A review of pedestrian group dynamics and methodologies in modelling pedestrian group behaviours

Lin Cheng¹, Ragamayi Yarlagadda², Clinton Fookes³, Prasad K.D.V. Yarlagadda⁴*

¹,²,³,⁴*Airports of the Future Research, Queensland University of Technology, Australia

Observations conducted by researchers revealed that the group interaction within crowds is a common phenomenon and has great influence on pedestrian behaviour. However, most research currently undertaken by various researchers failed to consider the group dynamics when developing pedestrian flow models. This paper presented a critical review of pedestrian models that incorporates group behaviour. Models reviewed in this paper are mainly created by microscopic modelling approaches such as social force, cellular automata, and agent-based method. The purpose of this literature review is to improve the understanding of group dynamics among pedestrians and highlight the need for considering group dynamics when developing pedestrian simulation models.

Keywords: Group dynamics, pedestrian model, simulation, crowd behaviour.

INTRODUCTION

Pedestrian behaviour has been persistently studied for approximately a century. Early studies were mainly focused on designing traffic regulations and pedestrian safety protections (Ceder, 1979; Moore, 1953). As time progresses, improving the quality of construction projects to create more pleasant and user-friendly pedestrian facilities has been the relentless pursuit of modern architects and designers. With the improvement of computer technology, pedestrian models have been widely used and considered as an essential tool to assessing the performance of building design and quality of the pedestrian facilities (D. Helbing, Farkas, Molnár, and Vicsek, 2002; Osaragi, 2004; Schadschneider et al., 2011; Teknomo, 2006).

In the real world, it is a common phenomenon that many of the pedestrians are walking in groups. It is easy to identify a group of people through the interactions and characteristics of the members such as appearance, gender, age and exchanges. Although it has been proven that social interactions greatly influence crowd behaviours and decision making, far too little attention has been paid to group behaviour when developing passenger flow models (Ma, Fookes, Kleinschmidt, and Yarlagadda, 2012; Qiu and Hu, 2010; Singh et al., 2009). Santos and Aguirre (2004) also pointed out that one common shortcoming of emergency evacuation models lay in the absence of inclusion of socio-psychological relevant group level processes.

*Corresponding author: Dr. Prasad K.D.V. Yarlagadda, Airports of the Future Research, Queensland University of Technology, 2 George Street, Brisbane, Queensland, 4000, Australia. E-mail: y.prasad@qut.edu.au
This paper demonstrates the importance of pedestrian social groups and existing pedestrian models that incorporate pedestrian group dynamics. Section 2 investigates the characteristics of pedestrian behaviour and highlights the importance of group dynamics. Section 3 introduces current pedestrian modelling approaches that include the group dynamics and analyses the advantages and disadvantages. Finally, Section 4 summarises the literature review and discusses the trend of future pedestrian modelling.

**Pedestrian Group Dynamics**

**Ubiquitous Pedestrian Social Groups**

Researchers have been studying the behaviour of pedestrian social groups for more than half-century. In order to investigate the size determinant in small human group interaction, James (1953) observed 22,625 pedestrian samples in 18 public situations in Eugene and Portland, Oregon. The observations were taken in the winter and spring, 1950. Several different places including public markets, playgrounds, schools, swimming pools, public beaches were chosen as observation sites. The diversity of observation times and locations ensures that the observation results reflect the common behaviour of pedestrians of different roles. The observation shows that crowds are split into 'free-forming' small groups with varying sizes. The group relationship was identified through the face-to-face interactions such as gesture, laughter, smiles, talk, play, or work. A total of 15,486 small groups were recorded in the observation. The observation results are consolidated into Table 1.

Group size 1 indicated that individuals are also considered as small groups that only have one group member. From Table 1, it can be calculated that more than one third of the observed population are in groups with at least two members.

A similar field study was conducted by Aveni (1977), who interviewed 204 celebrating fans in a football event. The findings of the study showed that three quarters of the crowd were with one or more friends. This result shows higher group proportion in crowds than James’ observation. The reason for this difference may be that the data in this research was collected in a special sports event, which may not reflect the group behaviour of mundane crowds in a variety of different locations.

