Modelling pedestrian behaviour under emergency conditions – State-of-the-art and future directions

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1 Introduction

Movement of people forms an important component of a multi-modal transportation system. Promoting walking is an important part of the shift to more sustainable transport (OECD, 2002; Cotter and Hannan, 1999). Thus the planning and designing of amenities for efficient, comfortable and safe walking operations of pedestrian's movements in public places such as multimodal points, shopping malls, stadiums and concert venues is a great challenge to planners to create a liveable and sustainable infrastructure. The movement of large numbers of people is important in many situations, such as the evacuation of buildings, stadiums, theatres, ships, aircraft or outdoor events like public assemblies, open concerts, religious gatherings, community evacuation etc., under emergency conditions. Numerous incidents have been reported (for example Crowd Dynamics, 2008; Helbing *et al*., 2002) in which overcrowding has resulted in injuries and death during emergency situations. Modelling and empirical study of pedestrian behaviour under emergency conditions is imperative to assist planners and managers of emergency response to analyse and assess safety precautions for those situations.

The potential societal benefits of modelling and simulating pedestrian behaviour include:

- Planners and managers can use simulations to gain insight into possible problems regarding the evacuation of public buildings early in the planning of those facilities.
- Evaluating evacuation strategies through simulation can provide insight on efficiency of evacuation processes and subsequent optimisation of the evacuation plans.
- Managers of large events can use simulation to enhance their understanding of how to control crowd movements in different situations.
- Assessment of safety measurements of passenger vessels is of particular importance and so evacuation simulations are being performed for aircraft and ships to assess the safety of those vessels.
- Pedestrian dynamics, as an important component of group dynamics, is interconnected to several other fields including traffic engineering, architecture, socio-psychology, safety science etc. and as such the analysis and results have wider applications.

This paper aims to present the state-of-the-art in pedestrian modelling under emergency conditions, assessing their limitations and identifying potential future directions to develop realistic modelling capabilities. The next section of this paper outlines and assesses the state-of-the-art in pedestrian modelling. Future directions for the establishment of more realistic modelling capabilities are then outlined. The final section presents the conclusions.

2 State-of-the-art in modelling and simulating pedestrian behaviour

As with vehicular traffic, pedestrian traffic has been studied mainly from macroscopic and microscopic approaches and in some cases even from mesoscopic approaches as will be explained in the subsequent sections. Study and modelling of pedestrian behaviour has been conducted for over 30 years (Henderson, 1971; Fruin, 1971). In these earlier studies, the focus was to determine the level of service for pedestrian facilities and based on them architectural and building codes were developed. Many of the pedestrian planning and design, contingency planning and architectural and building codes used in practice are based on understanding developed from macroscopic models. However, with the advancement in computer power, recent trends have been towards microscopic modelling with a focus on emergency evacuation/panic situations. Microscopic modelling has the potential draw on the socio-psychological literature (Mintz, 1951; Quarantelli, 1957) to represent the influence of socio-psychological factors under emergency conditions. Those studies highlight that crowd behaviour during normal and panic conditions are entirely different. Interaction among individuals form an important component and as stated by Quarantelli (1957), *“the utmost importance of the nature of the interaction that occurs prior to and during panic flight should be especially stressed”.* Sime (1995) argues that engineering studies focus directly on design issues such as entrance and exit widths while psychological studies are more concerned with the motivations of people, the nature of the behaviour and the way it is interpreted. Sime concludes that there is a need to concentrate on crowd psychology in the context of crowd safety engineering concerns.

Many simulation models and software packages exist for simulating pedestrian motion. Those models can be classified based on their space representation (continuous / grid based / network structure), purpose (specific purpose / general purpose), and level of detail (macroscopic / mesoscopic / microscopic). Dedicated theory and models focused especially on panic/emergency conditions are however still at an early stage of development. It is not the focus of this paper to review commercial software packages for evacuation simulation but rather to examine the underlying theoretical foundations on which they are based. The discussion here is structured on the basis of the level at which the system is represented and followed with consideration of the validation approach for those models.

2.1 Macroscopic model

Macroscopic models focus on the aggregate representation of pedestrian movements in a crowd through flow, density and speed relationships (Fruin, 1971; Still, 2000; Daamen, 2004). The macroscopic behaviour reveals that the pedestrian average speed is reduced as the density increases. The flow equation, derived from analogy to fluid flow, is given by

Flow (Q) = Average Speed (V) x Average Density (K) (1)

The reciprocal of the density is called the Space Module or Area Module (M) (Teknomo, 2002) which is more convenient to relate pedestrian flow space to the human factors. This lead to

Pedestrian Flow (Q_p) = Average Speed (V_p) / Area Module (M) (2)

The Highway Capacity Manual (TRB, 2000) categorises level of service for footpaths, stairways and cross flows based on the relationship between space, average speed and flow rate. Daamen (2004) outlines flow, density and speed relationship for pedestrians as proposed by several researchers based on empirical observations and also presents a macroscopic model (SimPed) for modelling passenger flows in public transport facilities. The developed simulation tool, which is meant as an aid in the planning and design process, covers route choice, boarding and alighting as well as walking.

