an able-bodied person of evacuating a disabled person. The concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, amount of assistance they require and building design and environmental aspects. The index is modified by effects of assistance, environmental conditions and building design. This means that the specific changes in evacuation capability, that are often overlooked or underestimated, are more easily observable and can be altered as required. For example, the technique used to evacuate a wheelchair user down a stairwell could be assessed on the basis of stairwell design features. A narrow stairwell may create difficulties for occupants assisting in carrying a disabled person down a number of floors and the use of an *EVAC* chair may be a better option. The EPI provides a quantitative measure of the effect of using these modes of evacuation; the result being that the method of evacuation adopted can be judged on the basis of an actual measure of evacuation performance.

There is no hard and fast rule for designing a fixed evacuation strategy. However, legislative guidelines on evacuation should be adopted by management along with the their individual fire safety plan that is governed by the building type and purpose. Evacuation procedures should be assessed and modified where necessary with the assistance of fire safety authorities.

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Research Developments: Evacuating Mixed-Ability Populations

Rubadiri, L. and Roberts, J.P.

A Review of Research Developments in Evacuation Modelling of Mixed-Ability Populations

*The following article by **L. Rubadiri** and **J.P. Roberts** of the Department of Built Environment, University of Central Lancashire, examines some of the recent techniques, known as "modelling", which can be used in deciding how best to design means of escape for populations which include people with disabilities.*

Evacuation modelling serves as a tool to analyse factors that influence the time taken for occupants to escape from a hazardous situation such as a fire emergency. Certain weaknesses are evident in current modelling approaches, one primary limitation being the shortage of empirical data on the movement patterns of disabled people. Their movement is likely to be hindered due to either a disability they may have or a handicap in the design of the environment. This article briefly reviews the modelling techniques adopted to analyse the movement capabilities of mixed-ability populations in emergencies.

Evacuation modelling

Modelling is used to define the complex, dynamic and interactive processes in operation during the development of a fire. It provides a basis for evaluating stages in the development of a fire and consequent responses of occupants attempting to escape from a building.

The choice of stages or factors analysed is generally determined by the discipline of the model developer. Psychologists, for example, tend to emphasise *human behavioural* aspects while engineers may, in contrast, emphasise *structural and mechanistic* aspects of fire development. Ideally, a balance between approaches is desirable in the form of a unified model that incorporates a multi-disciplinary approach to evacuation behaviour.

Evacuation modelling is useful as a predictive tool which serves as an indicator of factors that hinder or enhance occupant movement. It enables the identification of potential bottlenecks and assesses the reliability of evacuation procedures used particularly in multi-storey buildings where there are relatively large populations.

The basic principle of evacuation modelling is to ensure that for a proposed building design, the time taken before fire resistance exceeds allowable limits for different classes of fires will be greater or equal to the maximum likely evacuation time of the occupants to leave a building.

The time for tenability levels to exceed their maximum limits depends on a number of factors, but primarily on the size and type of the fire source. The fire size determines the volume of effluents produced, and its type determines the chemical nature of these effluents. The maximum likely evacuation time, t, is generally governed by the physical and behavioural characteristics of occupants as well as the external factors such as building design aspects that affect these characteristics.

Models to investigate the evacuation of mixed-ability populations

Three basic ideologies in evacuation modelling of mixed-ability populations are evident:

1. **The qualitative approach:** is based on predictions of occupant movement using guide-lines that formulate the design of evacuation procedures and means of escape elements. BS 5588 Part 8 [1] is a classic example in its provision of procedural guidelines for evacuation of disabled people. It, however, fails to recognise the importance of quantitative relationships that are useful to the design of means of escape. The management guide-lines it provides are rather vague and do not have, for example, information on economic staff levels assigned to monitor evacuation procedures [2].

   However, its flexibility is desirable since it permits the use of various engineering solutions to fire safety problems, as opposed to prescriptive and over-constrained approaches of several codes of practice. Further guidelines are provided in the Personal Emergency Egress Plan (PEEP) [3] which is a questionnaire-styled approach completed by disabled employees who are required to give their views on suitable methods of evacuation.

2. **The weighting factor approach:** involves assigning weighting factors to the parameters relating to occupant mobility [4, 5, 6]. These factors include the ability to respond to an alarm, the pace of movement and the type of warning system used. The main application of this approach has been in monitoring evacuations involving elderly people in board care homes, although it can be applied to a wider occupant profile. One advantage of the system is that there is an adequate balance in the assessment of fire safety parameters, i.e. both structural and those relating to occupants. One disadvantage, however, is the

need to significantly modify the system in order to make it adaptable to varied building types that are subject to different regulations.

