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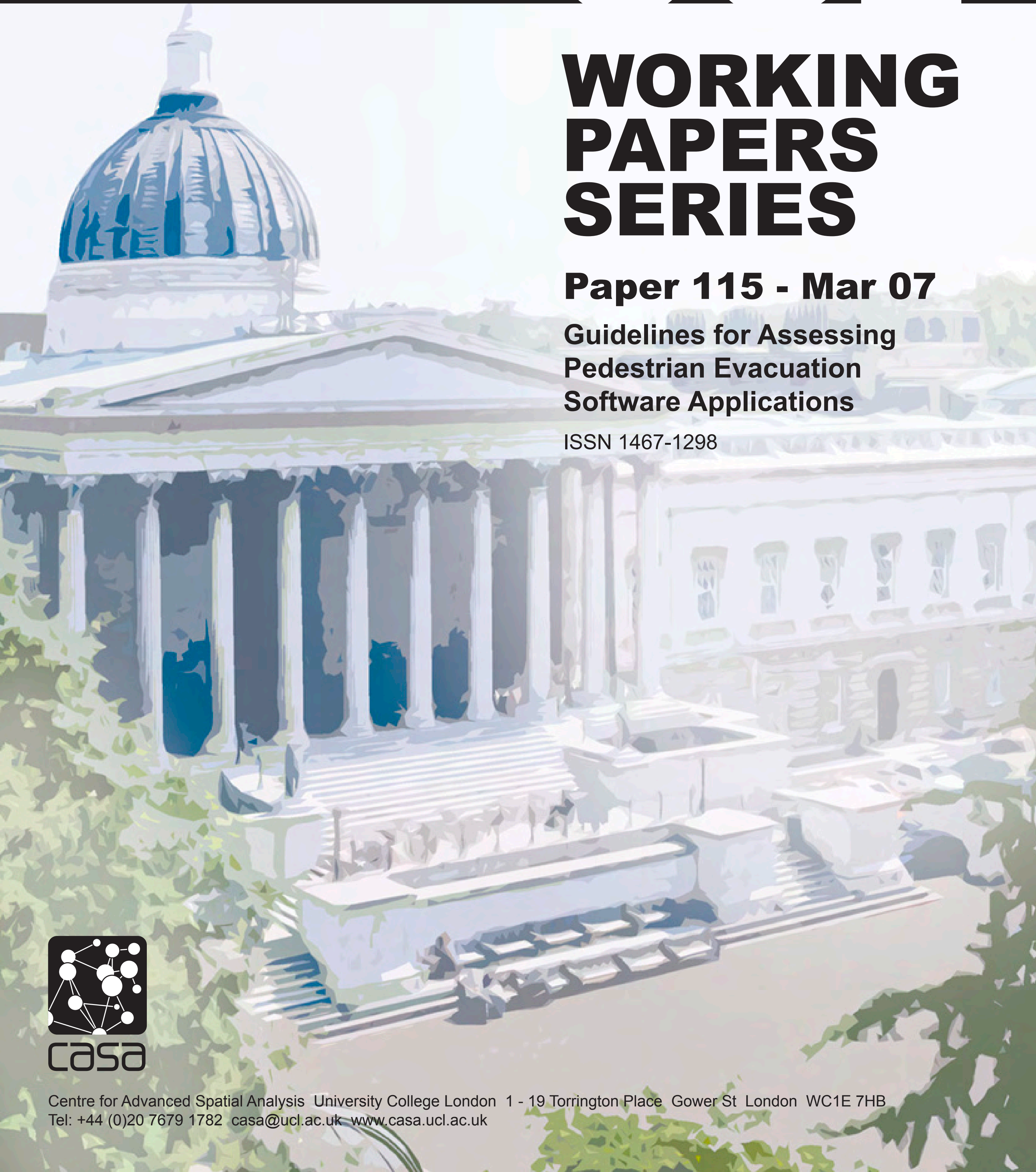

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Guidelines for Assessing Pedestrian Evacuation Software Applications

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Centre for Advanced Spatial Analysis University College London 1 - 19 Torrington Place Gower St London WC1E 7HB
Tel: +44 (0)20 7679 1782 casa@ucl.ac.uk www.casa.ucl.ac.uk

Guidelines for Assessing Pedestrian Evacuation Software Applications

Christian J. E. Castle

Centre for Advanced Spatial Analysis

University College London, 1-19 Torrington Place, London, WC1E 7HB, England

Tel. +44 (0)207 679 0510 · Fax +44 (0)207 813 2843 · E-mail:c.castle@ucl.ac.uk

Abstract

This paper serves to clearly identify and explain criteria to consider when evaluating the suitability of a pedestrian evacuation software application to assess the evacuation process of a building. Guidelines in the form of nine topic areas identify different modelling approaches adopted, as well as features / functionality provided by applications designed specifically for simulating the egress of pedestrians from inside a building. The paper concludes with a synopsis of these guidelines, identifying key questions (by topic area) to found an evaluation.

Key words: Pedestrian evacuation, software applications, models, modelling, buildings, egress, simulation, guidelines, evaluation criteria, pedestrian movement and behaviour.

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Guidelines for Assessing Pedestrian Evacuation Software Applications

1: Introduction

The primary objective of this paper is to present a guide for evaluating pedestrian evacuation software applications designed for simulating the egress of pedestrians from inside a building. Specifically, nine topic areas delineate different modelling approaches and features / functionality that should be considered when choosing an application (Section 3). While extremely useful for their primary (practical) purpose, the considerations that arise from these guidelines can also provide a useful structure for understanding key principles and techniques that underpin the broader class of pedestrian modelling. Based on the information within this paper, Castle and Longley (in press) have reviewed and interpreted pedestrian evacuation applications in relation to a hypothetical building assessment. The discussion, however, begins by distinguishing differences between a pedestrian evacuation software 'application' and a pedestrian evacuation 'model'.

2: Pedestrian Evacuation Software Applications

For the purpose of this discussion, it is important to distinguish between pedestrian evacuation software 'applications' (e.g. buildingEXODUS, Legion, etc) and pedestrian evacuation 'models' (e.g. Okazaki and Matsushita's (1993) magnetic model, Kerridge, Hine, & Wigan's (2001) PEDFLOW, etc). Both can be designed specifically to assess emergency egress of occupants from inside a building (opposed to evacuation from aircrafts, ships, the external built environment, etc). The two are not mutually exclusive; any pedestrian evacuation software application will incorporate a model or models. However, the models that drive any given application are usually more flexible, in terms of the type and scale of building that can be represented, and more general in terms of emergency scenario in which they can be applied. For example, some pedestrian evacuation models have been specifically developed to explore a designated building (e.g. the evacuation of patients from a hospital within London, or a school in Los

Angeles) or a class of problems characteristic of particular enclosed settings (e.g. experimenting with room configurations to relieve congestion at a pinch point, such as an exit, or to increase bi-direction flow within a corridor). Consequently, many pedestrian evacuation models are unsuitable for a purpose beyond their original remit. Finally, applications invariably include features or functionality beyond that of a pedestrian evacuation model. For instance, the ability to import and interpret a building's floor plan in different file formats (e.g. CAD, GIS, image file, etc); two- and possibly three-dimensional visualisation of the building and simulation; and dynamic presentation of output in multiple forms (e.g. charts, graphs, etc), for instances.