It has been decades since the research carried out by James and Aveni. The social background has greatly changed, so are the ways people communicate and interact. Therefore, it is necessary to examine whether the crowd preserves group behaviour in more recent studies. Singh et al. (2009) investigated the behaviour of pedestrian subgroups by means of filming and observation. The behaviour of crowds was recorded every 10 seconds for half an hour in the following four locations: Nottingham train station, Broadmarsh shopping centre, Clumber Street and Nottingham University campus. Pedestrians in these four locations represent crowds in three environments: travelling, shopping and working. As can be seen from Figure 1, a large percentage of people in crowds are in subgroups of two or more members. In travelling environment (train station), the percentages of people in groups are about 55%. In shopping environments (Broadmarsh shopping centre and Clumber Street), the percentage is about 65%. On university campus where people study or work, the figure is about 47%. The varying numbers in different observation locations indicate that the proportion of people in groups can be influenced by the surrounding environment. One limitation of the observation approach is that the observation period is not long enough. Therefore it is possible that observers only captured a small section of the big picture which may cause deviation to the ‘ground truth’.

To investigate the walking behaviour of pedestrian social groups, Moussaid, Perozo, Garnier, Helbing, and Theraulaz (2010) analysed pedestrian behaviour in a low population density condition A and moderate density B. Detailed observation time and location are not given in the research. The result shows that the proportions of pedestrians belong to a group are 55% in population A and 70% in B, which occupied the majority of total populations. The author made an explanation to the difference between populations A and B: population A was recorded in a working day, while population B was observed on a Saturday afternoon in a popular commercial walkway. This means one can expect a higher frequency of groups in leisure areas and spare times.

Popovic, Kraal, and Kirk (2009) presented an observation technique that investigated how passenger activities mediate people’s experience in the airport. In the study, detailed passenger behaviour in the airport was recorded. It was found that passengers travelling in groups had a considerable waiting time at the security process. The video showed that after the security screen, people wait for their group members in the middle of the walkway to passport control. Using the same observation technique, Livingstone, Popovic, Kraal, and Kirk (2012) reported results of passenger landside retail experience in airports. Through the data collection from 40 passengers, researchers found that the existence of passenger’s travel companion can influence passenger’s landside dwell time and shopping behaviour in discretionary activities.

**Pedestrian Group Sizes in Statistic Models**

In order to quantitatively calculate the distribution of free-forming pedestrian group size, James (1953) fitted the sample group sizes (shows in Table 1) into two
A review of pedestrian group dynamics and methodologies in modelling pedestrian group behaviours

Table 1. Frequency distributions of 18 observations (James, 1953).

<table>
<thead>
<tr>
<th>Group Size</th>
<th>Frequency</th>
<th>Percentage in total groups (%)</th>
<th>Percentage in total population (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10,149</td>
<td>65.54</td>
<td>44.86</td>
</tr>
<tr>
<td>2</td>
<td>3,945</td>
<td>25.47</td>
<td>34.87</td>
</tr>
<tr>
<td>3</td>
<td>1,075</td>
<td>6.94</td>
<td>14.25</td>
</tr>
<tr>
<td>4</td>
<td>238</td>
<td>1.54</td>
<td>4.21</td>
</tr>
<tr>
<td>5</td>
<td>65</td>
<td>.42</td>
<td>1.44</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>.09</td>
<td>0.37</td>
</tr>
<tr>
<td>N</td>
<td>15,486</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Mean 1.46

Figure 1. The sizes and proportions of subgroups within a crowd (Singh et al., 2009).

distribution models: the negative binomial model and the Poisson model. The goodness of fit was compared by the chi-square test. The result showed that the fitting of the negative binomial model was much closer to the observation data than the Poisson model. The explanation to this was that Poisson distributions require a constant mean throughout the observation, thus it is more suitable when the social situation is relatively stable. On the other hand, the negative binomial can be considered as a group of different Poisson distributions collected together, therefore it is more accurate to use the negative binomial model in fitting data collected from 18 different observations in this case. Although this is a reasonable explanation to the fitting results, the author failed to make further attempts to support his conclusion. Therefore, this study would have been much more convincing if the author had tested the Poisson model in a stable social context and compared the goodness of fit with the negative binomial model.

