A configurable agent-based crowd model with generic behaviour effect representation mechanism

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Abstract: *Most of the existing crowd models were designed for specific behaviours or scenarios. Significant modifications were often required to include new behaviours and new scenarios. This paper proposed an approach to develop a generic crowd model with the ability to incorporate different behaviours under different scenarios. At the higher level of the proposed crowd model, the agent-based modelling method was used to enable the individual heterogeneity. At the lower level, a unified mechanism to represent effects of different individual behaviours was introduced. A core formula with seven generic parameters (i.e. agent's position, target's position, behaviour angle, effect of base speed, agent factor, target factor, and distance factor) has been developed to form the basis of the unified mechanism. This paper also presented a Behaviour Library that consisted of a set of basic behaviours which were able to construct complex behaviours through their combinations. In order to demonstrate the capability of the model in various scenarios, the following simulations have been conducted and discussed: queuing at an exit, bi-directional pedestrian walk flow, evacuation in a building, and consensus decision making in a large group.*

1 INTRODUCTION

Many studies (Liu & Lo 2011; Kobes, Helsloot, de Vries, et al. 2010; Drury et al. 2009; Kobes, Helsloot, Vries, et al. 2010) on emergency events suggested that crowd panic in a crowded environment (e.g. shopping malls, football stadiums) could cause fatalities. In the past 20 years, crowd models and simulations (Santos & Aguirre 2004; Kuligowski & Peacock 2005; Zheng et al. 2009; Chu 2009; Ng et al. 2010) were developed to assist designers and emergency services to have a better understanding of the crowd behaviour in those events. Several typical crowd phenomena (e.g. clogging, pushing, and "faster-is-slower" effect) have been demonstrated by various models (Zheng et al. 2009; Cheng et al. 2008; Musse & Thalmann 1997; Ebihara et al. 1992). In general, the modelling approaches of those crowd models can be mainly divided into three categories: force-based models, Cellular Automata (CA) models, and agent-based models.

The force-based models consider that the individuals in the crowd are affected by some forms of forces (have similar natures to the forces in physics) and their motions are determined by the total effects of those forces which were calculated through mathematic methods. This concept was firstly introduced in the 'Boids' program (Reynolds 1987) in 1986 which simulated the motion of bird flock. In the flock, each bird updated its position by applying a steering force. In 1995, the social force model (Helbing & Molnar 1995) was proposed to describe the movements of pedestrians that were determined by the forces which were generated from nearby crowd and physical objects. This model had been further developed (Helbing et al. 2000) to simulate panic situations by interpreting social psychology issues, and then was tested by Parisi and Dorso (2007) in a room exit scenario. Heigeas et al. (2003) had also introduced a physics-based particle system to model the emergent crowd behaviours such as jamming. The force-based models can provide precise position and orientation information of individuals as they have continuous time and spatial representations of the crowd. However, individual behaviours (e.g. following, communications, or interactions) are often ignored in the force-based models as the process of thinking and decision-making is difficult to be interpreted by mathematical equations.

The Cellular Automata (CA) model was originally invented by Von Neumann (1966) to create self-replicator machines in 1966. It was later introduced to crowd modelling by Wolfram (Wolfram 1983; Wolfram 1986; Wolfram 2002). In the CA model, the fields (e.g. buildings, streets, and etc.) are represented by a collection of equal size cells. Each cell can only be occupied by an individual at one time and the cell updates its state depend on the states of adjacent cells. The CA modelling approach has been widely used in the simulations of evacuation processes (Kirchner & Schadschneider 2002; Perez et al. 2002; Zhao et al. 2006) and the studies of crowd movement in bi-directional counter flow (Yu & Song 2007; Wang et al. 2012; Yue et al. 2010; Jian et al. 2005). Although the CA model has the strength of simplicity in field and crowd movement representation, it has some limitations because of its fixed size cells. For example, the maximum crowd density is limited by the total number of cells; flow rates through doors could be inaccurate because the cells may not totally align with the environment geometrically (Pelechano & Malkawi 2008); individual's physical size has to be the same size as the cell thus the movement is not continuous in terms of time and space.