Bearing in mind this distinction, the following section of this paper identifies key criteria pertaining to the different modelling approaches and features / functionality worth considering when choosing an application.

3: Guidelines for Assessing a Suitable Pedestrian Evacuation Application

Pedestrian evacuation applications adopt various modelling approaches to simulate the egress of pedestrians from an enclosed space. For instance, there are different ways of representing an enclosure (i.e. as continuous or discrete space), the population within an enclosure (ranging from a homogeneous ensemble to an assemblage of individuals with unique characteristics), the movement and behaviour of individuals (e.g. deterministic, probabilistic or a combination of both), etc. Generally, as the level of detail encapsulated within a model increases, the effort required by the user to initialise the application increases, as well as the time required to run the computer simulation. Furthermore, an application reflects the purpose for which it was originally designed, the nature of the application developer (e.g. engineer, psychologist, architect), and the computer power available to the developer at the time. A wide range of applications designed to simulate the evacuation of pedestrians from buildings alone (i.e. excluding models designed for aviation, maritime, the external built environment, etc), have been developed. These applications can be distinguished apart by their choice of development strategy, and the features and functionality they included.

In order to assist potential users in the decision making process of choosing a pedestrian evacuation application, Nelson and Mowrer (2002) published a few pertinent questions a user should consider. Kuligowksi and Gwynne (2005) supplemented these questions, providing a brief explanation as to why they are important. The following discussion expands upon these questions, providing a more detailed assessment and examples to illustrate the argument where necessary. These questions fall within nine general topic areas, which can be split into two subject types (Figure 1): 1) questions designed to understand the simulation model within the application, and; 2) questions concerned with general features / functionality of the application. It is imperative to investigate the former topics (Sections 3.4 - 3.7) in order to comprehend how the simulation model works, and how the application can be sensitive to data input and variables defined by the user. Although the topics explored with the remaining sections (3.1 - 3.3 and 3.8 – 3.9) are more general in nature, defining the overall approach and functionality incorporated within different applications, they are still essential to the evaluation process. The order in which these topics are presented approximates the order in which a user should consider them, although it is necessary to consider many questions within each topic, and some questions between topics, concurrently. By following this logical order it is possible to reduce redundant effort choosing an application (e.g. time investigating and understanding information pertaining to an application when the application might have been deemed unsuitable earlier; because it is not longer available or accessible, for instance).

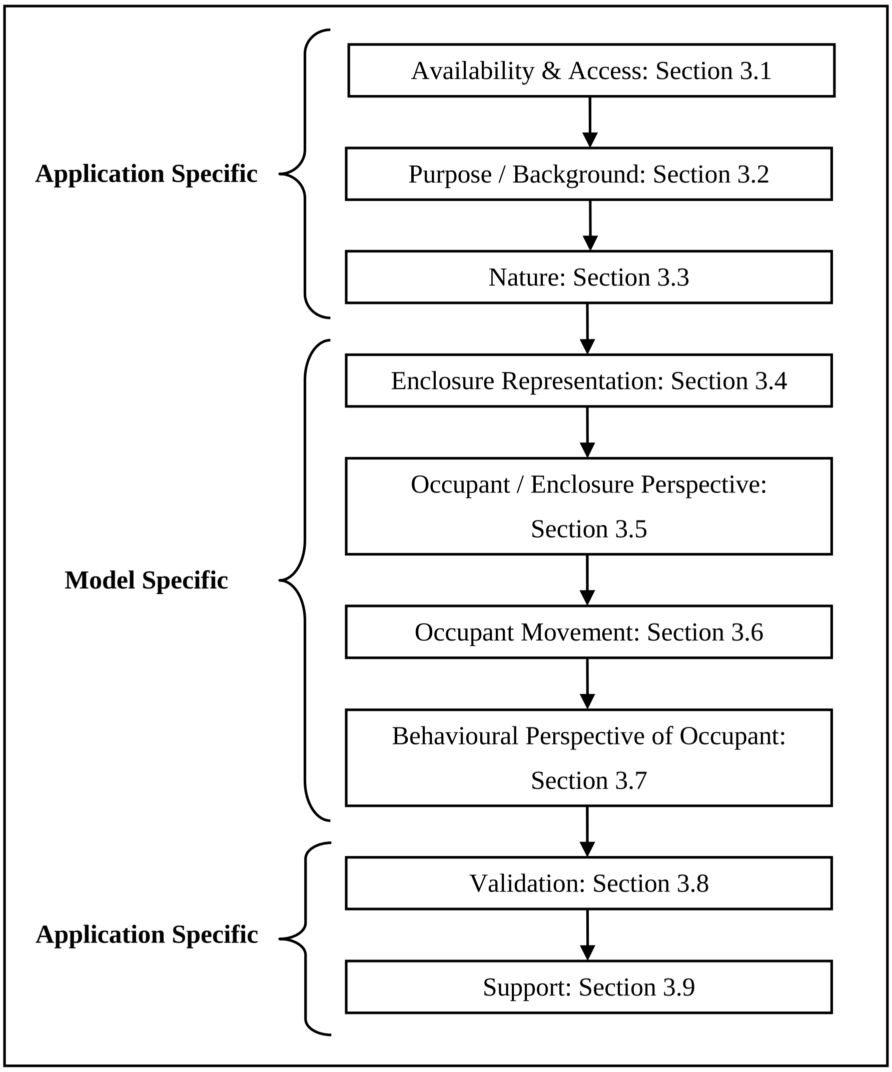

Figure 1: Topic areas of questions to consider when choosing a suitable pedestrian evacuation application.

3.1: Availability and Access

In relation to the amount of time and funding available to complete a research project, it is import to consider the availability and access of an application. These are useful criteria to initially establish, as a user can rule out an application before spending valuable time investigating additional information. For example, an application may have been removed from the market if it is no longer supported or has become severely out dated. Applications are available under various financial terms (e.g. free of charge, consultancy basis, one-off fee, annual licence and support fee, or a combination of these agreements), and have different computer hardware requirements (e.g. RAM, central processing unit, etc), and / or operating system requirements (e.g. Windows, Linux, Mac OS X). These factors may have a critical influence on the pedestrian evacuation application chosen; possibly excluding applications that are financially and / or computationally too expensive. Furthermore, access to applications can vary. For instance, some pedestrian evacuation applications are distributed as 'off the shelf' solutions for the user to apply locally, whilst others are implemented by the developers or a third party on a consultancy basis, with the results supplied to the user. In the former situation, the user formulates the model input, runs the simulation and analyses the output. In the latter, the user works with the developer or agency to construct the model, and is supplied with the output (and possibly interpretation) at the end of the process. This is an important consideration, especially if a user might require access to the model at a later date – as, for example, in investigating new or different simulation scenarios. In addition, where documentation has ostensibly been published about an application, it may be 'unavailable' because usage is restricted to in-house use, or because it is incomplete (perhaps because the model is unfinished, not validated, etc), or because a model has subsequently been withdrawn from the market.

3.2: Purpose / Background

In relation to the nature and scope of the research investigation, it is important to determine whether the application is fit for purpose. For instance, if the aim is to evaluate the evacuation potential of a building, it might be unsuitable to use a pedestrian evacuation application that has been developed and validated primarily for maritime purposes (e.g. the evacuation of pedestrians from a ship, where a primary concern is to simulate the effect of pedestrian sway imparted on the vessel by a water mass). Furthermore, some applications capable of simulating evacuation from a building focus upon particular building types. Thus, it may be inappropriate to use an application designed specifically for residential buildings, high-rise residential tower blocks, low-rise buildings (less than 22.9 metres / 15 stories in height), buildings with only a single exit, etc. This criterion can be difficult to assess, especially when an application has evolved significantly over time. Supporting evidence should be sought if claims are made that an application can be applied to settings other than those for which it was designed.