3. **The prescriptive approach:** entails the provision of dimensional values such as maximum distances to fire exits, suitable door and stairwell widths [7, 8]. Parameters that influence the behaviour of occupants using a typical evacuation route are often ignored. Pre-evacuation behaviour of occupants, in particular, has been shown to significantly influence evacuation times. This approach is therefore lacking in this respect.

All the approaches provide valuable insights on some of the factors involved in fire safety, but fail to define a general framework for designing solutions to fire safety engineering problems.

Each approach tends to be presented in isolation with hardly any mechanism for integration with others. What is lacking is some common unifying design philosophy embodying a clear safety criterion.

A coherent approach

A coherent approach in evacuation modelling has been suggested based on a concept of an Evacuation Performance Index (EPI) [9]. Defined simply, it is the relative ease of evacuating a disabled person to evacuating an able-bodied person. It is founded on a consideration of the effects of disabilities and mobility aids on evacuation times.

The concept relates three aspects of fire safety, namely, individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. The EPI of a class of individuals is considered to be primarily dependent on these three categories. Use of the index should enable assessment of the relative effects on the evacuation capability of an evacuee of changes to the amount and type of assistance provided to the evacuee, and changes to the building design and environmental factors.

The practical application of the EPI concept is confirmed by observation and monitoring of occupant movement during fire drills. It provides a strategy for measuring each occupant's escape potential as one travels along individual sections of a given evacuation route. EPI's benefits include the following:

- It can identify the key factors that influence occupant movement and can measure their relative effects. The results from observations provide insight to the design of evacuation procedures.

- It can be used in a design procedure for an actual calculation of the worst possible evacuation time. The procedure demonstrates the changes in evacuation time for a given route when the EPI is high or low and the changes in time when parameters such as travel distance are altered.

The EPI concept does not favour one technique of evacuation modelling over another but rather provides a framework to integrate the different methods of measurement while sustaining a comprehensible classification system for classes of disabled people.

There appears to be shift towards quantitative measurements of evacuation capabilities of occupants in order to provide a more effective basis for means of escape design.

Conclusion

There is great potential for the design of improved strategies for evacuating mixed-ability populations using research findings.

However, the diversity in research methods has led to isolated studies providing potentially useful information that is not utilised to its full capacity. In addition, the lack of empirical data on evacuation capabilities of disabled people has been a major shortcoming. The concept of a coherent approach which links research findings in evacuation modelling has proved to a valuable tool enabling the efficient transfer and use of model predictions in means of escape design.

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Assessment of Human and Structural Safety of Sports Grounds

Rubadiri, L., Ndumu D.T. and Roberts J.P.

Assessment of human and structural safety of sports grounds

Evaluation de la securite des humains et des structures des terrains de sport

Testverfahren von human und struktureller sicherheit auf dem Sportgelände

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SUMMARY
This paper describes a flexible automated decision-support system for assessing the safety of sports grounds. The system focuses primarily on three factors: the occupancy, management and structural aspects. It considers the overall interdependencies between these factors, and makes managerial and design recommendations for improving the safety of a venue.

RÉSUMÉ
Cet article décrit un système flexible de décisions d'appointment automatisées afin d'évaluer la sécurité des terrains de sport. Le système converge primitivement sur trois facteurs: l'occupation, l'orientation de la structure et de la gestion. Le système

prend en compte l'interdépendance générale de ces facteurs, et engendre des suggestions pour le design et la gestion afin d'améliorer la sécurité de l'ensemble.

ZUSAMMENFASSUNG

Dieses dokument beschreibt ein automatisches, entscheidungsunterstützendes, flexibles System, Sicherheit auf dem Sportgelände, zu integrieren. Das Zusammenhang zwischen die folgende drei Hauptfaktoren wird betrachtet: die Belegung, management und strukturelle Aspekte. Das System enthält geschaftsführende und design Empfehlungen, um die Sichenheit auf dem Sportgelände zu verbessern.

1 INTRODUCTION

There has been a continual attempt to raise safety standards of places of close assembly, for example, sports grounds. Major disasters including the incidents at Ibrox stadium (1971), Bradford (1985) and Hillsborough (1989) in which many people died and extensive damage was experienced, have led to more stringent scrutiny of safety legislation. Guidelines on measures for improving safety of spectators at sports grounds first became available when the Wheatley Inquiry was published after the Ibrox Park disaster [6]. Along with the Safety of Sports Ground Act 1975, these guidelines formulated the basis of the document commonly known as the 'Green Guide' [7]. Revision of this guide resulted from the Popplewell Inquiry [11] that followed the Bradford Football Stadium disaster. Further changes were incorporated, based on recommendations made in Lord Justice Taylor's inquiry, after the Hillsborough tragedy [14]. The Guide basically outlines measures for improving spectator safety and applies to all types of sports grounds where accommodation is provided for spectators [8]. In this paper, the authors concentrate on football stadia which have a long history of major and minor crowd disorders. In addition, football attracts a large number of spectators making their safety an item of primary concern.