The agent-based modelling was introduced to integrate human decision making process in crowd simulation (Dijkstra et al. 2000; Macal & North 2007; Bandini et al. 2007; Luo et al. 2008; Bonabeau 2002) because the agents were designed to be autonomous, independent, interactive, and intelligent. The agent-based models were usually combined with the CA modelling to represent the movements of agents (Hamagami & Hirata 2003; Bandini et al. 2007). They can also be combined with the force-based modelling to take into account of individual behaviours. For example, intelligent autonomous agents could be implemented on top of steering behaviours (Reynolds 1999). Or the agents could be used to simulate group behaviour with the social force model (Braun et al. 2003). It was suggested (Pelechano & Badler 2006) that an agent-based model can be created at high level for communication and navigation, while the social force model can be applied at low level to represent the crowd local motions.

However, in most of existing studies, the crowd was usually treated homogeneous, but some research studies (Pelechano & Badler 2006; Braun et al. 2003; Shendarkar et al. 2008) showed that individual behaviours can affect crowd behaviours (i.e. heterogeneous crowd do have a different performance). Several recommendations (Pelechano & Malkawi 2008; Zheng et al. 2009) have been made to improve crowd modelling. For example, it is crucial to include physical interactions between individuals to model the crowd behaviours; further research should consider combining different modelling approaches; models should increase the crowd heterogeneity in simulation. Although these recommendations have been realised to some extent in previous studies (Helbing & Molnar 1995; Helbing et al. 2000; Pelechano & Badler 2006; Bandini et al. 2007), there is still a lack of crowd models to describe the relations between behaviours and movement systematically and to enable the crowd heterogeneity.

Furthermore, the existing crowd models were usually designed for specific scenarios or for certain crowd behaviours. It would be difficult for them to represent new behaviours without significant changes in the model. There have been some attempts to address this issue partially. For example, Pelechano et al. (2008) proposed a framework (HiDAC + MACES + CAROSA) to offer a configurable crowd simulation environment but it mainly focused on behaviour animations and graphic representation. Moussaid et al. (2011) introduced a solution to combine cognitive heuristic rules and contact forces to simulation crowd dynamics but it did not consider individual differences. It is still a challenge to build a model which can integrate different crowd behaviours and interpret how they affect the individuals' movement under a unified mechanism with the flexibility to be configured to represent various scenarios.

In this paper, we presented a generic crowd model aiming to achieve the flexibility of configuration and potential future expansion, which is based on the authors' previous conceptual crowd model prototype (Sun & Wu 2011). A mathematical formula contained seven parameters was proposed to calculate the behaviour effects to determine the individual's motion. A unified mechanism of individual behaviour representation and integration was introduced. The relations between the crowd model and simulation environment were also presented. For the demonstration and validation purpose, three types of simulations have been conducted and analysed. The conclusion and future works were also discussed in the end.

2 CROWD MODEL DESIGN

Overview

The design of this crowd model combines the force-based modelling and the agent-based modelling approach. In this model, the movement of each individual is determined by behaviour effects (i.e. the forces generated from its behaviours). The agent is used to represent individual with independent physical and psychological attributes who can make independent decisions, which enables the crowd heterogeneity. *(The term 'agent' will be used to refer the individual in the crowd from now on)*

These two approaches represent individual/crowd behaviours at two different levels. At the lower level, the force-based modelling method interprets how the behaviours affect the movements of agents. Such behaviour effects are calculated through a set of pre-defined behaviour rules (via derivations of a core formula) and the continuous positions of the agents are represented in the Cartesian coordinate system. At the higher level, the agent-based modelling approach is adopted to model the intelligent individuals (known as agents) and their decision-making process. It determines the selection of the agent's behaviour configuration. The effects of those behaviours are then calculated at the lower level by the corresponding formulas.