Coleman and James (1961) reanalysed the data collected by James (1953) and stated that the frequency distribution of group sizes can be fitted by the truncated-Poisson (T-P) formula. The derivation of this formula is based on the assumptions that there is a constant probability for a group to lose and gain a member at any time, and finally the distribution of group sizes in the system will reach an equilibrium state. Using this mechanism, Moussaid et al. (2010) collected crowd observation data from two crowd density conditions and fitted the data with a zero-truncated Poisson formula. The fitting results show that the Poisson model well presents the observed group sizes in population A, while in population B, the model predicts a higher proportion of individuals and lower proportion of groups of size 2. Nevertheless, the model reflects a similar tendency of the group sizes in observation. The use of statistical models in fitting the distribution of the group size provides a reference for generating pedestrian groups in the proposed model in this paper.

Walking Speed of Pedestrian Groups

Henderson (1971) had suggested that the desired speeds within pedestrian crowd are Gaussian distributed with a mean value of 1.34 m/s and a standard deviation of 0.26 m/s. More recent research shows that pedestrian walking speed can be influenced by many factors. Those factors include environmental factors such as crowd density, widths of the walkway, and mixture of the flow as well as personal factors like age, gender, physical abilities and...
purposes of trip (Harney, 2002; Moussaïd et al., 2010; Rastogi, Thaniarasu, and Chandra, 2011). In addition to these determinants, some research has observed that the group size significantly contribute to pedestrian speed.

Moussaïd et al. (2010) measured the walking speed of pedestrian groups with different sizes and concluded that pedestrian walking speed decreases linearly as the size of the group increases (Figure 3). However, as can be seen from Figure 3, this linear relationship is obtained by fitting curve to merely three data points. Therefore, a more persuasive conclusion would include more data points that stand for group speed of different group sizes. Besides this, the speed of individuals (group size of 1) is also worth investigating. Nonetheless, this research reveals a trend that the group speed reduces with the increase in size of the group.

Similar findings were discussed in the research of Schultz, Schulz, and Fricke (2010), who recorded and analysed the walking behaviour of passengers in Dresden International Airport by using a video surveillance system. Figure 4 compares the differences in speed between groups with one and three members. As the author had expected, the walking speed for groups with three members is clearly slower than for groups that have only one member. Since it was mentioned in many studies that the environment has great influence on pedestrians’ walking speed (Finnis and Walton, 2008; Harney, 2002; Rastogi et al., 2011), above research results can only be applied in airport environment and cannot represent the pedestrian speed at any other situations wilfully.

For comparison, Table 2 summarises the mean walking speeds for pedestrian group with varying sizes at
A review of pedestrian group dynamics and methodologies in modelling pedestrian group behaviours

Figure 4. Group size interdependencies regarding to speed (Schultz et al., 2010).

Table 2. Mean walking speed (m/s) of pedestrians in different group sizes

<table>
<thead>
<tr>
<th>Source</th>
<th>Locations</th>
<th>Group sizes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>&gt;5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarawneh (2001)</td>
<td>Crosswalk</td>
<td></td>
<td>1.35</td>
<td>1.35</td>
<td>1.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Klüpfel (2007)</td>
<td>World Exhibition</td>
<td></td>
<td>1.38</td>
<td>1.28</td>
<td>1.24</td>
<td>1.24</td>
<td>1.22</td>
<td>1.10</td>
</tr>
<tr>
<td>Schultz et al. (2010)</td>
<td>International Airport</td>
<td></td>
<td>1.36</td>
<td>1.06</td>
<td>0.96</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rastogi et al. (2011)</td>
<td>Wide Sidewalks</td>
<td></td>
<td>-</td>
<td>1.13</td>
<td>1.01</td>
<td>0.98</td>
<td>0.90</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Precincts</td>
<td></td>
<td>-</td>
<td>1.09</td>
<td>1.00</td>
<td>1.00</td>
<td>0.89</td>
<td>0.83</td>
</tr>
</tbody>
</table>

different locations in previous research. Tarawneh (2001) investigated the speed of pedestrians at 27 crosswalks in the Great Amman Area, Jordan. Nearly 3500 pedestrian crossing operations were collected. Results show that pedestrian group size with three or more people walk much slower than smaller groups when crossing the street. Tarawneh argued that the reasons could be: (1) pedestrians in small groups (single or couple) feel less secure in the crosswalk; and (2) larger groups of pedestrians are more likely to engage in conversations during the walk. However, the author overlooked the particularity of the environment. In crosswalks, the speed of pedestrians is often constrained by traffic signals. Moreover, dwelling in the crosswalk may cause potential safety hazards. Thus, pedestrians in crosswalks tend to finish crossing as fast as possible and the effect of group interactions is relatively weak during this time. This can be seen from that individuals or couples were faster than larger groups by only 0.02 m/s, which is hardly noticeable.