Finally, it is useful to understand the origin of an application to build confidence in its credibility. Establishing the environment in which the application was developed allows the user to assess whether developments were driven by a desire / need for improvement or by constraints (e.g. commercial pressure such as time or funding). The expertise of the developers during the development period is also an important criterion. Applications may have been developed by an individual who specialises in computer science or by a team with a diverse background in mathematics, psychology, sociology, engineering, etc. The experience of the people developing the application will inherently affect the ability of the application to capture some of the more salient occupant movement and behavioural features during an evacuation. However, it may be difficult to ascertain the origin and expertise of the development team from the literature available; thus dialogue with the developers is advisable. Communication with an application developer is useful and often necessary to obtain more detailed information identified within the following sections.

3.3: Nature

Initially, it is very useful to determine the general nature of a pedestrian evacuation application, before exploring specific details of the simulation model. The nature of the application provides an excellent indication of its capabilities, permitting the elimination of an unsuitable application that would be unable to fulfil the aims of a research investigation. Generally, the simulation of pedestrian evacuation can be divided into two approaches: those considering movement; and those attempting to link movement to human behaviour (Stahl and Archea, 1977; Pauls, 1988; Gwynne *et al.*, 1999a; Proulx, 2002). Movement models consider only the carrying capacity of the structure and factors (such as walking speed and average density) that affect this capacity. Less sophisticated movement models treat individuals as unthinking objects that automatically respond to external stimuli in an orderly fashion, without communicating or interacting with each other (e.g. upon hearing an alarm it is assumed they will immediately stop their current activity and begin to evacuate). This simple type of movement model is often referred to as an optimisation model (Nelson and Mowrer, 2002). An extreme example of an optimisation-movement model treats the population's egress *en masse*. The average density of a room's population is used to determine the flow of pedestrians between different sub-divisions of a structure (e.g. rooms, corridors, stairs, etc). On the other hand, movement of pedestrians within a behavioural model is based upon the surrounding environmental conditions within an enclosure. Each pedestrian is treated as an individual, with a simulated behavioural response or reaction to a range of stimuli (e.g. emergency alarm, emergency signage, staff assistance, etc). Pedestrians can be defined with different pre-evacuation (e.g. speed of response to an evacuation cue – investigating the alarm to determine if the evacuation is real, locate relatives or friends, etc), and evacuation (e.g. knowledge of an enclosure's layout and exit routes, walking speed, etc) movement responses.

While every application considers the movement (to some extent) of pedestrians, the level of sophistication in (implied or explicitly considered) behaviour varies. Consequently, a partial-behavioural model can be defined as another group of model that primarily calculates occupant movement but (to some degree), attempts to simulate occupant behaviour. Establishing the nature of a modelling approach adopted by an application in tandem with the aim of a research investigation will help to eliminate unsuitable applications (e.g. will it be sufficient to assess the movement of pedestrians without considering individual behaviours?).

3.4: Enclosure Representation

This section identifies the scales at which an application may represent an enclosure. This is a very important facet of an application, as it directly influences much of the simulation model. Figure 2 illustrates a coarse scale network application (sometimes referred to as zone modelling in a pedestrian evacuation modelling context), which segments a structure into a number of discrete geometrical sections (e.g. rooms, corridors, staircases, etc: Watts, 1987). The nature of these models is strictly limited to pedestrian movement. The majority of coarse scale network applications represent pedestrians as a mass or aggregate of people that move between each section of the building. No consideration is given to the individual, and the simulation of their movement is not deemed to be dependant upon behavioural considerations. Their speed of movement is specified by a mathematical flow equation (see Section 3.6.1 for an overview) determined from real-life observations of crowd movement. More sophisticated coarse scale network applications incorporate queuing theory (the dynamics of waiting lines or queues) in order to determine which flow has precedence at bottlenecks (e.g. at an exit).

Coarse scale network models are useful for reducing a system to the constituent parts of time and distance of travel from a starting location to a building's exit(s). This can prove valuable in certain circumstances. For instance, coarse scale network applications are practical for calculating first approximates of a building's maximum and minimum total evacuation times. They are less suitable for systems that entail non-linear relationships and other complexities (i.e. where scenarios diverge from simple distance / time based approximations). For example, coarse scale network applications are unable to represent obstacles within the building sectors (e.g. furniture, columns, ticket barriers, other pedestrians, and even injured pedestrians), and the impact these obstacles may have upon the evacuation process. Local movement and navigation such as overtaking, pedestrian interaction / conflict, and obstacle avoidance cannot be considered either. For example, Helbing *et al.* (2001) have simulated how the flow of pedestrians at a known bottleneck can be affected by the angle of walls adjacent to an exit or the position of columns in strategic positions. Furthermore, since individuals are subsumed below the scale of representation, visualisation and post simulation analysis pertaining to exit choice, areas of high density, etc, cannot be observed or calculated. Indeed, the output of some coarse scale network applications is limited to print line(s) of total egress time of the building or the time taken to clear each individual building section.

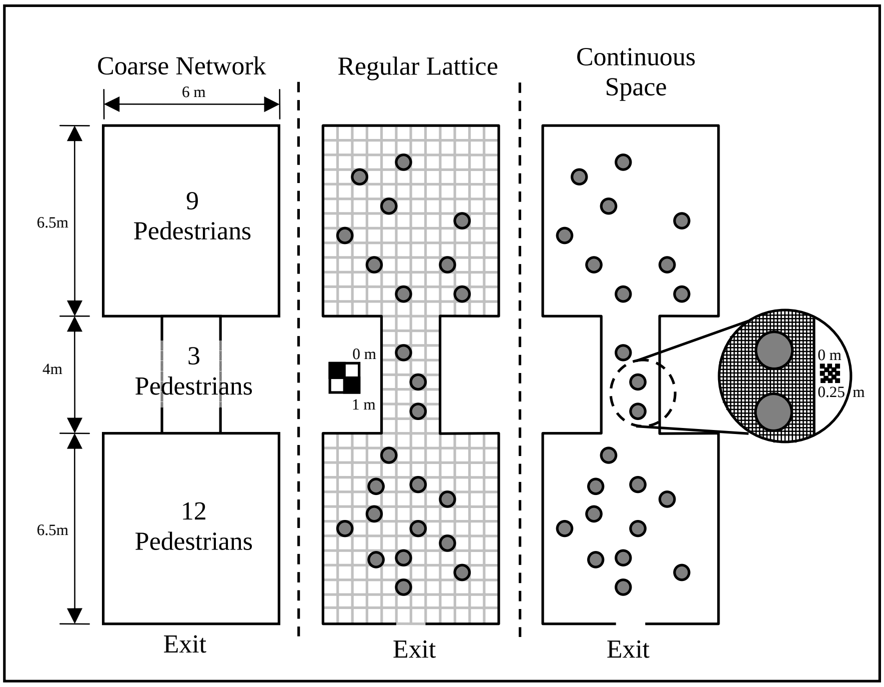

Figure 2: Illustration of the three different types of enclosure representation.