Behaviour effect representation and calculation

The behaviour effect is measured by the displacement of the agent in an update interval. The theoretical basis of representing behaviour effect as the positional change of the agent is based on kinematics, where the displacement of an object in a period of time can be calculated via its average velocity during that period. Therefore, the behaviour effect is viewed as an equivalent to agent's average velocity and the calculations are based on Classical Mechanics and Newtonian laws. Similar ideas have been seen in existing models (Reynolds 1987; Helbing & Molnar 1995; Reynolds 1999; Helbing et al. 2000). However, in this model, the authors proposes that all the behaviour effects can be represented and calculated by applying a set of generic parameters. The following seven generic parameters have been identified to be included in the behaviour effect calculation:

- **The position of the agent ($\vec{P}_a$)** and **the position of the target ($\vec{P}_t$)**: Because a behaviour is an action happened between an agent and a target (could be a virtual target) and both could affect agent's movement. Therefore, the agent's position and target's position are two must-included parameters for the calculation.
- **The behaviour effect angle (α)**: It is important to include the direction of the behaviour as it could affect the action result (e.g. the behaviour of avoid collision and walk towards may have the same strength but different behaviour effect angles).
- **Effect of base speed (E_s)**: This parameter represents the influence of agent's base movement speed on the behaviour effect. It defines the distance which an agent can travel in one update interval (1/60 second by default in this model)
- **Agent factor (F_a)**: Its value is determined by the agent's own characters and behavioural preferences. It is a scalar value and works as a coefficient.
- **Target factor (F_t)**: This factor is used to adjust the influence from the target to the agent'. It is a scalar value and works as a coefficient.
- **Distance factor (F_d)**: The distance between the agent and its target may affect the result of the behaviour effect as the distance factor has been widely considered in physical systems such as Newton's law of universal gravitation and social force models (Helbing & Molnar 1995; Helbing et al. 2000). It is a scalar value and works as a coefficient.

The behaviour effect is proposed to be calculated through the following formula by applying the above seven parameters:

$$Behaviour\ Effect = Rotate\left(Normalise(\vec{P}_t - \vec{P}_a),\alpha\right) E_s F_a F_t F_d \quad ......(1)$$

Formula 1. The core formula of behaviour effect calculation.

In this formula, the first part "$Rotate\left(Normalise(\vec{P}_t - \vec{P}_a),\alpha\right)$" stands for the direction of the effect and the second part "$E_s F_a F_t F_d$" provides the scalar value of the effect. The functions of the operators in the formula are defined as follows:

- $\boldsymbol{Normalise(\overrightarrow{vector})}$: It refers to the normalise operation on a vector, which does not change the direction of the vector but set its norm to 1.
- $\boldsymbol{Rotate(\overrightarrow{vector},\alpha)}$: It is defined as turning the vector anti-clockwise with an angle α.

The natures of the parameters remain the same for all calculations but their values are dependent on the behaviour and the agent's attributes. More specifically, $\vec{P}_a$ and E_s are behaviour independent parameters and their values are the same to all behaviours, where $\vec{P}_a$ always represents the position of the agent and E_s is a scalar value which indicate the distance that the agent could move in that period under normal condition. The rest five parameters are behaviour dependent ($\vec{P}_t$ is behaviour dependent because it refers to the position of the behaviour target). The calculations of these behaviour dependant parameters will be introduced in more details in the "Behaviour Library" section (*In this study, it only presents simple rules to decide the values of those parameters as a guideline. Complex artificial intelligence could be easily integrated when expanding the agent model in further studies*).

It is possible that an agent may have several behaviours at the same time. In order to combine these effects, the authors propose to use the standard vector operation - "addition" to combine multiple behavioural effects. In the case of combining more than two effects, the additions of effects can happen in any sequence (which is known as the commutative law). However, the final combined behaviour effect should not exceed the agent's movement ability (i.e. agent's behaviour effect can only change the agent's position by the distance of which its maximum physical speed can achieve).