Rastogi et al. (2011) collected pedestrian walking data from 18 locations in 5 cities in India. The pedestrian speed data were collected by marking a longitudinal section of known length on the pedestrians within this section in two peak periods in a day. It was reported that pedestrians travelling in groups walk at an average speed and almost 73% of the pedestrians who fall behind will catch up with other group members by increasing their speed. Rastogi also observed an interesting phenomenon: on sidewalks, pedestrians in large groups (have 5 or more people) often split into smaller sub-groups in order to avoid incoming pedestrian flow. This splitting behaviour decreases the group sizes, but increases the speed of pedestrian sub-groups. Therefore, it can be seen from Table 2 that the mean speed of five-person groups is faster than that of four-person groups on the sidewalks. This phenomenon is absent on wide sidewalks and precincts because there is no restriction in space and large groups are not necessary to split into small sub-groups.
Walking Behaviour of Pedestrian Groups

From the filmed evidence, Singh et al. (2009) discovered the avoidance behaviour of pedestrians that walk in groups. Figure 5 shows the percentage of avoidance action taken when facing incoming pedestrians. It shows that in most cases, a person or a group of people will move to the right (34%) or left (44%) to avoid colliding with others (the ratio of people moving to the left is higher than that of moving to the right, a possible explanation of this phenomenon is that the experiment was conducted in UK, where left-hand traffic rule is applied). Only 22% of the groups will split in order to avoid colliding. This finding indicates a group of people are trying to remain together if possible. The social connection between group members creates an invisible bond that forces them to maintain a group structure, as is described in Helbing’s ‘social force’ theory (Dirk Helbing and Molnár, 1995). Singh also noticed in their research that if a group is split to avoid more than one obstacle, the group will remain apart and regroup once all the obstacles have been avoided.

To understand the crowd behaviour and its consequences for pedestrian flows, Reuter et al. (2014) conducted observations on the behaviour within large groups (groups of 5 and more people). Approximately 1800 observations around a soccer stadium were conducted. The observations showed that crowds at the soccer stadium consist of a high percentage of large groups. Furthermore, large groups often split up into smaller subgroups with a loose coherence. A recurring splitting up and re-joining was observed depending on the actual surroundings.

Moussaïd et al. (2010) investigated the spatial organisation of walking pedestrian groups in two different population densities. It has been suggested that at low density, people in the same group walk in a horizontal formation which enables them to communicate with other group members easily (Figure 6 (a)). While at moderate crowd density, this structure is hard to maintain without interfering with pedestrians outside the group. Therefore, the linear group structure will bend in the middle and form a ‘V’-shaped formation. Moussaïd, et al. pointed out that...
this bending is forward in walking direction instead of backward, thus facilitates the social communication between group members (Figure 6 (b)). Though bending backward is a more flexible structure against the opposite pedestrian flow, it impedes the interaction within the group. Finally, at high density, the physical constraints would prevail over the social interaction, group members will walk behind each other and form a 'river-like' formation (Figure 6 (c)). This 'river-like' formation is also noticed in the crowd observation conducted by Singh et al. (2009).

MODELLING APPROACHES

Model Classification

In the past decades, large numbers of approaches have been proposed for modelling pedestrian behaviours. Modelling methods can be classified according to different characteristics. In terms of modelling scope, there are macroscopic models and microscopic models. The main object of macroscopic models is the temporal evolution of the crowd density (Bauer, Seer, and Brändle, 2007). Macroscopic models treat pedestrians as a whole and ignore the local dynamics of individuals and interactions between pedestrians. Because of this, macroscopic models have the advantage in terms of computational load. However, researchers found that they are also not well suited for illustrating the effect of environmental change on pedestrian flow performance (Teknomo, Takeyama, and Inamura, 2000). Moreover, macroscopic models often assume that the population is comprised of homogeneous agents in an equilibrium state, which cannot represent real-world situations (Johansson et al., 2012).