The assessment of sports grounds before, during and after an event is a time-consuming and costly exercise requiring much co-ordination and planning. Because of the excessive number of factors that have to be considered in the assessment process, the assessment personnel generally suffer from a cognitive overload of information. This overload tends to result in some fairly obvious scenarios not being anticipated at all, or the implications of a change in a parameter not being completely appreciated. A significant amount of assessment is done from experience but it is rightly stated [15] that, "...those dealing with disasters and their prevention know that they have to continually re-learn old lessons stated in new ways".

In order to significantly speed up the assessment of sports ground safety, and to provide a system whereby the influence of different parameters on a safety plan can be thoroughly investigated, the authors suggest a flexible model, implemented as a knowledge-based decision-support computer program that contains relevant evacuation, crowd behaviour and structural safety knowledge.

2 BACKGROUND

Evacuation modelling has been a useful technique in simulating human behaviour and movement patterns of occupants and has been used by several researchers to investigate the effects of various parameters on evacuation time and procedure [1,5,9]. In this paper, the authors have utilised certain evacuation modelling principles in the design of a safety assessment system for sport grounds.

2.1 Basis of the assessment model

Three factors are critical in affecting safety: occupancy, management and structure of football stadia. In order to identify critical parameters that operate during emergencies, and to develop relationships between these factors, the authors adopted the molecular kinetic theory of gases as the basis of a safety assessment model. The molecular kinetic theory of gases [2] relates the temperature, pressure and volume of a gas by the equation $PV = nRT$; where P denotes pressure, V volume, T temperature, n the number of moles of the gas, and R the real gas constant.
For a constant volume, the pressure of a gas varies linearly with its absolute thermodynamic temperature. Temperature is a measure of the kinetic energy of the molecules. Raising the temperature results in an increase in the velocity of the molecules and consequently, an increase in the frequency of collisions that the molecules experience with each other and with the sides of the vessel containing them. This is manifested as a pressure increase. This basic behaviour shares certain similarities with that of a large number of occupants in confined spaces, at least in the two-dimensional sense. The kinetic theory is adopted purely to generate conceptual ideas that simulate human behaviour. Differences between the two concepts have been accounted for in the assessment model.

The analogy between molecular kinetic theory and a real-life emergency on a sports ground is evident form the following scenario: Assume gaseous molecules represent occupants while the vessel containing these molecules represents the stadium. A fire, for example, on any part of a ground would stimulate some response from occupants. After they perceive the fire as endangering their lives they would attempt to leave the ground to go to a place of safety. As a result of the fire, speed of movement of occupants as they attempt to distance themselves from the danger, would most likely increase as would the number of collisions or impacts between the occupants and between occupants and the physical structures in the stand. Thus 'temperature rise' or an emergency has an effect on occupancy, management and structural aspects. Table 1 summarises some of the analogies between molecular kinetic theory and the assessment model.

Molecular kinetic theory	Assessment model
Concentration of molecules	Density of occupants in football stand
Uniform or non-uniform mixture	The distribution of occupants in accommodation areas
Type of molecules	Type of occupants present (disabled, able-bodied, young, old, in groups, etc.)
Forces of attraction between molecules	Affiliation ties between occupants
Material of the vessel	Structure of the stand
Path of motion of molecules	Movement patterns of occupants

Table 1: Analogy between molecular kinetic theory and safety assessment model

2.2 Observations from evacuation study

The kinetic theory analogy of crowd behaviour was reinforced by observations of a football stand evacuation exercise carried out at Preston North End football ground [12]. The stand evacuated was the Fulwood End terrace which has a maximum holding capacity of 3,500 occupants. The number of spectators occupying the stand on this occasion was estimated at 1,350.

Before the match, the ingress of occupants into the stand could be likened to filling a vessel with gaseous molecules. The movement of occupants to their positions appeared to be random, but in fact, they were likely to be influenced by factors such as group relationships, familiarity with the stand layout etc. From the safety point of view, an even distribution of occupants was desirable in order to avoid surging and pressure build-up near crush barriers. This was achieved primarily by effective stewarding. In the kinetic theory analogy, stirring a gaseous mixture would eventually give a uniform mixture.