Agent design

In this model, each individual is represented by an independent and intelligent agent. The parameters of an agent consist of two parts: roles and attributes. Roles define the types of behaviours an agent is capable of during the simulation. It is simulation scenario dependant (See details in "simulation and discussion" section). The agent's attributes are used to describe the agent's characters and action abilities which influence the calculations of behaviour effects (See details in "Behaviour Library" section). The agent's attributes can be divided into three categories:

Physical attributes

They describe how the agent is presented in the model and the simulation. Attributes include: position, body size, orientation, movement mode (walk or run), base movement speed, maximum movement speed, and base movement speed adjusters.

Range attributes

They define the ranges that certain behaviours can take effect or are used by the behaviours that related to distance. Attributes include: sight range (the distance one agent can observe), range for group behaviour, desired distance from others, minimum distance from others, desired distance from wall, minimum distance from wall, desired distance from obstacles, and minimum distance from obstacles.

Personality attributes

They reflect the personality and the characters of an agent. Attributes include: leadership, willingness to follow, willingness to stay in group, probability of being affected by POIs (point of interests, e.g. signs), repulsive feeling to people, and repulsive feeling to obstacles.

Behaviour Library

In the previous sections, a core formula (Formula 1) to calculate behaviour effect and an agent model to represent the individual have been introduced. This crowd model proposes the calculations of different behaviour effects can be deviated from the core by taking into account agent's information. In order to demonstrate this concept, a Behaviour Library which includes a set of basic behaviours is developed by applying the agent model and the core formula.

Before introducing the behaviours and their parameters, the values of the two behaviour independent parameters are given as:

- $\vec{P}_a$ denotes the current position of the agent.
- E_s is calculated by $E_s = \frac{v_{default} \times representation\ scale}{simulation\ frame\ rate}$, where $v_{default}$ denotes the default speed of the agent, simulation frame rate is 60fps and representation scale is 1 pixel : 0.05m.

For the behaviour dependant parameters, they are introduced with behaviour calculations as follows:

Seek to (Move to)

This behaviour describes the basic movement that an agent moves towards the target directly. The behaviour effect can be calculated using the core formula with the following settings apply:

- $\vec{P}_t$ is the position where the agent wants to move to.
- α equals to 0 because the agent is moving directly towards targets.
- F_a has a default value of 1 to reflect the normal walking condition. This value could be higher if the agent is in a hurry or lower if the agent is slowing down.
- F_t has a default value of 1 to represent an ordinary target. A value above 1 indicates the target has more weighting to attract the agent, vice versa.
- F_d equals to 1 because this behaviour is irrelevant to distance.

The formula for "Seek to" behaviour is:

$$Behaviour\ Effect = Rotate\big(Normalise(\vec{P}_t - \vec{P}_a)\ ,0\big)\big)E_sF_aF_tF_d \quad ......(2)$$

Formula 2: Seek to effect calculation.

Wandering

Wandering means the agent moves randomly or moves without a specific target. However, its movement is considered to be a smooth trajectory rather than a totally irregular trajectory. In this model, the wandering behaviour is defined as "during each update interval (i.e a frame), the agent will turn a random angle between [-ɵ,+ɵ] which happens at a certain probability". Its behaviour effect can be calculated using the core formula with the following settings apply:

- $\vec{P}_t$ denotes the position of a virtual target which is located in front of the agent. The distance of this virtual target from the agent does not matter due to the "*Normalise*" operation.
- α is chosen randomly from the interval $[-\theta, +\theta]$ ($\theta = 18°$ by default). Furthermore, it has been suggested the random angle need to be constrained with a time-dependent function to prevent a twitchy moving trajectory (Reynolds 1999; Couzin et al. 2005). In the case of the simulation frame rate was 60 frames per second, the function to determine α is given by:

$$\begin{aligned}&at\ each\ frame,\\ &\alpha := f(\theta) = \\ &\begin{cases} Random\ ([-\theta, +\theta])\ , & at\ 5\%\ probability, \\ 0 & ,\ at\ 95\%\ probability \end{cases}\end{aligned} \quad ...(3)$$

Formula 3. The default function to determine **α** at each frame for Wandering behaviour.