In contrast, individual properties are distinguished in microscopic models. These models focus on the behaviour and decision making of individual pedestrians, as well as the effect on other pedestrians around them. Microscopic models have the potential to overcome the limitations of previously discussed macroscopic models by incorporating a set of pre-determined rules. By defining the behavioural rules properly, the microscopic models are able to present more accurate pedestrian behaviour in a greater variety of situations (Camillen et al., 2009; Pluchino, Garofalo, Inturri, Rapisarda, and Ignaccolo, 2013). However, a detailed pedestrian model needs support of rich data sets that slow down the computational speed (Bauer et al., 2007). Examples of microscopic models are: physical-based social force models (Dirk Helbing and Molnár, 1995), geography-based cellular automata models that follow pre-designed rules (Fukui and Ishibashi, 1999), and agent-based models which allow agents to interact with others as well as surrounding environments according to their own attributes (Macal and North, 2005). Apart from the modelling scale, pedestrian models can also be categorised by whether they are discrete or continuous, deterministic or stochastic, rule-based or force-based, high or low fidelity (Schadschneider et al., 2011). This paper will mainly introduce the following three microscopic models: social force model, cellular automata model and agent-based model.

Social Force Models

Social force models are probably the most known method in the group of continuous models. Lewin and Cartwright (1952)suggested that the changes of human behaviour can be guided by social forces or social fields. Based on this concept, Dirk Helbing and Molnár (1995) proposed the basic equation of the social force model to describe pedestrian motion,

\[ \vec{F}_α = \vec{F}_α^0 + \sum_β \vec{F}_{αβ} + \sum_β \vec{F}_{βα} + \sum_i \vec{F}_{αi} \]

They assumed that a pedestrian’s total motivation \( \vec{F}_α \) can be influenced by four main factors: (1) \( \vec{F}_α^0 \) – the desire of this pedestrian \( α \) to reach a certain destination or goal; (2) \( \sum_β \vec{F}_{αβ} \) – the total influence from other pedestrians \( β \) such as the repulsive effect of others; (3) \( \sum_β \vec{F}_{βα} \) – the total repulsive force generated to avoid a border or an obstacle \( B \); and (4) \( \sum_i \vec{F}_{αi} \) – the attraction of other persons or objects \( i \).

In addition to the above four main effects, the social force model can be applied to demonstrate complex pedestrian behaviour by adding a fluctuation term. This fluctuation term enables modellers to consider random variations of pedestrian behaviour and make extension from the basic formula. Therefore, a more general form of the social force model is now defined by,

\[ \frac{d\vec{F}_α}{dt} = \vec{F}_α^0 + \text{fluctuations}. \]

Using the social force model, several observed collective phenomena in pedestrian crowds have been successfully reproduced. This includes the lane forming behaviour in crowds and the oscillatory walking pattern at a narrow exit (Dirk Helbing and Molnár, 1995) as well as the mechanisms in escape panic situations (Dirk Helbing, Farkas, and Vicsek, 2000). Dirk Helbing, Buzna, Johansson, and Werner (2005)conclude that the simplicity and small number of parameters are the main advantages of the social-force-based simulation. Moreover, it is suggested that those parameters in the model do not need to be calibrated for each new situation, which makes social force models adaptive when applying to different simulation environments.

Moussaïd et al. (2010)had extended Helbing’s model to simulate the walking behaviour of pedestrian social groups by adding an extra social interaction term \( \vec{F}_{i,\text{group}} \) into Helbing’s social force formula. It was suggested that individuals in a group continuously adjust their position to facilitate communication, while trying to avoid collision with group members. Therefore, three
factors were considered to demonstrate the inner-group relationship. The gaze direction of each group member is important in group communication. This can be modelled by a vision field term $f^\text{vis}_i$. Pedestrian $i$ keeps a certain distance to the group’s centre of mass. Therefore, a second attraction term $f^\text{att}_i$ is defined. Finally, a repulsion effect $f^\text{rep}_i$ was added so that group members do not overlap each other. In summary, the social interaction term $f^\text{group}_i$ was defined as,