Alternatively, the floor plan of an enclosure can be tessellated into a regular lattice of cells (Figure 2). These cells can take different forms, but are usually square. The dimension of these cells is often of the order of 0.4 by 0.4 or 0.5 by 0.5 metres, the approximate area an average person occupies. In effect, pedestrian movement is still represented as a network but movement can be represented at a much finer scale. Consequently, applications that employ a regular lattice approach for representing an enclosure have several advantages over coarse scale network applications. Firstly, the internal geometry of a structure can be represented (e.g. furniture, columns, ticket barriers, etc). Secondly, every pedestrian can be represented as an individual, with different movement and behavioural characteristics allocated to each pedestrian. Sections 3.6 and 3.7 explore characteristics that have been incorporated within applications, and how these can affect a simulation outcome. Juxtaposed, each pedestrian has the ability to assess the environment that is local to them, and make route choice decisions based on this information; subject to their personal characteristics. Consequently, regular lattice applications can provide a far richer output, allowing two-dimensional and sometimes three-dimensional visualisation of the simulation, as well as post simulation analysis of predominant exit choice, areas of high density, etc.

Finally, the layout of an enclosure can be represented as a continuous space. Applications that simulate the movement of pedestrians within a continuous space inherit all of the functionality of the regular lattice model outlined above. Indeed, Figure 2 illustrates that the continuous space approach also tessellates a building into cells, but at a much finer resolution (potentially millimetres) compared to the regular lattice approach (e.g. metres). Thus, the critical distinction between the regular lattice and continuous space approaches relates to the more precise representation of the internal layout (e.g. furniture, columns, ticket barriers, etc) and the ability to more accurately simulate the movement of pedestrians within the enclosure. Unfortunately, the major limitation of this approach relates to the high computational burden of representing an enclosure at such a fine resolution. Thus, very few applications have adopted the continuous space approach to date. In particular, it can be prohibitive to simulate the movement of several thousand pedestrians with a rich set of behavioural and decision making characteristics. Consequently, applications that have adopted a continuous space approach tend to represent a limited number of behavioural characteristics. However, several pedestrian evacuation ‘models’ have applied the continuous space approach to enclosure representation. Nevertheless, all of these models assume a homogenous population of occupants whose movement and behaviour are implied by some functional analogy (see Section 3.6).

3.5: Occupant / Enclosure Perspective

Occupants within a pedestrian evacuation application can be perceived from either a global or an individual level. If the application considers occupants at the individual level (typical of regular lattice or continuous space applications), characteristics of each pedestrian or group of pedestrians can be assigned by the user. These attributes are the basis for the movement and decision-making processes of each occupant (see Section 3.6 and 3.7 respectively). At present, except for the consideration of crowd density and avoidance, the movement and decision making process of occupants within many applications is independent of influence from other occupants (i.e. pedestrians do not communicate amongst themselves). However, the individual approach allows for a diverse population of occupants to be represented, each with their own personal characteristics that can (to some extent) affect their evacuation process.

Conversely, if occupants are considered from a global perspective within an enclosure (typical of coarse scale network applications), pedestrians are represented as a homogeneous ensemble, with an average attribute assigned to the population (e.g. speed and density). The number of pedestrians able to exit the enclosure after a certain time is the predominant output of applications adopting the global enclosure approach, rather than where and when specific occupants exit an enclosure, and potentially their state of well being. The inability to incorporate factors such as individual occupant characteristics, occupant response to communication or emergency signage, complex interactions between occupants, etc, limits the accurate representation of a population's behaviour during an evacuation (Gwynne *et al.*, 1999b). On the other hand, if it is unnecessary to consider individuals for a particular investigation, or the user does not have information or knowledge of probable occupant characteristics with which to initialise the model, the global perspective may be a suitable alternative.

Similarly, the occupant can perceive the enclosure from either a global or individual level. Occupants with a global perspective will have unfettered access to information about the layout of the building (i.e. optimal exit path or paths) in the event of an incident. This information may be recalculated continuously throughout the evacuation process (e.g. a pedestrian can dynamically recalculate the shortest or quickest exit route if their primary exit becomes congested or blocked). Conversely, a pedestrian with an individual level of perception can be simulated with a limited degree of awareness about a building exit(s) and the state (i.e. availability) of passageways to them. For example, a simulated pedestrian will follow known exits paths (if they have prior knowledge of the enclosure) or follow an exit route based on local information available to them (emergency signage, staff assistance, adjacent occupants, etc). However, they will be unaware of possible congestion further ahead in the evacuation process, and will continue on their initial route until they encounter the point of congestion. In essence, the global perspective of occupants is akin to a model based on the rationale-choice paradigm, whilst the individual perspective adopts a bounded-rationality approach (see Castle and Crooks, 2006).

3.6: Occupant Movement

Evacuation movement is affected by both physical and psychological considerations. The discussion within the following section focuses on the physical aspect of occupant movement (Section 3.7 considers psychological considerations). Approaches to simulating occupant movement vary considerably, but to accurately predict occupant behaviour it is essential that an application incorporates realistic and comprehensive movement characteristics, which include speed (Section 3.6.1) and direction (Section 3.6.2) of movement.

3.6.1: Speed of Occupant Movement

One facet essential to all applications is the speed of pedestrian movement during an evacuation. Methods of representing this factor are intrinsically dependent upon the scale of enclosure representation. For example, applications that represent an enclosure as a coarse scale network invariably use an equation (often referred to as a flow / hydraulic equation; see Section 3.6.1.1) to simulate pedestrian movement. Secondary data are a common source for specifying pedestrian walking speeds required by flow equations. The sophistication and method of implementing the flow equation (i.e. for the population as a whole, or individual pedestrians), can vary considerably between applications. For instance, an application using a coarse scale network model and a global occupant perspective, will invariably input one average walking speed into the flow equation for all pedestrians, based on an average density of pedestrians within each section of the building. For example, the ALLSAFE application (Heskestad and Meland, 1998) is a coarse scale network application which uses a flow equation to calculate the total 'unimpeded' evacuation time of an enclosure. The unimpeded movement of pedestrians assumes a constant maximum walking speed throughout the evacuation, usually observed during low density conditions. To determine the total impeded evacuation time, predefined (by the application) time penalties pertaining to delays (e.g. length of time before occupants react to the emergency alarm, congestions at bottlenecks, unfamiliarity with the building, etc) are added to the total unimpeded evacuation time.

At the other end of the continuum, in terms of sophistication, a coarse scale network application adopting an individual perspective for occupants (of which there are few), can implement a flow equation that varies depending on the terrain of each building sector (e.g. stairs, horizontal pathway, ramps) and occupant characteristics (e.g. age, gender, mobility). Furthermore, the density of pedestrians within each room can be recalculated during the simulation, thus replicating the effect of higher densities upon walking speed. Nevertheless, even this type of coarse scale application is limited by the scale at which the enclosure is represented. Only an average occupant density can be calculated, based on the number of pedestrians per room, and this does not account for the location of each pedestrian within the room. A best case scenario, of equally distributed pedestrians within the room, is always assumed. This assumption does not incorporate considerations such as queuing and pedestrians interaction (e.g. bottlenecks, collision avoidance with other pedestrians, etc). In addition, the layout of a room (e.g. obstacles such as furniture) which can have a critical affect upon the efficiency of the evacuation process cannot be factored into the model. The ALLSAFE application is a particularly extreme example, where the limitations of a coarse scale network model are compounded by the rudimentary addition of fixed time penalties for assumed conditions such as congestion and room layout. The use of such an application should be strictly limited to a first approximate of total maximum and minimum evacuation times.