Macroscopic models treats pedestrian movement like a continuous fluid and rely on the behaviour of the fluid as a large scale interactive system. Macroscopic analysis may be suited for very high density, large systems in which the behaviour of groups of units is appropriate. However, by representing the particle (pedestrian) as unthinking elements, these models do not account for the fact that varied behaviour of individual particles can significantly change the way in which the fluid (crowd) as a whole behaves especially in emergency situations. Hughes (2002) proposed a theory for the flow of pedestrians based on continuum modelling which attempts to model the flow of pedestrians as a “thinking fluid” based on well-defined hypotheses. The theory has been designed for the development of general techniques to understand the motion of large crowds; however, it has the potential to be used as a predictive tool. The behaviour predicted by the proposed macroscopic model has been compared with aerial observations for the Jamarat Bridge near Mecca, Saudi Arabia. The continuum hypothesis is stated to be invalid for a supercritical flow (low-density) and thus there is scope to extend in a probabilistic manner the continuum theory of pedestrian flows to low-density flows. Such an extension is believed to provide an important interface between discrete and continuous models of human flows. Lee and Hughes (2005) have reported that the theory (Hughes 2002) was able to identify the dangerous locations for a crowd-related accident and to explain the development of trampling and crushing accidents.

Most building codes of practice for pedestrian planning and design are macroscopic models. However, the assumption of a linear relationship between space and flow at the macroscopic level has been questioned by several researchers based on microscopic simulations. Teknomo (2002) illustrates with an example that the performance of the movement of two opposing pedestrian streams can be enhanced by assigning the movement of pedestrians in only one direction to each door of a two-way door instead of letting them move through any of the two doors. Hence, by controlling the interactions of pedestrians, a more efficient pedestrian flow can be achieved with less space. Consideration of these interactions enables better estimate of delays to pedestrians, which is particularly important in emergency situations (Shiwakoti and Nakatsuji 2005). These are some of the prime reasons for shift of modelling approach from macroscopic to microscopic.

2.2 Microscopic model

Microscopic models treat each pedestrian in a crowd as an individual agent occupying a certain space at an instant in time. These models can provide valuable insight over a wide range of behavioural inputs. The microscopic models deal with the factors that drive pedestrians towards the destination by considering the interaction between the pedestrians (Helbing *et al*., 2002; Teknomo, 2002). Such models give a more realistic representation of pedestrian movements. However there are problems of analytical manipulability and computation effort and cost (cost is proportional to the level of detail) (Still, 2000). The models can be classified broadly into four groups: Physical based models, Cellular based models, Queuing network models and Multi agent models. The following sections review these approaches while the comparisons of the different microscopic modelling approaches have been presented in Table 1.

2.2.1 Physical based models

The physical based models recognise that the crowd is made up of individuals who react to events around them. These models have been primarily used to study indoor emergency and panic situations to design evacuation strategies. In the physical based model, optimal acceleration is determined based on various physical forces. By applying equations of motion, the simulation is updated in each time step. Some emerging models based on this are Magnetic Force Model (Okazaki and Matsushita, 1993), NOMAD (Normative Pedestrian Behaviour Theory) (Hoogendoorn, 2004) and the Social Force Model (Helbing *et al*., 2000).

The Magnetic Force Model (MFM) represents the movement of each pedestrian as if it was a magnetised object in a magnetic field. The movement is based on two forces, magnetic forces from Coulomb's law to drive the pedestrians to their goal and other forces to avoid collisions with other pedestrians. The effectiveness of the simulation model has been shown by two simulation examples (Okazaki and Matsushita, 1993):

- Evacuation from an office building
- Movement of pedestrians in queue spaces

The MFM is simple in terms of its formulation. Collision avoidance is considered in the model. Variations in microscopic pedestrian characteristics have not been considered. It is particularly suited to fire safety evacuation and queue related problems in architectural and urban spaces. Planners can observe the flows and congestions occurring in the architectural space. The parameters used are not directly estimable and thus the challenge lies in validation of the model.

The Social Force Model (SFM) is a physical model based on social field theory. In the simplified version of this microscopic model, the dynamics of each pedestrian is determined by three kinds of forces:

- Driving forces (that direct the pedestrian towards their destination)
- Social or pedestrian forces (that avoid collisions between two pedestrians through repulsive forces) and
- Granular forces (that come into play when two pedestrians touch each other and start pushing each other in a panic situation).

Despite its simplicity, SFM has been successful in reproducing several collective pedestrian flow phenomena and analysing different characteristics of pedestrian flow. Its strength lies in dealing with panic situations and several simulation case studies on escape panic from a room have been performed (Helbing *et al.*, 2000). The parameters used in the model have physical meaning and can be measured unlike the abstract values used in the MFM. The model is flexible enough to simulate both normal behaviour as well as panic behaviour of pedestrians. However the SFM has not been calibrated and validated on real world data for a panic situation. Parameters values have been based on visual inspection. Variations in microscopic pedestrian characteristics have not been considered. The model might not be sufficient in simulating complex scenarios where route finding is important.