- F_a has a default value of 1 to reflect the normal walking condition. This value could be higher if the agent is in a hurry or lower if the agent is slowing down.
- F_t equals to 1 because this virtual target does not affect the value of behaviour effect.
- F_d equals to 1 because the behaviour effect is irrelevant to distance.

The formula to calculate the wandering effect is:

$$Behaviour\ Effect = Rotate\Big(Normalise(\vec{P}_t - \vec{P}_a)\ , f(\theta)\Big)E_sF_a \quad ......(4)$$

Formula 4. Wandering behaviour effect calculation.

Following

Following is a behaviour that the agent tries to keep walking behind its target. This behaviour can be interpreted as seeking a virtual position that is behind the target. It can be illustrated in the following figure:

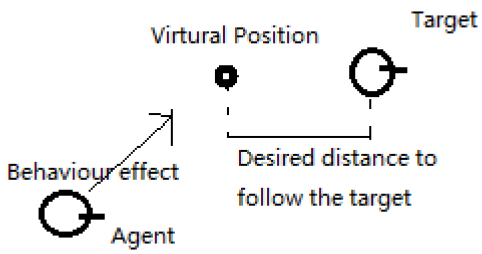

Figure 1. Illustration of the following behaviour.

Two big circles are the agent and its target (with a dash line to indicate its orientation). The small circle is the virtual position that the agent wants to walk toward, which is located somewhere behind the target. Its distance behind the target is given by the agent's desired distance to follow the target.

The behaviour effect can be calculated using the core formula with the following settings apply:

- $\vec{P}_t$ is defined as a virtual position. Its location is given by the follow formula (where $\vec{P}_{target}$ is the position of the target that the agent is following, $D_{desire\ follow}$ is the desired following distance, θ is the orientation of the target):

$$\vec{P}_t = \vec{P}_{target} - \left(D_{desire\ follow} \sin\theta, D_{desire\ follow} \cos\theta\right) \quad ...(5)$$

Formula 5. Virtual position calculation for the following behaviour.

- α equals 0 because the agent is moving directly towards the virtual position.
- F_a has a default value of 1 to reflect the normal walking condition. This value could be higher if the agent is in a hurry or lower if the agent is slowing down..
- F_t has a default value of 1 to represent an ordinary target. A value larger than 1 indicates the target has more weighting to attract the agent, and vice versa.
- F_d equals to 1 because this behaviour is irrelevant to distance.

The formula is:

$$Behaviour\ Effect = Rotate\left(Normalise(\vec{P}_t - \vec{P}_a), 0\right) E_s F_a F_t \quad ......(6)$$

Formula 6. Following behaviour effect calculation.

Keep certain distance from another agent

This behaviour describes the agent's willingness to keep certain distance from another agent. The behaviour effect is comparable to the repulsive effects introduced in the social force models (Helbing & Molnar 1995; Helbing et al. 2000). It is calculated using the core formula with the following settings apply:

- $\vec{P}_t$ is the position of the "another agent" who is the behaviour target.
- α equals to 180° because this behaviour represent a repulsive effect and the agent is moving away from the behaviour target.
- F_a has a default value of 1 to reflect the normal circumstance. A higher value indicates the agent is more sensitive to the nearby others and wants to reach the desired distance quicker, vice versa.
- F_t has a default value of 1 to indicate an ordinary behaviour target. A higher value indicates the target has some special attributes to push others away from itself more quickly, for example, the target agent could be dirty and smelly so it generally produces a larger repulsive effect, vice versa.
- F_d is considered to reflect the agent's following reactions:
  1) If the target is too close to the agent, the agent will try its best to move away from the target.
  2) If the target is too far from the agent, the agent simply ignores that target and feels no repulsive effect.
  3) If the target is within certain range, the agent will received a repulsive effect from the target. Such effect is represented by a decreeing function depending on the distance between the two.