At the half-way interval of the match, a cue was given to evacuate the stand. This cue can be taken to represent a 'temperature rise' which invoked a reaction manifested as movement of the occupants into the assembly area. From kinetic theory, a localised temperature rise would result in increased energy of nearby molecules, which would cause them to move at a higher velocity and experience more frequent collisions. This effect spreads throughout the mixture until equilibrium is reached. In the football ground situation, a localised hazard would cause a reaction from occupants closest to the hazard. This reaction would spread to other occupants via a 'collision effect' at a rate proportional to the degree of danger perceived to result from the hazard. During the evacuation exercise, movement was initiated by spectators nearer the front gates. These spectators set the pace of evacuation for the crowd behind them.

The occupants left the stand passing through the gaps between the barriers, moving randomly within the available space. A significant amount of queuing was experienced as occupants moved through the exits. The choice of exit appeared to be governed by proximity to the exit. This is in agreement with the behaviour of gaseous molecules which tend to flow through an available nearby opening. If an opening is surrounded by group of molecules, the remaining ones will move along the path of least resistance to find a less-crowded alternative. In the same way, during an evacuation of occupants, if queuing occurs at an exit, an alternative nearby exit is sought. In case of equally crowded conditions, where there is queuing at all exits, occupants cannot avoid becoming part of a queue.

3 A COMPUTER SYSTEM FOR ASSESSING THE SAFETY OF SPORTS GROUNDS

The molecular kinetic theory analogy outlined above served as a vehicle for identifying and developing simple condition-action rules describing the interactions between occupant behaviour, managerial decisions and structure in sports grounds. These rules incorporate evacuation, crowd behaviour and structural safety knowledge, as well as normative knowledge from the Green Guide. The rules have been implemented in computer-usable form as the knowledge-base of an intelligent decision-support system.

The computer program comprises principally of a knowledge-based component, implemented using the CLIPS 5.1 production-rule system [4], and a custom-built hypertext system, HTEX 1.0 [10]. The two subsystems are fully compatible with one another, allowing two-way information exchange. Based on a user's input specifications, the knowledge-based component makes decisions about whether or not safety requirements are satisfied at a ground. In the latter case, it recommends corrective actions, whereas in the former, it may suggest methods to improve on the safety of the ground. The recommendations arrived at may, for justification, reference relevant sections of the Guide or the research literature, which are also represented in the system (in textual form) in the hypertext module.

Hypertext systems allow the representation of normative knowledge, such as is contained in the Guide, as a network of related but independent information units [3,13]. Two units of information are linked in the network if one is referenced in the other. The network representation allows a user to transverse the Guide as he desires, following links that he deems important. This is in contrast to a flat representation which constrains the user to follow the author's chain of reasoning.

Once within the hypertext module, the system allows the user to query the status of the Guide's clauses, that is, whether they are violated or satisfied. This is achieved through a call back to the knowledge-based component. The queried clauses do not necessarily have to be the same as those in the initial recommendation that caused the jump into the hypertext module. Fig. 1 illustrates English versions of some of the rules in the system, and Fig. 2 depicts hypertext windows invoked by querying the recommendation arrived at by Rule 1. The top window shows the information displayed when the recommendation is queried, while the bottom window shows additional information displayed when the underlined phrase Stewards in the first window is queried.

1. **If** (distribution of occupants) is (locally clustered around exits) **then** recommend(managerial, "stewards disperse the crowd in order to attain uniform distribution")
2. **If** (pre-event planning) **then** data((ground assessment), needs-to-be, (routine))
3. **If** (some occupants) have (disabilities) **then** recommend(managerial, "proper provision should be made to accommodate the disabled occupants")
4. **If** (surveillance/communication system) needs-to-be (checked) **then** recommend(managerial, "perform surveillance/communication system check")