$$f^\text{group}_i = f^\text{vis}_i + f^\text{att}_i + f^\text{rep}_i.$$  

A computer simulation had been run for testing the group behaviour. At the start of the computer simulation, pedestrians were given random positions and specifications of the walking direction parallel to the street. Group members were initialised with a same desired walking direction and distributed desired speed. Measurements were made every 5 seconds and the simulation results were averaged over 1000 runs. The result of computer simulations based on this model is shown in Figure 7. The model parameter $\beta_1$ represents the strength of social interaction among group members. It was suggested that when $\beta_1$ is set to 0 (there is no communication between group members), an inverse ‘V’-like structure is generate and the walking speed of pedestrian groups is close to pedestrians walking alone (indicated in the dash curve). When the group communication is strong ($\beta_1=4$), a V-shaped structure is created and the group speed is reduced.

**Cellular Automata Models**

A relatively novel model called Cellular Automata (CA) uses intuitive rules that make the model easy to understand without complex mathematical equations and thus demand less computation than social force models. In cellular automata models, space is represented by a uniform grid of cells. At each discrete time step, the values of variables in each cell are updated according to a set of local rules and the values of variables in the cells at its neighbourhood (Zheng, Zhong, and Liu, 2009).

Köster, Seitz, Treml, Hartmann, and Klein (2011) applied the cellular automata to study the influence of group formations in a crowd. In their work, they divided space into hexagonal cells (Figure 8), thus creating two additional natural directions than square cells. An experiment for classroom egress was conducted and compared with simulation results. 30 students were asked to stand at their desks and leave the classroom at the signal. In the hallway outside the classroom, students were asked to walk across a line and enter a larger entrance hall. During this procedure, the door was identified as the only one bottleneck. It was observed that virtual agent groups in the model tend to stay together and walk one behind the other through the bottleneck. Once they reach the open space, they tend to walk abreast. The resulting simulations matched the experiment not only qualitatively, but also quantitatively. However, the local rules applied in this model are based on the intuition of the designers and lack of support from social science. Therefore, the authors highlighted the need for greater cooperation between social scientists and modellers.

Reuter et al. (2014) introduced a combination of empirical studies and computations to investigate how the presence of large groups impacts the flow of a crowd. The group model is realised within a cellular automaton model of pedestrian movement described by Köster et al. (2011). In the model, large groups were assembled from small communication groups using the empirical results. The computational simulations suggested that large groups behave as moving obstacles especially at crossroads. Band pattern was found at crossings where...
two pedestrian streams drag each other along. It was suggested that the presence of groups have influence on the typical band pattern at pedestrian crossings. However, the detailed modelling process of the simulation was not demonstrated in the paper. It is lack of universality to use empirical data collected from a special location (soccer stadium) to assemble pedestrian groups in other scenarios.

Sarmady, Haron, and Talib (2009) presented a variation of least effort cellular automata algorithm that considered the effect of pedestrian groups on crowd movement. In the model, a group leader is defined for each group, and other follower will maintain a short distance to the leader of the group. On the other way round, the leader will observe its distance with group members and adjust its speed to wait for the stalled group members. The model was tested in a walkway scenario, where pedestrians enter from one side and move towards the other. The simulations were run under different pedestrian densities and pedestrian group sizes. The results suggest that pedestrian groups act as virtual barriers and can slow down the crowd. Although the simulation results show acceptable results for group formations, the proposed model was not validated by comparing simulation results with real-world experiments.

Agent-Based Models

Agent-based modelling and simulation (ABMS) is a relatively new approach to modelling systems comprised of autonomous decision-making entities called agents. Unlike the Systems Dynamics approach that applied the 'top-down' systems view, the agent-based models are built from the 'bottom-up' by simulating the interaction between individual agents (Macal and North, 2005; Zheng et al., 2009). In agent-based models, agents follow some pre-determined rules of behaviour, which allow them to execute various behaviours appropriately in the modelled system. This unique characteristic makes ABM particularly suitable for the study of pedestrian behaviour in complex environments for both outdoor and indoor conditions.