NOMAD has a theoretical background based on the micro-economics of cost minimisation. It describes the execution of human control tasks where pedestrians are assumed to minimise the so called "running cost of walking". It has been reported to be successful in reproducing collective pedestrian flow phenomena, lane formation, homogenous strips in crossing pedestrian flows, behaviour at bottlenecks and to be consistent with important empirical and experimental findings on microscopic pedestrian behaviour, such as anisotropy (reflects the difference in behaviour when reacting to stimuli in front or behind, relative to stimuli from other side) and pedestrian's cooperation. It has been further shown that NOMAD provides a generalisation of the SFM (Hoogendoorn, 2004). No indication of validation of the model has been reported, however comparison of headway distributions from the model have been compared with the observed headway from experiments.

2.2.2 Cellular based models

The basic idea of a cellular based, also know as Cellular Automata (CA) or matrix-based system, is to divide a floor area into cells. These cells can only contain one pedestrian. Cells are used to represent free floor areas, obstacles, areas occupied by individuals or a group of people, or regions with other environmental attributes. People transit from cell to cell based on occupancy rules defined for the cells (Pan, 2006).

Blue and Adler (1999) presents a CA micro-simulation model for a bidirectional pedestrian walkway. Simulation experiments indicate that the basic model is applicable to walkways of various lengths and widths and across different directional shares of pedestrian movements. Schadschneider (2002) presents a cellular automaton model and reports (Burstedde *et al.*, 2002) that the model is able to reproduce collective effects and self-organisation phenomena encountered in pedestrian traffic, e.g. lane formation in counter flow through a large corridor and oscillations at doors. Furthermore, simple examples are presented where the model is applied to the simulation of evacuation processes. However, no indication of validation of the model has been reported. Klüpfel (2003) proposed a cellular automation model for handling complex scenarios and egress simulations. The evacuation scenarios that have been considered are the orderly evacuation. The simulation results have been validated by comparing evacuation time from evacuation trials for a theatre, primary school and a ship.

Although researchers have demonstrated the potential of cellular automata to model pedestrian dynamics, problems with the simulation of crowd cross flows and concourses have been reported (Pan, 2006). Also the movement of people appears unrealistic particularly when the model is illustrated graphically and people appear to hopping on or across the cells as the simulation proceed.

2.2.3 Queuing network

Queuing models have been applied to model the evacuations from buildings. Løvas (1994) proposed a discrete event based model which uses a probabilistic approach to represent pedestrian movement toward a destination with priority rules governing the interaction between pedestrians. Queuing models are based on the following assumptions:

- Any pedestrian facility can be modelled as a network of walkway sections, and
- Pedestrian flow in this network can be modelled as a queuing network process, where each pedestrian is treated as a separate flow object, interacting with the other objects.

The proposed theoretical model has been illustrated by several examples showing the effectiveness of the model to estimate the congestion and evacuation time in a building network (Løvas, 1994). There is however no indication of the validation of the model.

2.2.4 Multi-agent model

Multi-agent based modelling is a particular type of computational methodology that allows the building of an artificial environment populated with agents that are capable of interacting with each other (Pan, 2006). In these models, a set of agents act for themselves beneficially in terms of their strategies. An agent is an identifiable unit of computer program code that is autonomous and goal-directed. Agents may also possess other capabilities such as intelligence and adaptability. The agents usually act on the multi-agent system interacting with the other agents and the interactions can be characterised by certain conditions of mobility such as the following other agents, leading other agents, and the inhibition of travel through congestion. These multi-agent simulations are thus quite suggestive for space-time dynamics in that they allow exploration of relationships between micro-level individual actions and emergent macro-level phenomena (Batty and Jiang, 1999). For large scale evacuation scenario and complex systems, multi agent based modelling has been the preferred approach.

However, multi agent simulations generally do not account for the force effects, which are particularly important in modelling crowd behaviours. Although people generally try to move toward goals, force effects can cause them to be pushed away from their desired trajectories and accurate models must reflect this. Also, the presence of crowd members injured by excessive force can significantly affect the ability of others to move freely. Models that do not represent pushing forces therefore cannot directly account for all these additional causes of delay (Henein and White, 2005).

Pan (2006) prototyped a multi agent system framework able to model emergent human social behaviours, such as competitive behaviour, queuing behaviour and herding behaviour through simulating the behaviour of human agents at a microscopic level. In the framework, each person is modelled as an autonomous agent who interacts with a virtual environment and other agents according to an 'Individual Behaviour Model' and some global rules on crowd dynamics.

Pan (2006) reports the validation of the developed multi-agent based model through comparison of the simulation results (crowd flow rate for different passageway width) with the results obtained by other evacuation models and software. The developed model have been applied to simulate and replicate a case of crowd evacuation and also to facilitate egress design analysis for a multi-storey university building.

2.3 Mesoscopic model

Mesoscopic modelling of vehicular traffic does not focus on single vehicles but considers groups of vehicles in an identical environment. For example, where there is the same speed for all vehicles in the same section of the road and this could be considered a group or platoon. The idea of grouping individuals has been transformed to mesoscopic pedestrian flow models developed by Hanisch *et al*. (2003) for the online simulation of pedestrian flow in public buildings. Instead of modelling a single pedestrian, groups of pedestrians are used and every group has its own rules of behaviour. The main components of the model are groups of pedestrians and an abstract network to represent the environment. The groups move through a network which consisting of nodes and links. Nodes are subdivided into sources, sinks and storages. Sources generate and sinks respectively destroy groups. A storage represents an area and this node can delay the pedestrian flow. Storages are basically internal resources in the environment which are used by pedestrians. Similarly, Tolujew and Alcalá (2004) follow a mesoscopic approach for the simulation of pedestrian traffic flows in public buildings.