The distance that the agent starts to feel too close is defined as the minimum distance from others - $D_{minimum\ agent}$. The distance that the agent starts to ignore the target is defined as the desired distance from others - $D_{desire\ agent}$. F_d is given by a piecewise function (where d denotes the distance between the agent and the target. k is a coefficient to adjust the influence of the distance. It is set to 1 in this model when the default graphical representation scale is used):

$$F_d := g(d) = \begin{cases} 0, (d \geq D_{desire\ agent}) \\ \frac{k}{d}, (D_{minimum\ agent} < d < D_{desire\ agent}) \\ 1, (d \leq D_{minimum\ agent}) \end{cases} \quad ....(7)$$

Formula 7. Distance function for repulsive effect.

The formula to calculate the behaviour effect becomes:

$$Behaviour\ Effect = Rotate\left(Normalise(\vec{P}_t - \vec{P}_a), 0\right) E_s F_a F_t g(d) \quad \cdots (8)$$

Formula 8. Repulsive effect from another agent.

Keep certain distance from a wall

This behaviour describes an agent trying to keep certain distance from a wall, which is similar to the behaviour "Keep certain distance from another agent" (similar reaction but the target is changed to a wall). The repulsive effect is perpendicular from the wall to the agent. The projection of agent's position to the wall stands for the position of the target in the calculation. *(Note. Due to the page limits of the paper, the calculation of this behaviour is not presented as it can be referred to the behaviour "Keep certain distance from another agent").*

Avoid collision

This behaviour describes an agent adjusts its moving direction to walk around a target, and keep a desired distance. This behaviour only happens if the agent's current behaviour will result in a collision. For example, this behaviour will happen when the agent is moving forward and it is going to collide with an obstacle. Figure 2 illustrates the "avoid collision" behaviour: the agent will adjust its direction with a certain angle α to avoid the collision (The agent can either turn left or turn right, the angle is defined as α or $-\alpha$).

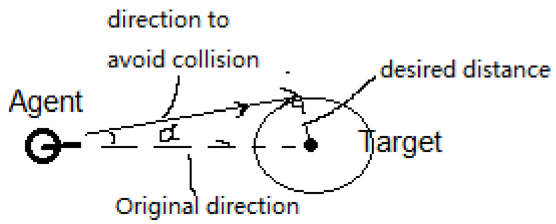

Figure 2. 'avoid collision', agent will choose an angle to perform the behaviour.

The behaviour effect can be calculated using the core formula with the following settings apply:

- $\vec{P_t}$ is the position of the object that will collide with the agent.
- α is the angle that the agent will adjust its moving direction. It is calculated by the following formula:

$$\alpha := h(d) = r \cdot sin^{-1}\left(\frac{R_a + R_t + D_{avoid\ distance}}{d}\right) \text{..(9)}$$

Formula 9. The calculation the behaviour angle for the "avoid collision" behaviour.

In this formula, r returns a value of 1 or -1 randomly to indicate whether the agent goes through left or right. R_a is the radius of the agent (once r is determined, its value will remains the same until this behaviour finished). R_t is the radius of the target. $D_{avoid\ distance}$ represents the desired distance that the agent wants to keep while avoiding collision. d denotes the distance between the agent and the target.

- F_a is set to the same value of the intended behaviour before detecting the collision.
- F_t has a default value of 1 to represent an ordinary obstacle. A value above 1 indicates the obstacle has more weighting to push away the agent.
- F_d equals to 1 because the distance factor has already been considered in the calculation of behaviour angle α.

The formula is:

$$Behaviour\ Effect = Rotate\left(Normalise(\vec{P_t} - \vec{P_a}), h(d)\right) E_s F_a F_t \text{ …..(10)}$$

Formula 10. The behaviour effect calculation for the "avoid collision" behaviour.

Walk towards the group

This behaviour describes the movement that an agent tries to manoeuvre its position to the centre of a group (A similar behaviour called "cohesion" was presented in Reynolds' study (1987)). The centre of the group is defined as the average position of all the agents in that group rather than the geometric centre of the group. The group contains the people who are within certain range of the agent. The relations are illustrated in Figure 3 where the group contains ten agents. The small circles with a dot indicating their orientations represent the crowd. The large circle indicates the group boundary. The agent is at the centre of that circle. The solid black dot is the centre of the group. Those individuals located outside the group circle have no effect in this behaviour.