⋮

Fig. 1: Near-English representation of some of the rules in the system

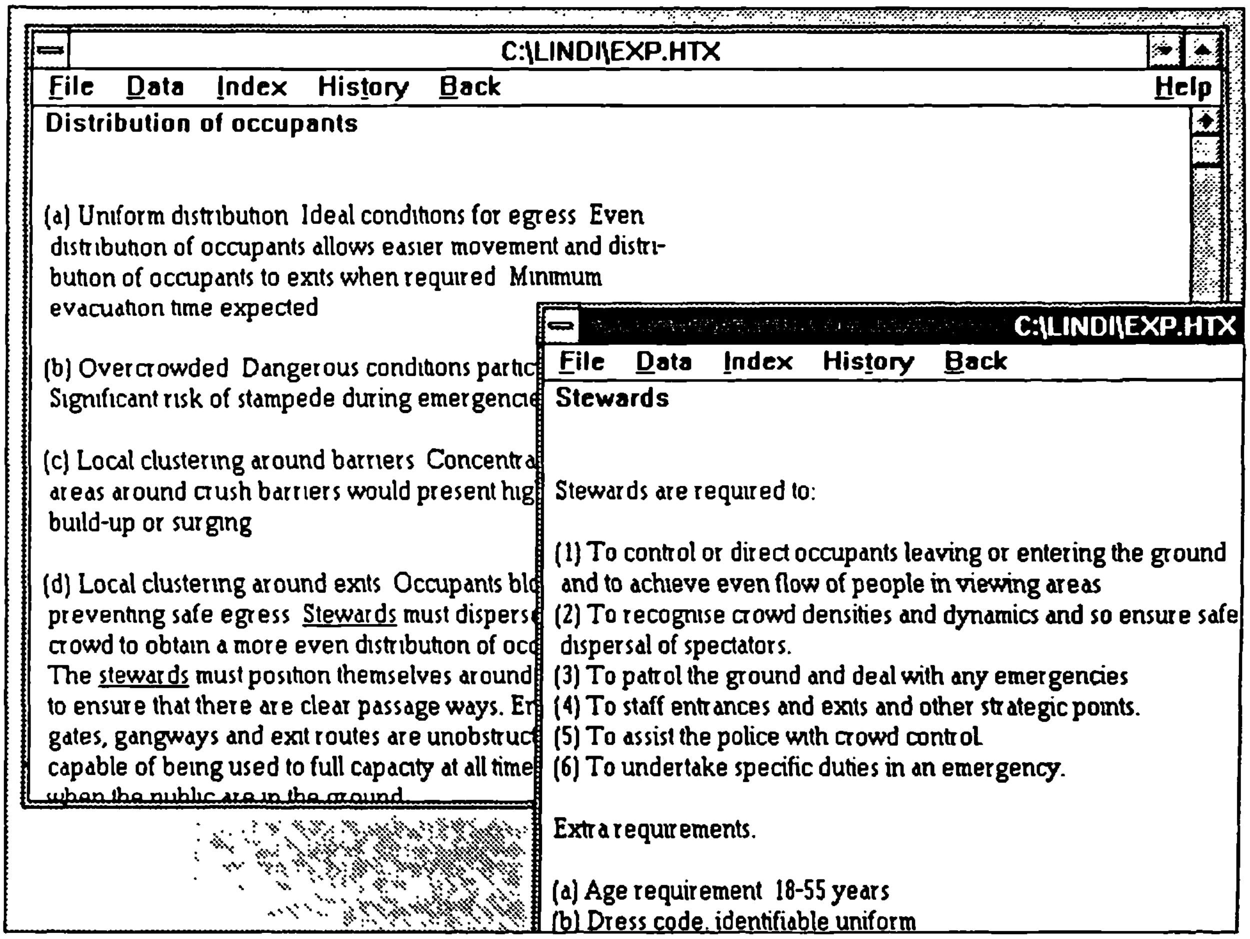

Fig. 2: HTEX windows providing further information

CONCLUSIONS

This paper has described a simple but flexible knowledge-based computer system for quickly assessing the safety of football grounds. The system considers the inter-relationships between occupancy, management and structural aspects in accommodation areas, assembly points and evacuation routes, and makes recommendations for improving the safety of a ground. This system will be particularly useful to building control and fire safety officers and management personnel desiring to quickly assess the safety of a sports venue. In addition, it could be used as a preliminary design assessment tool by designers of new sports grounds. The time and cost-saving benefits of the system derives primarily from automating the significant amount of paperwork involving cross-referencing of several documents inherent in conventional methods of assessment. The system attempts to unify all essential safety information, while providing a facility for incremental modification. Further application of the system should be feasible in a range of places of close assembly on extension of the knowledge base.

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Analysing Evacuation Modelling Techniques of Mixed-Ability Populations

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ANALYSING EVACUATION MODELLING TECHNIQUES OF MIXED-ABILITY POPULATIONS

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Abstract
With an average of over eight hundred persons dying in fires in the UK each year, and several more suffering injuries as a result of fire, there is a pressing need to investigate the critical aspects affecting fire safety in different occupancy settings. This paper discusses the basic principles of evacuation models that investigate occupant movement in fire emergencies and discusses, in particular, their limitations; the most prominent being the omission of disabled people from the simulated populations. The notable effects of disability on occupant movement are revealed by using a novel concept that provides a mechanism for measuring evacuation capabilities of various classes of disabled people. This concept is developed through the use of an *evacuation performance index* (EPI) which is the relative ease of evacuating a disabled person compared to evacuating an able-bodied person. The application and use of the concept in research in Fire Safety Engineering is described in the final section of the paper.
Keywords: Evacuation modelling, *evacuation performance index*, fires