Mesoscopic modelling techniques have specific application, especially for real time pedestrian flow to determine the delay and congestion in public areas. The models as described above seem to be a theoretical proposition only with no indication of the validation approaches. However, Tolujew and Alcalá (2004) mention that in order to test both the accuracy and performance of their mesoscopic approach; a prototype simulator was designed and implemented. It is designed to be used in a control centre of a train station or an airport to deliver information on expected system behaviour to a decision support system. Likewise, Hanisch *et al*. (2003) also mention that a prototype simulator of their mesoscopic approach has been set up at the Fraunhofer Institute of Magdeburg, Germany. The concept of dealing with groups of people may have potential in the context of the SFM in order to reduce the simulation time, especially when a large number of people are to be simulated.

Table 1 – Comparison of different approaches to microscopic modelling

Microscopic Model Approaches			
Physical based	**Cellular based**	**Queuing network**	**Multi-agent**
General Procedure to Develop the Model			
• Continuous-space • Optimal acceleration based on physical forces • Equations of motion determining the movement of people in each time step e.g. SFM, MFM, NOMAD	• Discrete-space • Space divided into cells • People transit from cell to cell based on occupancy rules defined for the cells in each time step e.g. Schadschneider (2002), Klüpfel (2003)	• Pedestrian facility modelled as a network of walkway sections • Pedestrian flow modelled as a queuing network process-oriented discrete-event simulation e.g. Løvas (1994)	• Each individual is modelled as an autonomous agent and process-oriented. • Agents characterized by certain conditions of mobility such as the following the other agents, the lead to the other agents, the inhibition of travel with congestion etc. e.g. Pan 2006
Strengths			
• Even without 'decision making' capability, pedestrians keep distance from each other and shows self-organization phenomena • Suited to help design evacuation strategies	• Simple to develop and fast to update. • Suited for simulations of large complex structures	• Simple to develop and computationally efficient • Suitable to assess critical events in flow of people (like congestion) in a building and also assessing effectiveness of evacuation	• Possible to assign "decision making" capabilities to agents • Suitable for large scale evacuation scenario and complex system
Weaknesses			
• Crowd does not completely follow laws of physics • Complex structures may be hard to simulate.	• Difficulties of simulating crowd cross flow and concourses have been reported • The movement pattern seems unrealistic with the people hopping on the grid cells	• Heavily based on probabilistic assumptions • Visualization of actual movement patterns of each individual not possible	• Formal basis of the model is weaker than other modelling approaches. • Additional delay due to force effects are not considered which is important in emergency situations
Validation			
• No indication for emergency validation except visually verified observed behaviour. Validated for normal situation with experiments using human subjects.	• Comparison with evacuation exercises for egress time from buildings, and even ships.	• No indication	• Comparison of simulation results obtained by other evacuation models for egress analysis.
Common Features			
Most microscopic approaches have terms that drive pedestrians towards the desired target and to detect collision among pedestrians although the mathematical representation might be different for those terms.			

2.4 Validation approaches

Complementary data are required to test the theoretical models quantitatively for their validity and reliability and also to compare the performance of alternative models. Data under emergency and panic conditions are rare as they are difficult to capture. Attempts have been made to validate the models' prediction through evacuation trials (Klüpfel, 2003), experiments with biological agents (Altshuler *et al*., 2005; Dussutour *et al*., 2005; Saloma *et al*., 2003) and comparison with existing models and softwares (Pan 2006). Experiments using human subjects have been also performed to understand the behaviour and characteristics of human flow under normal (non-panic) conditions. Teknomo (2002) used video recordings of real life data at pedestrian crossing in normal situations to validate the model that had been developed. But still, models simulating the behaviour of crowds in emergencies have been mostly inspected, verified and validated visually based on computer graphics.

2.4.1 Experiments using human crowds

Some researchers have tired to perform experiment on humans to understand the behaviour and characteristics of human flow. Most of the human experiments performed aims to understand the behaviour and characteristics of human flow under normal conditions. Delft University of Technology has collected data from video-based experiments by carrying out experimental pedestrian flow research (Daamen, 2004). These experiments have been used to observe pedestrian walking behaviour and characteristics under different conditions. Free speed, walking direction, density and bottlenecks were the experimental variables considered. Experiments have been performed for one, two and four directional traffic flows; and with bottlenecks of varying width. The experiments produced insight into the free speed distributions, speed variances, fundamental diagrams, self-organisation, and capacity of bottlenecks both for one directional and multi directional flows. It has been reported (Hoogendoorn, 2004) that many of the observations made in these experiments were reproduced by the NOMAD model. Based on a frame-by-frame analysis of video recordings, Helbing *et al*. (2005) determined the passing times of pedestrians at certain cross sections and the related time headway (gross time gap) distributions for the following situations:

- Uni and bidirectional pedestrian streams in corridors with and without bottlenecks,
- Two intersecting pedestrian streams, and
- Pushy pedestrians rushing toward an exit with and without an obstacle in front of it.