A STREETS model was proposed for investigating pedestrian behaviour in urban centres (Schelhorn, O'Sullivan, Haklay, and Thurstain-Goodwin, 1999). Pedestrians are initialised with socio-economic characteristics and behavioural characteristics. Socio-economic characteristics defined the attributes such as gender and income of the agents and are used to create pedestrians' travel plan. While behavioural characteristics include the detailed behavioural factors such as speed, visual range and fixation. Pedestrians were 'released' into the simulation environment according to a Poisson distribution. The whole simulation was controlled by a SWARM observer, which also collects the interaction information in the model. However, this STREETS model was under development and no experiment had been run on this model to test its performance. The authors pointed out that the navigation of pedestrians was sometimes unreliable and pedestrian group behaviour should be incorporated in the model.

Vizzari, Manenti, Ohtsuka, and Shimura (2012) introduced a GA-PED model which investigated the pedestrian and group dynamics in crowds. It was observed in their proposed experiment that pedestrian pairs can easily form a line to avoid facing crowds. However, pedestrian groups with bigger numbers of members had difficulties to form such a line shape, thus they tend to form a triangular shape which is similar to the 'V' shape observed by Moussaïd et al. (2010). Then, a simulation model was applied to the experimental scenario and showed consistent pedestrian dynamics with the previous experiment. After the validation, the model is further adopted to simulate real-world scenarios in which large groups of pilgrims moving in an open space outside a train station. The simulation successfully generated results regarding the pedestrian waiting times and the space utilization in the assigned "waiting boxes" outside a train platform. Those results provide positive reference for the crowd management. Pedestrians in the GA-PED...
model have a limited form of autonomy. Although they were able to make decisions about where to move according to their perception of the environment and their desire, they can only be activated at each simulation turn. Based on Reynolds's flocking technique and steering behaviours (Reynolds, 1999), Qiu and Hu (2010) proposed an agent-based simulation system for modelling crowd behaviour with group structures, in which agents can move randomly, avoid obstacles and maintain group structures. A pedestrian crowd simulation was conducted in the scenario of a circular rectangle-shaped hallway. A virtual gate was positioned at the top lane of the hallway to calculate pedestrian flow. The flow is defined as the number of agents passed by the gate during a time interval in the simulation. The simulation showed that pedestrian flow decreases as the intra-group influence strengths or the inter-group relationships increase. Also, a larger group size will increase the pedestrian flow. The group movement is governed by the rule that each group is assumed to have a group leader and the leader would influence the decisions of other group members. However, in real-world situations, pedestrian groups are often composed of friends and families, where it is not necessary to have a group leader. Ma, et al. (2013; 2012; 2011) introduced an individual agent decision model to simulate stochastic passenger behaviour in airport departure terminals. Using Bayesian networks, the conditional probabilities of passengers' advanced traits (shopping preference, hunger level, technology preference, etc) were calculated through the basic traits (age, gender, nationality, flight class, etc.). By considering the restriction factors (such as remaining time and walking distance) passengers in the simulation can behave autonomously based on the results of Bayesian network inferences. However, the simulation did not explain how the group dynamics influence the passengers’ decision making process and what will happen if passengers were in a group where group members have very different behaviour in their advanced traits. Inspired by the work of Moussaïd et al. (2010), Karamouzas and Overmars (2010) presented a novel approach to simulate the walking behaviour of small groups of virtual humans. The model used a two-phase approach to ensure that the group members will stay as close as possible while avoiding collisions with other groups, individuals and static obstacles. This model has been implemented in different scenarios including group interactions in a narrow corridor and a shopping mall. The results indicated that the model is in accordance with empirical data of pedestrian groups collected by means of video recordings. The authors suggested that this model is not designed for simulating pedestrian groups in densely packed scenarios and some collisions may occur in complex environments. Cheng, Reddy, Fookes, and Yarlagadda (2014a) presented an agent-based model to simulate passenger behaviour at the airport check-in process. The simulation results showed that the passenger group dynamics have significant influences on the performance and utilisation of services in airport terminals. Cheng, et al. also conducted a case study to demonstrate how the agent-based passenger flow model can be used to examine the efficiency of an airport evacuation strategy (Cheng, Reddy, Fookes, and Yarlagadda, 2014b). By comparing evacuation time of individual passengers and passengers in groups, the impact of group dynamics during an airport evacuation process was analysed. The simulation results shows that group dynamics can significantly impact passenger behaviour during airport evacuation processes and consequently affects the total evacuation time.