1 Introduction

Fire has significant potential to cause costly destruction. A vivid reminder of the large number of lives lost and the extent of damage in fires is illustrated in major disasters such as the Bradford [1], Hillsborough [2] and Woolworth's fires [3]. Both structural design and occupant behaviour were seen to be at fault in these scenarios due to the lack of early warning and the delayed occupant response in attempting to evacuate. A strategic approach towards understanding the relationship between the design of fire warning systems and occupant response in fires is therefore essential. Evacuation modelling techniques are generally used for this purpose and some current ones are described in subsequent sections.

The basic principle of evacuation modelling is defined by the following equation which should be satisfied if occupants are to evacuate safely during an emergency: $t_{TL} \geq t$, where t_{TL} specifies the time for tenability levels to exceed their allowable limits for different classes of fires, and t specifies the maximum likely evacuation time of the occupants to leave a building.

For the purposes of this paper the emphasis is on t the available evacuation time and the sub-components that affect this value.

2 Background of basic model categories

Most of the current evacuation models can be grouped into two basic categories: psychological [4] [5] [6] and mathematical [7] [8] [9]. In both categories, models can be probabilistic, in that a range of possible occurrences is allowed for, or they may be deterministic which means that they are scenario specific and predict single possible outcomes. Most models are predominantly mathematical in that their underlying relationships are described by mathematical functions. Alternatively, mathematical models can be described as phenomenological in that they simulate the actual physical phenomena that affect safety. They can be further divided into several groups which include: analogue, empiric, systemic and knowledge-based models.

Psychological models focus on human behavioural aspects and can be sub-divided into two groups, namely: those with a time-based approach describing specific occupant behavioural stages and those with a time-based approach defined by discrete time frames. The fundamental difference between the approaches lies in the fact that the former emphasises the stages in behaviour that occupants experience as a fire develops and environmental conditions change. These stages are described as occurring within a series time frames of no specific duration. In the latter group, at every discrete time frame of a specific duration the action of an occupant can be determined as a result of analysing the surrounding environmental conditions. In this group the development of stages in behaviour are not discrete because they are governed by momentary changes in the surrounding conditions and are not necessarily manifested in clearly defined stages.

3 Objectives

The objective of this paper is to highlight the relevance of evacuation modelling in fire safety engineering, from a research viewpoint. Oftentimes greater emphasis is given to fire modelling and the time components affecting t_{TL}. The paper identifies the areas in which there is a significant need for further research into occupant movement and behaviour in fire emergencies. Some notable limitations are highlighted, particularly the need for investigative studies into the evacuation of occupants with disabilities and the need for a coherent framework relating current research findings on evacuation movement, which at present tend to be somewhat isolated. In attempting to find a solution to the above mentioned problem, the author describes a system for measuring evacuation capability of a mixed-ability population using an *evacuation performance index* (EPI) which relates three aspects of fire safety, namely; individual characteristics of disabled occupants, the amount of assistance they require, and building design and environmental factors. The author believes that the *evacuation performance index* of a class of individuals is primarily dependent on these three categories. Use of the index enables the assessment of the relative effects on the evacuation capability of an evacuee of changes to the amount and type of assistance provided to the evacuee, and changes to the building design and environmental factors. The concept encourages the use of a coherent approach to analytical research methods in evacuation modelling [10].

The following section discusses some of the weaknesses in evacuation modelling. The author hopes that this overview will highlight key areas that warrant further research and where improvements to modelling techniques can be made.

4 Limitations in Evacuation Modelling

There are several limitations in evacuation modelling of which the most important are as follows:

- *Evacuation modelling does not lend itself to precise observation or analysis.*

As a result several assumptions are made during the use of simulation methods to study occupant movement and behaviour during fires. According to Kendik [11] who has analysed a number of major evacuation models, ".. all of them appear to make several assumptions partially to overcome the gaps in technical literature which makes their validations against real-world events or fire drills necessary...". She continues by stating that only a few of these models are in fact calibrated in this manner and are able to provide quantitative results.

- *The use of complex of equations and the attaching of unjustified significance to numbers in these equations*

Basic principles are sometimes hidden behind sophisticated and complex notations. This limits the scope of understanding of those responsible for the application of model findings in the design of means of escape. According to the EGOLF research group [12] the quantification of levels of safety rely heavily on statistical information and techniques. The models are mainly computer-based and are criticised by some engineers as being too complicated. Frequently unjustified significance is attached to numbers resulting from model equations because they cannot be interpreted with adequate background knowledge.