In an experiment with pushy pedestrians rushing toward an exit, it was observed that without an obstacle at the exit, there is considerable reduction in the efficiency of escape and production of high pressures in the crowd due to a clogging effect. Placing an obstacle in front of the exit could avoid the clogging effect and increase the flow. Similar increases in flow of people due to the introduction of obstacles like column at exits have been predicted through simulation of SFM (Helbing *et al*., 2002) as shown in Figure 1.

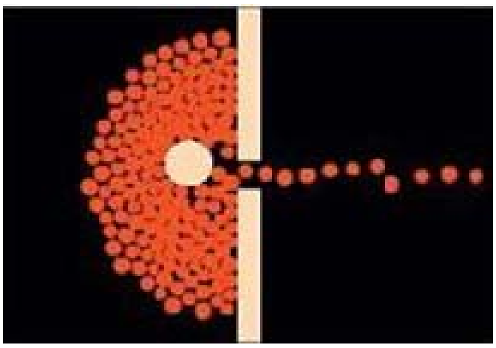

Figure 1 – Simulation showing flow in the presence of a column at the exit (Helbing *et al*., 2002)

It is to be noted here that experiments on humans as performed above during non-panic conditions are of fundamental importance in understanding the behaviour of people under emergency conditions as well as the calculation of evacuation time. For example, bottlenecks represent the congested part of buildings, bidirectional flow is important when both rescuers and the victims have to use the same path during emergency evacuation. However, the problem with models dealing with emergency/panic situations is that complimentary data on panic to validate the model's prediction are rare as they are difficult to capture. Also, it is not desirable from either an ethical or a cost point of view to perform controlled experiments on humans under emergency conditions.

2.4.2 Evacuation trials

Evacuation exercises for buildings and passenger vessels can provide data for model validation. Evacuation trials in the past ranges from public buildings (Proulx, 1995; Olsson 2001), industrial premises (Ko *et al*., 2007) to passenger vessels (Galea and Galparsoro, 1994). Usually evacuation times, response time of the occupants and occupancy movement have been observed from such evacuation trials. Problem with trying to perform such evacuation trials is the high number of repetitions required for statistical significance. Also researchers have to confine themselves to small numbers of participants with no control on level of panic, which then does not represent the true scenario for crowd behaviour. Klüpfel (2003) validated a proposed cellular automation model by comparison to empirical data from the literature and evacuation trials from a theatre, primary school and ship. The egress time based on evacuation trials of people with that of egress time obtained from simulation for those scenarios were compared. The evacuation trials were recorded on videotapes which provided the information about the initial population distribution and the time each person reaches the exit. The appropriate parameters for the simulation have been reported to be obtained in two ways:

1. by measuring them as far as possible during the evacuation trail (e.g. response times and walking speed)

2. by comparing simulations and evacuation trial.

While deviations between simulations and evacuation trials exist, however it has been reported that the deviations are mainly due to subtleties in the behaviour on a microscopic level and thus on a macroscopic level (like the overall evacuation time), the differences are reported to be small.

2.4.3 Experiment on biological agents

Altshuler *et al*. (2005) report experiments on Cuban leaf-cutting ants that agree with symmetry breaking (ineffective use of exits) of individuals. By introducing insect repelling liquid in an enclosed acrylic circular drum cell with two opposite symmetrically located exit that contained Cuban leaf-cutting ants, it was seen that use of only one exit was dominant in the case of panic situation compared to the symmetrical use of exit in normal situations as shown in Figure 2. Statistical differences in the use of the two exits averaged 10.4% (±0.1%) on normal situation while it was 50% (±4%) for a panic situation. Similar case of ineffective use of exits has been predicted for human while escaping from a smoky room with two identical exits through SFM by Helbing *et al.* (2000) and illustrated by Low (2000) as shown in Figure 3.

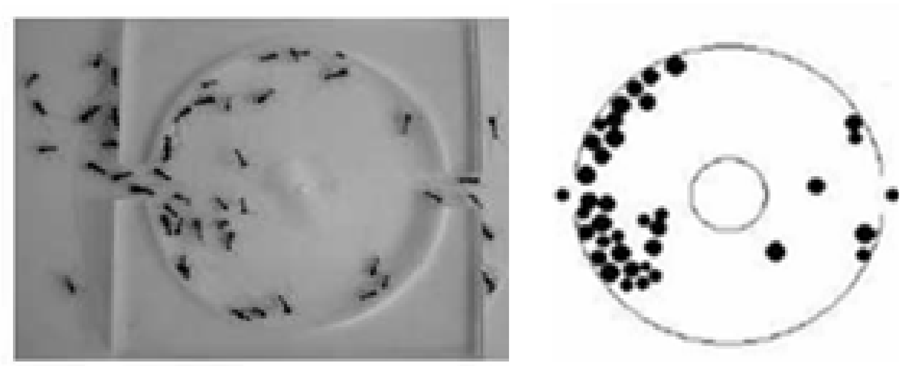

Figure 2 – Symmetry breaking at high panic during the ant experiment (left), and the corresponding simulation (right) (Altshuler *et. al.*, 2005)