Applications that model an enclosure as a regular lattice of cells or as a continuous space, the majority of which represent occupants at the individual perspective, do not suffer from the same limitations. Sophisticated applications of these two modelling approaches can simulate different walking speeds depending on the terrain (e.g. stairs, horizontal pathway, ramps), the characteristics of each pedestrian (e.g. age, gender, mobility, etc), and the density of the local area / personal space (e.g. a buffer of a specified size) surrounding each pedestrian. For example, an application of this nature is capable of simulating a pedestrian travelling at their maximum personal walking speed (specified by each pedestrian's characteristics), when their chosen pathway to an exit is unobstructed and their personal space is unimpeded. If the pedestrian is required to negotiate an obstacle, or they come in contact with congestion (e.g. a queue at an exit), the pedestrian's walking speed will decelerate based on the degree of congestion / infringement of their personal space. In high density situations, a pedestrian's walking speed may become negligible. Similar to coarse scale network models, both types of application often use secondary data to specify the speed of movement for each pedestrian (see Section 3.6.1.2).

3.6.1.1: Flow / Hydraulic Equation

The flow / hydraulic equation, derived by analogy to fluid flow in channels, is a fundamental calculation often applied within coarse scale network models to simulate pedestrian movement (Fruin, 1971). Concisely stated, the equation has three variables. Density relates to the number of persons per unit of area, which can be expressed in tenths of a pedestrian per square metre (e.g. 2.3 persons/m^2). Speed is expressed as the distance covered by a person in a unit of time (e.g. 1.22m/s). Flow relates to the number of people that pass a reference point in a unit period of time. Flow is expressed as pedestrians per metre width of walkway per unit of time (e.g. 3.5 persons/m/s). Thus the equation takes the general form:

Flow Rate (p/m/s) = Speed (m/s) x Density (p/m^2)	Equation 1

Alternatively, density can be specified as the reciprocal or inverse (i.e. area per occupant e.g. 0.5m^2 per person, opposed to the number of pedestrian per square metre). Density is often specified in this way, as it is a more interpretable value that is easier to manipulate. When density is specified as the inverse the flow / hydraulic equation takes the form:

$\text{Flow Rate (p/m/s)} = \dfrac{\text{Speed (m/s)}}{\text{Density (m}^2\text{/p)}}$	Equation 2

Naturally, derivations of the basic flow equation exist, in order to manipulate the flow rate under different environmental conditions (e.g. upstairs, downstairs, high density, low density, etc) and for different occupant characteristics. Applications use coefficients to adjust the speed and density parameters and add specific constant values. Examples include FPETool (Deal, 1995), EXIT89 (Fahy, 1994), and EXITT (Levin, 1987). To clarify, although regular lattice and continuous space applications use an equation(s) to simulate pedestrian movement, the equation(s) used are not termed flow / hydraulic for one simple reason: movement is not based on a flow rate. Each pedestrian is simulated as an individual, where their personal walking speed is dependant on the local density of pedestrians. However, flow can be calculated from the movement of the simulated pedestrians past a reference point within the enclosure (e.g. an exit). Conversely, a coarse scale network model necessitates the use of a flow rate in order to simulate the movement of pedestrians because occupants are represented *en masse*.

3.6.1.2: Pedestrian Speed of Movement Data

Clearly, walking speed is a function of local density (Equations 1 and 2). In general, with an increase in density, the speed at which a pedestrian can walk decreases until a critical threshold, where movement becomes limited to a shuffle and flow becomes negligible. It is often incorrectly stated that movement ceases upon reaching a critical threshold. Studies have shown this notion to be incorrect. For example, Helbing (in press) evaluated video recordings of pedestrians in front of the entrance of the Jamarat Bridge during the Muslim pilgrimage in Mina / Makkah, Saudi Arabia. Pedestrian density reached extreme levels of more than 10 persons per square metre, equivalent to $0.1m^2$ per person. Although the authors observed a decrease in flow by a factor of three when density exceeded 6 persons per square metre, even when density exceeded this level the average ‘local’ speed remained finite. Indeed, there was no level of density at which people completely stopped moving. Conversely, the walking speed of pedestrians becomes variable at low densities. When density is low, it is not necessarily appropriate to infer high walking speeds. In fact, at low density the main factors that will affect speed are more likely to be an occupant’s characteristics such as age, mobility, and social affiliations (Proulx, 2002). For example, a family is more likely to move at the speed of its slowest member (e.g. a child or a senior person, for instance). In addition, a pedestrian's walking speed is influenced by conditions of the environment (e.g. horizontal passageways, stairs, inclining / declining ramps, etc).

Although research to quantify human movement can be traced back to the beginning of the twentieth century, the availability of secondary data sources is sparse. Work has progressed down two routes. Early research tended to concentrate on the movement of people under non-emergency conditions and focused on the movement capabilities of people in constricted areas such as stairs and intersections. Emergency or evacuation research followed, driven by investigations into human movement and behaviour during fires. Of the applications that use secondary data to specify walking speeds, key sources used within the majority of them include: Hankin and Wright (1958); Fruin (1971); Predtechenskii and Milinskii (1978); Ando *et al.* (1988); Pauls (1995); Nelson and Mowrer (2002). Although considerably less common, some pedestrian evacuation applications use primary data to specify the walking speed of occupants. However, very few applications use primary data as there only source; with the notable exception of Legion, Simulex and SGEM .

When considering a suitable pedestrian evacuation application it is prudent to identify whether the model requires input of occupant speed values by the user or whether a set of default values are provided by the application, derived from either a primary, secondary or a mixture of both types of data source. If values are provided by the application, it is imperative that the user is aware of the origin and validity of the data. If default values are not provided, the user should have sufficient knowledge, or will need to research the field in order to competently initialise the model.

3.6.2: Direction of Occupant Movement

Similar to the majority of features within a pedestrian evacuation application, the ability to simulate direction of occupant movement (e.g. path route choice, obstacle avoidance, collision avoidance with other pedestrians, etc), is dependant upon the scale of enclosure representation. For example, coarse scale network applications are incapable of simulating the direction of occupant movement below the implied scale of representation (i.e. movement can be simulated between building sectors, but not within a room). Regular lattice applications are better equipped to represent the direction of occupant movement, but pedestrians are limited to movement between adjacent cells. There are several techniques used to simulate movement between cells of regular lattice applications, although different applications apply subtle nuances. Thus, the following descriptions are broad definitions upon which many applications are based.