- *Simulated populations are limited to able-bodied occupants*

Empirical studies on occupant movement are often limited to able-bodied populations. Occupants with disabilities that may their hinder movement and that of others, are rarely acknowledged. This is despite the fact that disabled people appear to be at the greatest risk in fire emergencies where movement speed is so important. However, both disability and unsympathetic design of buildings appear to be key negative influences on occupant movement and the techniques used to measure movement are so diverse, often leading to inconsistent results.

- *Outdated validation studies*

The empirical data to test the validity of models is often outdated. It is unfortunate that the cost and the complexities associated with setting up validation studies for various models are prohibitive. However, they are essential in research to ascertain the credibility of these models.

- *Large numbers of parameters to analyse*

Some complexities arise from the development of models with a large number of parameters. In addition, the depth of analysis in these models is questionable. Hinks

[13] states that these parameters will have varying levels of importance and influence on escape potentials of occupants. It is essential therefore to have a system that classifies these parameters in some hierarchial arrangement and that has provision for accurately measuring their effects.

- *Closed characteristic of most models*

The closed characteristic of most models limits their expansion when new research information becomes available. This limitation implies that additional information may be continually tagged on to existing information with the risk of losing track of the primary objective of a given model.

Summary

It is true to say that, 'fire safety is often considered in a fragmentary way' [14]. The elements which combine to produce fire and possible loss of life and property tend to be effectively regarded as independent of each other. There is a lack of coherency in the techniques used in evacuation modelling. What is lacking is a unifying philosophy that links the approaches to modelling in such a way that these approaches are recognised as extensions of a basic safety criterion.

5 A Coherent Approach to Evacuation Modelling - EPI Concept

In this section the author describes a coherent approach to evacuation modelling that provides a method for predicting evacuation times and for applying these results to the design of escape routes [12]. In order to predict the time an occupant would take to evacuate a building, it is necessary to have a quantifiable attribute which defines his/her evacuation capability and which is sensitive to variable external conditions, for example, building design. This measure of the intrinsic evacuation capability of an occupant is described as his/her *evacuation performance index* (EPI), which is defined as the unassisted speed of a person relative to that of an able-bodied person along a straight obstacle-free route of a pre-specified distance.

Basic EPIs of occupants are determined primarily by their respective disabilities and mobility aids. During evacuations this basic EPI is dynamically modified into an effective EPI which determines the actual evacuation capability of the occupant during an emergency. The modification of basic EPI into effective EPI is brought about by the following primary factors.

1) Individual characteristics: of occupants can be either physical and psychological. Physical characteristics include occupants' disability-mobility aid combinations while psychological characteristics include behavioural factors such as 'panic'.
2) Managerial aspects: can be measured in terms of the assistance provided to occupants. EPIs have been observed to undergo notable changes if additional help is provided [10] [15]. Whenever necessary assistance is provided to evacuating disabled people, this has the general effect of increasing their speeds or EPIs. Unnecessary assistance typically leaves the EPI unchanged or may even reduce it.
3) Environmental factors: generally expressed as crowd densities have been shown to influence occupant speeds [10] [16]. The authors observed that at low crowd densities, able-bodied occupants make purposeful attempts to avoid being an obstacle to disabled people. In some cases, they may even assist a disabled person

by, for example, opening doors. In large crowd densities, however, occupant speeds tend to decrease.
4) Building design factors: such as the configuration or geometry of building layouts, number and positions of fire doors, dimensions of corridors, positions of lighting, floor coverings and textures also influence EPIs.

6 Application to Research

The actual process of measuring EPIs begins by deconstructing a given evacuation route into primary sections such as the rooms, corridors, stairwells etc. Having classified occupants according to their disability-mobility aid combinations, their EPIs could be measured along each section of the route. This could be carried out by using carefully monitored fire drills. The time taken to traverse each section could be recorded using strategically placed video cameras with a time-display mechanism. The simplest building layout would require not more than eight mounted cameras and some observers to monitor the evacuation.