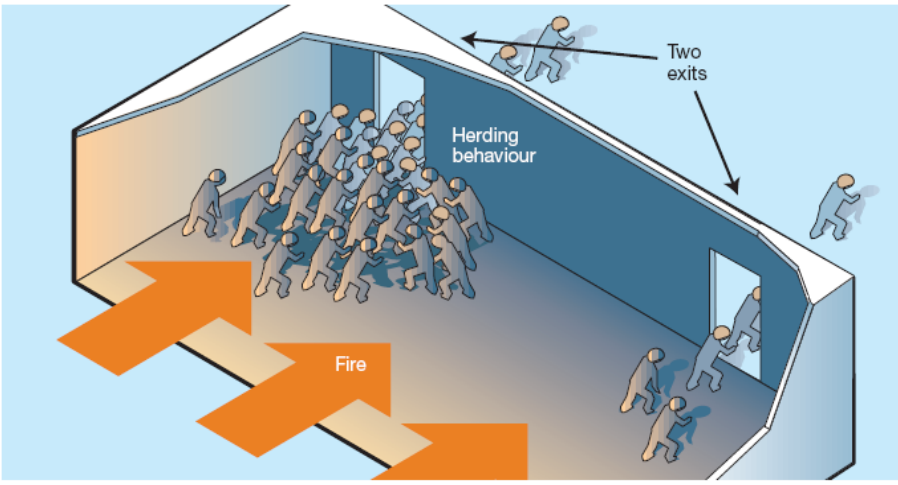

Figure 3 – A similar symmetry breaking phenomena predicted through SFM for people escaping from a smoky room with two identical exits (Low, 2000)

Altshuler *et al*. (2005) suggested that some features of the collective behaviour of humans and ants can be quite similar when escaping under panic in spite of sizable differences between traffic in humans and ants in normal conditions. The dynamical behaviour of ants and human pedestrians makes ant colonies a potentially valuable resource for testing models of panic behaviour and designs to minimise crowd disasters (Burd, 2006). Nishinari *et al.* (2006) also highlights the similarities between ants on a trail and pedestrians in evacuations, since both try to follow others through pheromone on a trail and information from one's eyes and ears, respectively.

Dussutour *et al*. (2005) performed an experiment which revealed that foraging ants also have to have to cope with traffic control problems like human beings. In the experiment, they allowed ants to forage for sugar solution (food source), but to reach their goal they had to cross a diamond-shaped bridge network giving them the choice of route once they started their journey. The mean rate of encounters per ant on a narrow bridge was observed to be lower than that on a wide bridge which suggests that ants regulate their density to cope with the delay incurred by too high a rate of contact. The number of head-on encounters was lower on the narrow bridge because ants progress on the bridge as clusters of individuals moving in the same direction rather than as isolated individuals. Similar processes of temporal organisation of bi-directional pedestrian flows moving through a narrow bottleneck have been reported by Helbing *et al*. (2005) from a simple experiment with human flow. As in ants, it is clusters of people rather than single individuals who pass the bottleneck from one side to the other before people from the other side have a chance to pass through the bottleneck.

Saloma *et al*. (2003) performed an experiment with a group of 60 mice escaping from a contained water pool onto a dry platform, through doors of various widths and separation. A series of experiments on panicked mice escape from the enclosed area showed that they behave in much the way computer models predict that panicked humans would. The mice made the most efficient getaway by self organised queuing in an order when their escape route was only large enough for a single mouse but as the width of the door was increased, the queuing phenomena disappeared and the mice started competing with each other resulting in blockage and making their escape inefficient.

3 Future directions

Any realistic model should be able to identify critical events in crowd movements backed up by quantitative observations and experiments to assess the model parameters. With the advancement in computation power of computer, it seems more attention would be towards microscopic modelling in future to address pedestrian dynamics under emergency conditions. Microscopic modelling deals with the interactions among pedestrians and accounts for any additional delays which is important in emergency situations. Future study, especially in the area of microscopic modelling needs to address the issues as discussed below for realistic simulations to be produced.

3.1 Exploration of alternative empirical system to validate the model

One of the problems related to modelling of pedestrians under panic or emergency conditions is the calibration and validation of model parameters. Calibration and validation is necessary to reproduce not only the qualitative features but also the quantitative outcomes, which acts as a reliable tool for emergency planners. Complementary data are required to test the model quantitatively and compare with alternate models. Such data, as discussed in section 2.4, are rare as they are difficult to capture and to perform controlled experiment studies on human under emergency conditions are not desirable from either a safety, ethical or a cost point of view. There is need to explore alterative empirical ways to validate the model in the absence of data on humans.

Attempts have been to use experiments on biological agents, such as ants and mice as an alternative empirical system to examine crowd behaviour. There is scope to use such biological agents to study crowd behaviour under panic conditions. Using ants to model pedestrian traffic behaviour shows promise since they naturally form collective traffic and follow physical pathways that closely relate to crowd movement. Another advantage of using ants to model human traffic is their easy availability, ease of handling, and the simplicity of equipment needed to perform the experiments.