Once an enclosure under investigation has been tessellated (at a specified resolution e.g. 0.5 by 0.5m), all most every application encodes the enclosure floor plan in a manor that allows occupants to determine a suitable exit route. A popular method involves the assignment of a value to each cell (e.g. Euclidean distance from an exit), which allows pedestrians to determine the shortest path to one of the building's exits. Some common terms for the resultant floor plan are cost surface, potential field, or flood fill map. Some applications subsequently simulate the movement of occupants based on the simulated throw of a weighted die, where the weighting pertains to the encoded direction of an exit. Generally, this technique will move the pedestrian based on the first acceptable cell chosen by the die (i.e. no other pedestrian occupies the chosen cell and the cell is nearer to the exit than the pedestrian's current location). Although the pedestrian will move closer to the exit, one disadvantage of this approach is that the pedestrian may not follow the shortest path to the exit. Alternatively, an application will assess adjacent cells to each pedestrian, determining an unoccupied cell with the lowest cost surface value. If all cells closer to the exit are occupied, the pedestrian will wait for a cell to become available. Where more than one occupant is waiting for the same cell a decision rule can be applied by the application to resolve the conflict (e.g. the pedestrian with least patience will move first, if both pedestrians have the same patience the pedestrian to move first is chosen randomly). More complex applications may use this patience function to allow pedestrians to move to a cell further away from an exit, if after an allotted period of time congestion has prevented them from moving to a nearer cell. However, unlike the weighted throw of a dice approach, it is possible for the pedestrian to follow the shortest path out of the building. Furthermore, several different cost surfaces can be incorporated within the application, or a cost surface can be evaluated in a different way by each pedestrian based on the behavioural characteristics of each pedestrian (e.g. aggression, prior knowledge of the structure, attractiveness of an exit, presence or visual identification of an obstacle such as smoke, etc). Essentially, the decision making of a pedestrian can weight their potential passage options across the cost surface. For example, a cost surface might be reinterpreted by a mobility impaired pedestrian in a bid to avoid staircases. In summary, the decision making process of pedestrians within an application can be classified as either deterministic, stochastic or combination of both deterministic and stochastic (see Section 3.7). It is important to understand that the approach adopted will have an affect upon the simulation output. Thus, a user should determine the approach used and appreciate the impact this will have.

Finally, applications that represent an enclosure as a continuous space can simulate the movement of pedestrians more explicitly than coarse or regular lattice applications. Generally, occupant movement is defined by an individual's walking speed and a velocity vector corresponding to their orientation, where orientation is determined by a pedestrian's location in geometrical space with respect to their individual goal (i.e. nearest exit, location a familiar member, etc). Stationary obstacles such as columns and ticket barriers as well as non-stationary obstacles (i.e. other pedestrians) will have an affect on occupant movement. Generally, pedestrians assess a local area to themselves (e.g. a buffer of a specified size) in order to adjust their walking speed (e.g. accelerate past a slower pedestrian, decelerate when approaching congestion, etc), and a minimum personal space that stationary and non-stationary obstacles cannot encroach within (Figure 3). Route choice can be influenced by a pedestrian's characteristics (e.g. knowledge of the building layout, attractiveness of an exit - in terms of the presence of smoke or avoidance of steps, etc) and the presence of other occupants (e.g. congestion). Consideration of these behavioural characteristics allows each pedestrian to alter their original egress route if necessary.

3.6.2.1: Functional-Analogy Approach

Another method of simulating pedestrian movement, which to the best of the author's knowledge has only been applied in continuous space, is the functional-analogy approach. This technique uses an equation or a set of equations to determine movement based on a function (e.g. magnetism, swarming, fluid dynamics, etc), often from another field of study, and consequently not derived from the observation of real-life occupant movement or behaviour. For example, the behaviour of occupants within Okazaki and Matsushita's (1993) magnet model are sourced from physics. The function is purported to simulate human movement and behaviour in an analogous way. Every pedestrian is treated as an identical individual, and both occupant movement and behaviour is simulated completely by this function.

Although this approach has not been adapted by any emergency evacuation application (as defined within this paper) to date, the following discussion explores several seminal models that have used the functional-analogy approach to represent pedestrian movement.

3.6.2.2: Fluid Dynamics / Gas-Kinetic Models

Before fluid dynamic[1] equations were applied to the modelling of pedestrian movement, they were widely used to model the dynamics of traffic flow; particularly automobiles (e.g. Lighthill and Whitham, 1955; Paveri-Fontana, 1975; Helbing, 1996). Henderson (1971; 1974) was probably the first person to compare measurements of pedestrian flow, using Navier-Stokes equations (a set of equations that describe the motion of fluid substances such as liquids and gases). Specifically, he extracted equations from the Maxwell-Boltzmann theory of a homogeneous gas comprising of statistically independent particles in equilibrium across a two dimensional space. Henderson examined crowds, observed to be in an 'analogous gaseous state' (i.e. approximately homogeneous and of sufficiently small particle density to ensure that most individuals were statistically independent), within the city of Sydney. The calculation of a

[1] The study of fluids (liquids or gases) in motion.

probability density function of pedestrian velocity from observed / measured distributions of pedestrian counts produced reasonable agreement with the Maxwell-Boltzmann distribution obtained from Henderson's equation of pedestrian movement (1971, pp. 381).

However, to realistically simulate pedestrian movement using fluid dynamics theory, a model must incorporate factors of human decision and interaction (e.g. deceleration or acceleration in avoidance manoeuvres). Consequently, Helbing (1991; 1992a; 1992b) extended Henderson's fluid dynamics approach to allow for factors of human decision and interaction, without making use of unrealistic conservation of momentum assumptions. In spite of his attempts, Helbing was still dissatisfied with several approximations of the fluid dynamics approach. Consequently, he proposed another model based on the 'social force' theory (Helbing and Molnár, 1995).

3.6.2.3: Social Force Model

It has been suggested that the motion of pedestrians can be described as if they were subjected to social fields / forces (Lewin, 1952). Helbing and his colleagues at the University of Stuttgart used this theory to develop a model where pedestrian movement is based on sensory stimulus, determined by personal aims chosen from a set of options, with an objective of utility maximisation. The following three main effects are used to determine the motion of each pedestrian:

1) It is assumed that a pedestrian wishes to reach a specified destination with minimal discomfort or inconvenience. Pedestrians therefore traverse the shortest route to an objective with a desired walking speed, both of which can be changed depending on local interaction (e.g. avoidance manoeuvres).
2) The motion of each pedestrian is influenced by their surrounding environment. Similar to continuous space applications, each pedestrian possesses a personal territory or buffer that they wish to keep between themselves and other pedestrians and obstacles. The size of each pedestrian's personal buffer is dependent on the density of surrounding pedestrians and the speed at which the pedestrian is travelling.

Pedestrians can exert a repulsive force upon other pedestrians or stationary obstacles if either becomes uncomfortably close.

3) Pedestrians can be attracted to other pedestrians (e.g. friends, relatives, etc) as well as objectives (e.g. an exit).

The derived equation (Helbing and Molnár, 1995, pp 4283-4284) for motion is formulated from the total motivation of each pedestrian (i.e. the sum of these effects). Over time, change in a pedestrian's velocity is therefore described by a vector based quantity that can be interpreted as a social force. The force represents the effect of the environment (e.g. other pedestrians and obstacles within the enclosure) upon the behaviour of the pedestrian. However, the social force is not exerted on the pedestrian's body; it is a quantity that describes the motivation to act. The acceleration and deceleration force of pedestrians is a reaction to the perceived information from the environment (i.e. pedestrians act as if they are subjected to external forces).

Despite the simplicity of the social force model rules, it describes several real-world observed phenomena, and demonstrates the emergence of spatio-temporal patterns of collective behaviour. For example, computer simulations of the social force model demonstrate the development of bi-directional lane formation, and the oscillatory changes of walking direction at narrow passages or bottlenecks (Helbing *et al.*, 2001). The model also demonstrates that lane formation is dependant on the width of a walkway, which changes for different crowd densities (e.g. the average number of lanes emerging on a walkway scales linearly with width when crowd density equals 0.3 m^{-2}). However, although these observed spatio-temporal patterns arise due to the non-linear interaction of pedestrians, these patterns are not the result of individual pedestrians strategic considerations of the environment, since every pedestrian is assumed to behave in a systematic manner regardless of the current situation (Helbing and Molnár, 1995).