Characteristic times could be calculated for each disability-mobility aid combination, made possible through the use of a design procedure incorporating measures of EPI. A first approximation of the proposed design procedure might proceed as follows: Consider that nominal EPIs have been determined for different disability-mobility aid combinations. Design in such a case may proceed along the lines of, for each evacuation route out of the building:
1) First, the designer computes the time t_{TL} for tenability levels to exceed their allowable levels, and the travel distance d through the escape route.
2) Second, the effective EPI of each disability-mobility aid combination along the evacuation route is calculated. This calculation will utilise expressions defined to take into account any assistance which will be available to disabled evacuees, and any building design and environmental factors of the evacuation route that might modify the nominal evacuation performance indices of the evacuees.
3) Next, the worst case evacuation time, t_W is computed from Equation (1)

$$t_W = \frac{d}{I_M \times v_O} \qquad (1)$$

where, I_M is the smallest effective EPI computed from Step (2) above, and v_O is the nominal evacuation speed of an able-bodied person. Note that v_O itself varies with building design and environmental factors, although not with level and type of assistance.
4) Finally, the designer ensures that $t_{TL} \geq t_W \times SF$, where SF is a factor of safety.

If the inequality $t_{TL} \geq t_W \times SF$ cannot be satisfied, the designer has to modify the assistance to be made available to disabled evacuees and the building environmental factors such that Step (2) returns a high enough I_M. However, if the fire safety evaluation is being performed at the architectural design stage, then the layout of the building may be modified so that Step (1) returns a higher value for t_{TL} or a smaller value for d. Once the inequality has been satisfied for a particular combination of level and type of assistance to be made available to evacuees and building environmental factors, then managerial steps have to be taken to ensure that these conditions prevail in an emergency. A real design situation is more complex as the inter-relations between a number of different possible routes have to be analysed.

The design procedure described above computes a lower bound or ultra-safe evacuation time since t_W is based on I_M, the smallest effective EPI over the range of disability-mobility aid combinations. An alternative procedure which is perhaps more realistic and which returns an upper bound value of t_W is to use characteristic times in place of the above relation in Step (c) such that,

$$t_W = \max \sum_{i=1}^{n} \frac{d_i}{I_i \times v_i} \qquad (2)$$

where, $i = 1,....,n$ subdivides the evacuation route into elemental sections for which EPIs are known and the summation in Equation (2) is computed for each disability-mobility aid combination.

7 The Value of the EPI Concept in Research

This novel concept defines a coherent procedure for fire safety engineering design founded on a measure of evacuation capability. The evident strengths in this concept from a research viewpoint include:

- *The use of simple, economical empirical exercises*

The suggested evacuation exercises to obtain EPIs are simple and inexpensive. Resources are limited to ordinary video cameras and measuring equipment such as tapes for measuring distances. In this way the difficulties experienced with complex experimental methods are avoided.

- *Flexibility in the number of parameters analysed in a given scenario*

Any number of parameters can be analysed in a given scenario. A wide range of parameters whose effects on evacuation capability are considered critical can be measured. The model is therefore flexible and grows with increasing knowledge from research.

- *Recognition and classification of disabled people*

The presence of disabled people is acknowledged using a classification system based on their disability-mobility aid combinations. Thus the differences in evacuation capabilities in an evacuating crowd are adequately represented.

- *The precise definition of evacuation capability and the flexibility of EPI*

EPI provides a precise definition of evacuation capability which is measurable. Although it shares some similarities with alternative measures of escape potential [17] [18], its uniqueness lies in its clear description of evacuation capability and its flexible nature which is manifested by its variation with changes in surrounding conditions.

[17] [18], its uniqueness lies in its clear description of evacuation capability and its flexible nature which is manifested by its variation with changes in surrounding conditions.

- *The use of simple methods for determining evacuation capabilities*

The determination of EPIs and the use of the design procedure are not complicated and simple to understand.

- *EPI provides link between research findings and design*

There has often been some degree of conflict between research findings and their application in the codes of practice. EPI provides a gateway for channelling results from research into a format that can be easily adopted by the design codes.

- *The role of EPI as an assessment tool*

The efficiency of an evacuation route can be assessed by computing characteristic times using EPIs. If EPIs are below acceptable levels for any class of people then the corresponding times will be too high and modifications may be implemented at the drawing board stage.

- *The wide scope of application*

The transferability of the concept to various occupancy settings is an added advantage.

8 Conclusions and prospects for further work

The EPI concept provides a valuable stepping stone for future strategies in research in evacuation modelling of mixed-ability populations. It is evident that this concept links all approaches to research without necessarily favouring any particular one. It provides a framework that coherently links all approaches to modelling all the while ensuring that the scope for investigating all critical evacuation parameters is sufficiently broad. It is a useful assessment and design tool that is simple to understand and apply. Further work in developing the concept is encouraged by the author using as many ranges of disability-mobility aid combinations to provide a representative mixed-ability population. The results could be adopted by the codes of practice. While the EPI concept may not solve all the drawbacks of modelling it has attempted to address some of the primary limitations.

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