Other Modelling Approaches

A modified discrete element model (DEM) had been used to investigate the behaviour of subgroups in crowd dynamics by means of filming and observation (Singh et al., 2009). By incorporating moving ‘formation attractor points’ in the Crowd DMX model, members of a subgroup will keep together while walking. Through simulation with the new code and direct comparison to the filmed footage, the model is successful in creating subgroups and simulating their behaviour within crowds. One limitation of this study is that the observation of pedestrian behaviour is only conducted in a university. Therefore, it is recommended that further observations at different locations are needed. Seung In, Quek, and Yong (2012) presented a pedestrian model based on the Common Ground (CG) theory to incorporate the impact of social interaction among group members in the crowd simulation. This proposed model inherited the social realism provided by the CG model and is computationally tractable for a large number of groups and individuals. The task of navigation in a group is viewed as performing a joint activity among agents, which requires effective coordination among group members. Peters and Ennis (2009) proposed a model to simulate plausible behaviours of small groups. Scenes were populated with different combinations of singles, pairs and groups of three and participants were asked to identify more realistic scenes. It is suggested that adding plausible groups to a pedestrian crowd scene is important for an increased sense of realism. Apart from microscopic models, some modelling approaches were developed to govern the macroscopic behaviour of agent groups. Kwon, Lee, Lee, and Takahashi (2008) introduced a novel group motion editing method that allows animators to manipulate existing group motion data interactively. Using this technique, the user can deform a group motion by pinning or dragging individuals. Takahashi et al. (2009) presented a spectral-based approach for synthesising realistic group motions. The main idea of this approach is to extract the spectral-based structures of group
formations using Laplacian matrices of the graph associated with their adjacency relationships among individuals.

**CONCLUSIONS**

Pedestrian models have made an important contribution to understanding the behaviour of human crowds. By successfully simulating pedestrian dynamics, pedestrian models are widely adopted in designing the layout of street networks, examining the efficiency of building evacuation strategy, evaluating the performance of pedestrian facilities, and so forth. The literature review suggests that crowds consist of both individual pedestrians and people in groups, and highlighted the need for incorporating group dynamics in developing pedestrian models.

It is shown that the percentage of people in groups within a crowd ranges from 40% to 70% at different occasions. Researchers also discovered that the size of a pedestrian group can influence pedestrian walking dynamics such as speed, group formation, and avoidance behaviour. As a result, one should pay attention to group dynamics when developing pedestrian flow models.

Although little attention has been paid to group dynamics when developing passenger flow models, some researchers had considered the group interaction in pedestrian modelling. To emulate the existence of pedestrian social groups in crowds, mathematical group size distribution models and group formation models were proposed. Some microscopic models have produced some very good results in understanding the influence of pedestrian groups on crowd behaviour. The social force models demonstrate how individuals' movement can be influenced by others and the environment; cellular automata models are good at describing behavioural rules and spatial relationships; agent-based models are often used to demonstrate emergent behaviour by simulating the interactions between heterogeneous agents and the environment.

The traditional pedestrian modelling approaches were mainly proposed to address certain specific behaviour problems. However, pedestrian behaviour and simulation environments are becoming more and more complex. In order to meet the challenges, one modelling approach may be used in combination with the advantages of others to provide more accurate pedestrian models in various scenarios. Moreover, current modelling approaches to some extent, involve the intuition and assumption of the modeller. Therefore, to produce more realistic pedestrian modelling results, it is necessary to have a better understanding towards the characteristic and decision-making process of individual pedestrians. This may require knowledge in the social and psychological field. Thus broader cross-discipline incorporation may be required in the future development of the model.

**REFERENCES**


Helbing D, Farkas I, Molnár P, Vicsek T (2002). *Simulation of pedestrian crowds in normal and

A review of pedestrian group dynamics and methodologies in modelling pedestrian group behaviours.
Reynolds C (1999). Steering Behaviors for Autonomous