The social force model has also been used to explore the route choice behaviour of pedestrians (Helbing *et al.*, 2001), as well as the mechanisms and preconditions of uncoordinated movement (e.g. panic) in crowds (Helbing *et al.*, 2000b). The latter investigation purported a phenomenon termed ‘freezing by heating’ or ‘faster is slower’, whereby fleeing pedestrians increase resistance between themselves thus slowing the overall speed at which people can exit a room, with potentially fatal consequences (Helbing *et al.*, 2000a). Finally, the social force model has been adapted to simulate typical features of trail formation on deformable ground (e.g. green areas in public parks) by active walkers, based on the idea of dendritic trail formation by ants (Helbing *et al.*, 1997; Helbing *et al.*, 2001). A comparison with empirical material showed good agreement between the model and reality.

3.6.2.4: Magnetic Model

At approximately the same time as details of the social force model were published, Okazaki and Matsushita (1993) proposed magnetism as a functional-analogy of pedestrian movement and behaviour. Each pedestrian and obstacle (e.g. walls, columns, handrails, etc) is positively charged within the model, while the exit of the building is negatively charged. Thus, pedestrians are repelled by one another and away from obstacles, but are attracted towards exits of a building. Within a complex building layout, where pedestrians are unable to move directly towards an exit, temporary goals (e.g. the corner of walls) usher pedestrian movement towards an exit. Importantly, pedestrian movement cannot be based purely on a magnetic force, because an occupant’s velocity would increase towards an exit without limit according to Coulomb’s Law (Equation 3):

$$\mathbf{F} = \frac{k_c \bullet Q_1 \bullet Q_2}{\mathbf{r}^2}\,\hat{\mathbf{v}} \qquad \text{Equation 3}$$

Where:
- $\mathbf{F}$ is an electrostatic force vector
- k_c is Coulomb’s constant
- Q_1 is the charge on which the force acts
- Q_2 is the acting charge
- $\mathbf{R}$ is the distance vector between the two charges
- $\hat{\mathbf{v}}$ is a unit vector pointing in the direction of r

In the light of this, a maximum velocity threshold is stated to prevent the continuous acceleration of a pedestrian. Furthermore, to prevent pedestrians from colliding with one another a secondary force is imparted. Figure 3 illustrates pedestrian ‘A’ trying to avoid a collision with pedestrian ‘B’. Here, a force with acceleration ‘**a**’ (Equation 4) is exerted upon pedestrian ‘A’ to alter the relative velocity between the two pedestrians, to the direction of plane ‘AC ‘(the tangent between pedestrian ‘A’ and the personal space with pedestrian ‘B’), thus averting a collision between the two pedestrians.

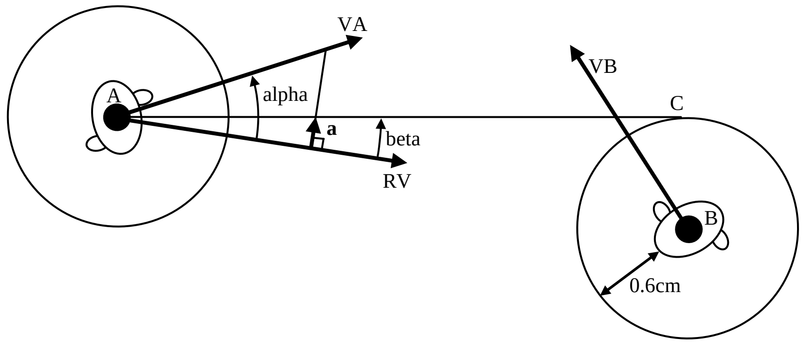

Figure 3: Acceleration imparted on pedestrian A to avoid collision with pedestrian B (redrawn from Okazaki and Matsushita 1993).

$$\mathbf{a} = \mathrm{RV} \bullet \cos(\mathrm{alpha}) \bullet \tan(\mathrm{beta})$$ Equation 4

Where:	VA	is the velocity of pedestrian A
	VB	is the velocity of pedestrian B
	RV	is the velocity of pedestrian A with respect to pedestrian B or relative velocity
	Alpha	is the angle between RV and VA
	Beta	is the angle between RV and AC

The velocity of each pedestrian at every time step (0.1s) equates to the sum of the forces from the exit, obstacles and other pedestrians. The velocity, density and flow volume of pedestrians can be varied depending on different scenarios. For example, to decrease the density and volume of pedestrians it is possible to increase the magnetic (repulsive) force between obstacles and pedestrians, thus pedestrians maintain a larger distance between themselves and obstacles or pedestrians.

3.6.2.5: Critique of Functional-Analogy Approach

Despite the relative success of simulating certain phenomena, there are limitations of modelling pedestrian movement based on the functional-analogy approach. Firstly, pedestrians do not abide by laws of physics; they are free to choose their direction and speed of movement, they are not required to conserve momentum, and they can stop and start at will. For example, modelling pedestrian movement as a fluid assumes an even distribution of people across all available space and the unbounded movement of pedestrians within this space (i.e. a pedestrian at the front of a crowd can, if they chose to, move directly to the back). Critically, while individuals can be represented within the functional-analogy approach, the population is assumed to be homogenous. All occupant behaviour is therefore governed by the same rule(s), and occupants will react in a deterministic manner to stimuli. Occupants have the same mass or attractive force enacted upon them; thus their potential walking speed is in constant equilibrium with local density. A model of this nature is less suitable for non-equilibrium situations (e.g. movement on stairs). In addition, any model that assumes a homogenous population makes no provision for individual behaviour and decision making (e.g. pre-evacuation movement, group affiliation, different degrees of knowledge about the enclosure layout, mobility, etc).

Helbing (1992a) also notes the equations used within functional-analogy models (including his fluid dynamics model), are extremely complicated, impossible to solve analytically, and very difficult to solve with a computer. This facet restricts the use of these models for many practitioners required to assess the evacuation of an enclosure, especially if parameters require modification for different scenarios. Moreover, most functional-analogy models have not been implemented for an entire enclosure, they have only been used to simulate a specific phenomena that occurs within a sector of a building (e.g. formation of congestion at an exit, lane organisation of bi-directional flow along a corridor). One explanation for this could be due to their extreme computational overheads. Additionally, most functional-analogy models have not been developed or validated for emergency evacuation situations. According to Helbing and Molnár (1995), functional-analogy models are best suited for relatively simple situations where the model is restricted to the description of pedestrian movement found in large homogenous populations.