Shiwakoti *et al*. (2008) documents the findings from an experiment with 'Argentine' ants under panic conditions in an attempt to correlate the results with human panic. It was observed from the experiment that putting a column-shaped obstacle at the exit helps to increase the efficiency of evacuation of ants compared to when no obstacle is present at the exit. For ants, interaction among individuals is the key to 'swarm intelligence,' unlike humans for whom interactions become problematic. When panic is created, ants tend to lose their natural interaction pattern, thus creating confusion and chaos, whereas in human group behaviour, it is the increase of interactions during panic that leads to inefficient evacuation. The column assisted in channelising the uncoordinated flow of ants (due to confusion and chaos) at the exit and improved the flow as shown in Figure 4. The presence of the column reduced evacuation times on average by 41% compared to the cases where the column was absent. Preliminary results can be viewed at ABC (2008). A similar increase in evacuation efficiency for a human crowd escaping from a room with a column at the exit has been reported through simulation using the SFM (Helbing *et al.*, 2002), with an increase in flow rate of up to 50%. Hughes (2003) also presents insight on locating the barriers that actually increases the flow of pedestrians compared to when there are no barriers present.

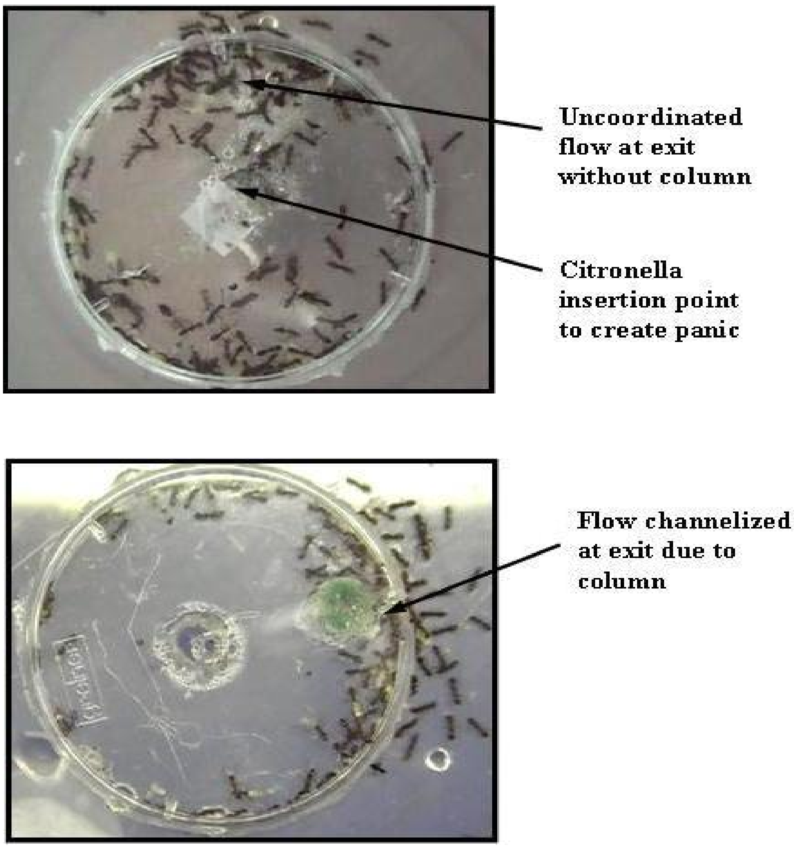

Figure 4 – Uncoordinated flow of ants without a column near the exit (top), and showing an increased flow with a column near the exit (bottom)

Mathematical predictions cannot be entirely relied upon when scaled up to a real human situation. However, using an alternative empirical system like ants or other biological agents can boost the reliability of models predictions. The presence of a column shows the importance of consideration of effects from physical geometrical structure to movement patterns during evacuation. Ingress and egress are critical activities and thus the layout of physical geometrical structure at the entry and exit point has an important role in determining the efficiency of the evacuation process and strategies. Such data can also show that a developed model is robust to differences in the size, speed, and other biological details of the panicking individuals, and thus by directly comparing the behaviour of ants and pedestrians, one can find good strategies of evacuation. Two points as mentioned below are thus important from such empirical experiments:

- movement patterns and effects of geometry
- strategies for efficient evacuation.

3.2 Incorporation of individual behaviour and socio-psychological factors

There are still many factors that need to be addressed by the current models to simulate realistic pedestrian behaviour under emergency conditions. The incorporation of individual microscopic characteristics like age, gender, variation in walking speed, etc. and environmental factors is a priority if realistic predictions are to be carried out. The model's prediction could become even more realistic if some "decision-making" capabilities are assigned to the individuals. The socio-psychological components of individuals during panic or emergency conditions are either missing or inadequately addressed. Although, it might not be possible to represent all the complex socio-psychological factors associated with panic in a model, an attempt should be made to represent the dominant factors.

Human socio-psychological behaviour ranges from lowest level (individuals) to highest level (group-behaviour) and needs to be included in the existing models for increased psychological realism. As have been noted from the literature, one of the interesting aspects of pedestrian crowds is the collective behaviour during emergency /panic situations. How crowds escape in panic conditions is thus highly dependent on how the group goals and individual goals are constituted and coordinated in the panic situation. Figure 5 shows the interdependence relationship of the individual, individual's interactions and group behaviour. Table 2 presents examples of some of the factors associated with each level. Multi-agent modelling is suited to handle factors related to socio-psychological behaviour of people as seen from the literature and hence there is the possibility of combining multi-agent modelling with other crowd models based on strong theoretical background (like SFM and NOMAD) to develop a more reliable model.