3.7: Behavioural Perspective of Occupants

The representation of occupant decision-making varies considerably between applications, with several different approaches used. The approach adopted by an application is fundamentally dependent upon the application's enclosure / occupant perspective (i.e. individual or global), which is intrinsically reliant on the scale of enclosure representation. In general, approaches of simulating occupant behaviour can be separated into one of the following five categories:

1) **No behaviour:** An application of this type does not attempt to simulate the behavioural response of pedestrians to stimuli; they rely completely upon their approach to simulating occupant movement (Section 3.6) in order to simulate the evacuation potential of a structure. For instance, coarse scale network applications that employ a global enclosure and global occupant perspective of pedestrians rarely incorporate behavioural considerations of pedestrians. In particular, this category of behavioural perspective applies to applications classified as movement or movement-optimisation in 'nature'.
2) **Implicit behaviour:** Some applications do not explicitly specify the behaviour of pedestrians; rather, it is implicitly represented by the rules or equation(s) that determine occupant movement. For instance, an application that calculates occupant walking speed based on the density of other pedestrians within a local area or buffer, and orientation by a pedestrian's location with respect to an exit or intermediary goal, relies solely upon these rules or equation(s) to simulate the decision making process of the occupant.
3) **Rule-based behaviour:** This type of application explicitly considers the behavioural traits of individual occupants, attempting to simulate occupant decision making according to predefined rules or reactions / responses. Evacuee decision making can be separated into pre-evacuation (e.g. length of time required to investigate or confirm, and subsequently react to an evacuation cue) and evacuation (e.g. the

influence of crowding, smoke, prior knowledge of the structure, etc, upon route choice and walking speed). In turn, occupants with different characteristics (e.g. age, gender, patience / aggression, mobility, etc), can be simulated to react to these stimuli in different ways. Three methods of specifying a pedestrians' reaction to decisions are:

- **Deterministically:** Rules trigger the same decision when confronted with the same stimuli, in a deterministic fashion. This method has the disadvantage of denying the possibility of natural variation in outcomes through repetition;
- **Stochastically:** Decisions are made stochastically based on the pedestrian's characteristics, and;
- **Deterministically / Stochastically:** Some applications apply a combination of both stochastic and deterministic reactions.

4) **Artificial Intelligence (AI) behaviour:** More recently AI has been implemented by some applications in an attempt simulate human behaviour or an approximation of human-behaviour during an evacuation. To date, this approach has been applied by very few applications, and details of the methodology are scarce.

For applications where the behaviour of occupants is explicitly simulated (approaches 3 and 4), it is important for a user to understand the decision making process and the effect of behavioural characteristics upon this decision making process, as well as the evidence upon which these rules are based. The rules and their weighting will affect the reaction of occupants (e.g. hesitance in pre-evacuation movement, change in exit route) and the speed and direction in which pedestrians move. Both of which could have a significant effect on the overall evacuation time of the enclosure. For those applications that do not explicitly simulate the behaviour of occupants (approaches 1 & 2), a thorough understanding of the movement approach adopted, and the rule(s) / equation(s) that dictate movement is very important.

3.8: Validation

The level of an application's validation is an important consideration. Documentation from the developer or the supplier should be available for the user to assess the validity of the application. A user will need to assess whether the validation is of sufficient quality and reliability. The quality of applications validation vary; simulation output is generally validated against fire regulations or codes (applicable to the enclosure under investigation), the outcome of a fire demonstration(s) conducted for the building in question, or published literature documenting similar evacuation experiments or fire drills. Assessment of an application's reliability, in terms of validation, relates to how well the validation process has been documented, whether it has been published in peer reviewed literature, if validation has been undertaken by an independent third-party, etc. While validation studies help to identify the capabilities of an application, they also help discover their limitations. Finally, a user should develop a verification suite of tests to provide adequate confidence in the application.

3.9: Support

It is useful to be aware of an application's age and developments / advancements since its inception. An application no longer maintained and developed, which has ceased advance in line with theory or technological progress, may no longer be useful or appropriate to use. Conversely, a mature application that has been continually updated and maintained can be appealing to a user, especially if it has been used in numerous modelling endeavours and has a track record of appliance. Equally, a user might be mindful of newly developed applications with limited employment since its release. Additional considerations include the availability of training and support for the application (e.g. training courses, software tutorials, phone or online support, bug reporting / fixing, etc).

4: Synopsis: Key Questions

The preceding discussion (Sections 3.1.1 - 3.1.9) identified nine topic areas to investigate during the decision making process of choosing a pedestrian evacuation application. Based on this information the following key questions, separated into each topic area, have been identified. To reiterate, the order in which the topics are presented approximates the order in which a user should consider them. Use of this sequence may allow a user to reduce redundant time spent investigating and understanding information pertaining to an application which could be deemed unsuitable at an earlier stage. However, many of the questions within each of these topics should be considered concurrently.

Availability and Access:

- What is the financial cost of the application (e.g. free of charge, consultancy basis, one-off fee, annual licence and support fee, or a combination of these charging bases?)
- How is the application available (off-the-shelf or on a consultancy basis through the developer or a third-party)?
- What minimum computer hardware specification is required (RAM, central processing unit, etc)?
- What operating system is required (Windows, Linux, Mac OS X, etc)?

Purpose / Background:

- Is the purpose (e.g. building, aviation, maritime, etc) of the application suitable for the research investigation?
- Is the focus of an application (i.e. residential buildings, high-rise residential tower blocks, low-rise buildings) suitable for the research endeavour?
- What is the origin of the application (e.g. development environment, expertise of developer / development team)?

Nature:

- What is the general nature of the application: movement; optimisation-movement; movement and behavioural; or partial-behavioural?

Enclosure Representation:

- At what scale is the structure represented?
    - Coarse scale network, regular lattice of continuous space.
- How, and in what format (e.g. CAD, GIS, image file, etc) can data be imported into the application to represent the enclosure and network connections?

Occupant / Enclosure Perspective:

- Does the application have a global or an individual perspective of occupants?
  - If the perspective is global, what characteristics of the population are represented, and how are they defined?
  - If the perspective is individual, what individual characteristics of the population are represented, and how are they defined?
- Do the occupants have a global or individual perspective of the enclosure?
  - If the perspective is global, what information is available to the occupants, and how is this information defined?
  - If the perspective is individual, what information is available to the occupants, and how is this information defined?

Occupant Movement:

- How is pedestrian walking speed specified: are default values given by the application, or does the user need to initialise this parameter?
- Depending upon the source of walking speed values, what is the origin and validity of these data, and does this correlate with the objective of the research endeavour (e.g. are non-evacuation walking speeds used or extrapolated by the application to simulate evacuation movement and / or walking speeds)?
- How is the direction of occupant movement simulated: flow / hydraulic equation; cell-based; velocity based vector, etc?

Behavioural Perspective of Occupants:

- What behavioural approach does the application employ: none; implicit; rule-based (deterministic or stochastic); or artificial intelligence?
- If the application attempts to simulate the behaviour of occupants, what behavioural considerations does it consider, and how will this affect the movement and decision choices of each pedestrian?

Validation:

- In terms of both quality and reliability, to what extent has the application been validated?

Support:

- Is the application maintained?
- Are developments still being made to the application?
- Is the application actively supported by the developer (training courses, software tutorials, phone or online help, bug reporting / fixing, etc)?

5: Conclusion

This paper has clearly identified and explained criteria for consideration when evaluating the suitability of a pedestrian evacuation software application to asses the evacuation process of a building. Guidelines in the form of nine topic areas identify different modelling approaches adopted, as well as features / functionality provided by applications designed specifically for simulating the egress of pedestrians from inside a building. The paper concluded with a synopsis of these guidelines, identifying key questions (by topic area) to found the evaluation process. Based on the information within this paper, Castle and Longley (in press) have subsequently reviewed and interpreted pedestrian evacuation applications in relation to a hypothetical building assessment.

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