Table 2 – Example factors associated with individuals, their interaction and group behaviour

Level	*Factors (examples)*
Individual	▪ Mobility (difference of instinct among older, adult, children) ▪ Familiarisation (environment)
Individual's Interactions	▪ Comfort zone ▪ Physical forces/friction ▪ Adaptive/non-adaptive
Group Behaviour	▪ Herding ▪ Competitive ▪ Queuing ▪ Helping ▪ Leader-follower

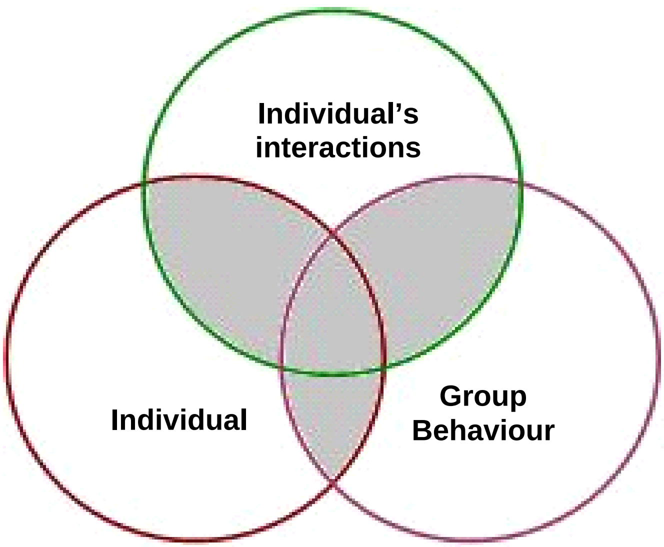

Figure 5 – Interdependence relationship of the individual, individual's interactions and group behaviour

Future model development should be directed at:

- identifying the factors possibly associated with each level
- analysing the degree of dominance among those factors
- developing techniques to represent those factors in the model.

3.3 Potentiality of existing models to address outdoor scenario

The existing models need to be applied to real world problems instead of limiting their use mainly to study basic phenomena of pedestrian / crowd movement and behaviour. Most of the study to date seems to be concentrated on exploring indoor scenarios while the study of outdoor events such as open public gatherings, community evacuation etc. (Shiwakoti and Nakatsuji, 2006; Shiwakoti *et al*., 2008) has been minimal. Outdoor scenarios are quite different to indoor scenarios in terms of the extent (scale), layout of infrastructure, the number of exits (limited in indoor scenarios), difference in walking speed or other factors. There is therefore scope to develop appropriate models that are flexible to address both indoor and outdoor events.

For the outdoor scenario, the future work could focus on simulating pedestrian crowds in an intersection during panic. Intersections form a regular part of any street network, and, in particular, intersections near public spaces attract huge crowds during special events. For example, huge crowd congregate at the Flinders Street / Swanston Street intersection in Melbourne on New Year's Eve. Intersections also serve as refugee points during natural disasters like earthquake and fire or terrorist attacks. It is imperative for event managers to assess flow management of crowds during outdoor events and to be aware of ways to control the crowd if emergency situations occur. The study of panic scenarios at intersections has not been addressed in the literature to date. At intersections, according to Helbing *et al.* (2002), one is confronted with various alternating collective patterns of motion of a temporal and unstable nature. When two pedestrian streams cross, evidence of a 'banding' phenomenon where 'bands' of people are observed moving in the same direction has been reported in the literature (Hughes, 2003). The experiment with ants has the potential to study and model the human panic at intersections. Although there are technical difficulties to create the crossing flow of ants, however the experiments with ants have the potential to investigate whether:

- There is a similar phenomenon of 'temporal roundabout traffic' and 'band formation' in ants as has been described for human crowd in crossing flows? How the ants behave under panic in crossing flows? How do they overcome the conflict? Subsequent observations are expected to provide useful information for developing strategies for efficient flow of pedestrians and may also provide valuable input for model development and prediction.

- If there are any substantial improvements in traffic flow by putting barriers in the intersection? The concept is similar to indoor situations where putting obstacles at exits breaks up the generated pressure.

4 Conclusion

Modelling and empirical study of pedestrian behaviour under emergency conditions provides a valuable tool to assist planners and managers of emergency responses to analyse and assess safety precautions for those situations. From the literature review on crowd dynamics, microscopic modelling approaches are emerging as a valuable platform to study pedestrian dynamics under emergency conditions due to their ability to deal with the interactions among pedestrians and account for any additional delays. Although several microscopic models exist, validating the models is a challenge due to the lack of complementary data in panic and emergency situations. The need for alternative empirical systems to address the lack of data, the need to incorporate socio-psychological factors in the models for realistic simulation and the need for models to address outdoor events under emergency conditions are the areas where existing models can be enhanced.

Human socio-psychological behaviour under emergency conditions needs to be included in the existing models for realistic simulation. Ideally models should focus on representing the interdependence and interactions of individuals, group behaviour and how these change under emergency conditions. The potential of enhancing existing models to address outdoor events such as the simulation of pedestrian crowds in an intersection under panic should be explored. Although it may not be possible to guarantee ideal safety, there is scope to use improved models to enhance safety levels. Experiments with biological agents like ants have potential to study crowd behaviour under panic or emergency conditions and validating model predictions. Continued research is needed in using biological agents as an alternative empirical system to validate models. There is the possibility that in future we will see more algorithms, design solutions and systems modelled for pedestrian traffic with contribution from social insects and other social animals.

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