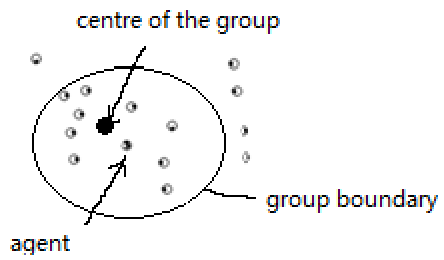

Figure 3. Illustration of the "walk towards the group" behaviour.

In this behaviour, the agent walks towards the average position (black dot in Figure 3) of a nearby crowd. Nearby crowd is defined as the crowd within the "range of group behaviour" attribute which is demonstrated in Figure 3 as group boundary.

The behaviour effect can be calculated using the core formula with the following settings apply:

- $\vec{P_t}$ is a virtual position that represents the average position of the group. Assuming the group contains N agents and $\vec{P_i}$ represents the position of agent i, $\vec{P_t}$ can be calculated through:

$$\vec{P_t} := \vec{P}_{average} = \frac{\sum_i^N \vec{P_i}}{N} \text{ …..(11)}$$

Formula 11. The calculation of the average position of a group.

- α equals to 0 because the agent is moving directly towards the virtual position.
- F_a has a default value of 1 to reflect the normal walking circumstance. Its value will be higher if the agent is in a hurry and lower if the agent is not in a hurry.
- F_t equals to 1 because this virtual target only represents the location.
- F_d equals to 1 because this behaviour is irrelevant to distance.

The effect of the "walk towards the group" can be calculated through:

$$Behaviour\ Effect\ = Rotate\big(Normalise\big(\vec{P}_{average} - \vec{P}_a\big), 0\big) E_s F_a \quad ......(12)$$

Formula 12. The behaviour effect calculation of "walk towards the group".

Align direction with the group

This behaviour describes an agent aligns its moving direction to the group (A similar behaviour called "alignment" was presented in Reynolds' study (1987)). The group has the same definition as it is in the "walk towards the group" behaviour. The group direction is defined as the average moving direction of all the other agents in the group. In this model, this behaviour is interpreted as the agent seeks to a virtual target that represents the average direction of the group. The settings of the core formula are:

- P_t is the position of a virtual target that is in the same direction of the group (contains N agents, where O_i represents the walking direction of $agent_i$. It can be any distance from the agent as long as it satisfies the follow equation:

$$Normalise\big(\vec{P}_t - \vec{P}_a\big) = Normalise\big(\textstyle\sum_{i \neq self}^{N} O_i\big) \ ...(13)$$

Formula 13. The requirement of $\boldsymbol{P_t}$ in the "align direction with the group" behaviour.

- α equals to 0 because the agent is moving directly towards the virtual position.
- F_a has a default value of 1 to reflect the normal walking condition. Its value could be higher if the agent is in a hurry or lower if the agent is slowing down.
- F_t equals to 1 because this virtual target only affect the direction of the behaviour.
- F_d equals to 1 because this behaviour is irrelevant to distance.

The behaviour effect can be calculated by the formula (where P_t is constrained by Formula 13):

$$Behaviour\ Effect\ = Rotate\big(Normalise\big(\vec{P}_t - \vec{P}_a\big), 0\big) E_s F_a \quad ......(14)$$

Formula 14. The behaviour effect calculation of "align direction with the group".

Action Engine

The Action Engine acts as the brain of an agent. It follows a predefined process (Figure 4) to decide preferred behaviours and calculate behaviour effects. It retrieves the relevant information from the Behaviour Library and the agent's attributes (It also interacts with the simulation environment. See Figure 5). The agent will check whether the decided behaviours result in confliction with other agent and will re-consider its behaviour when a confliction could happen. The end result of the behaviour effects calculated in the Action Engine will be used to update the agent's position. At each update interval, this action process will be performed by each agent.

Model Implementation

This crowd model has been implemented into a real-time (i.e. the simulation time equals the "wall clock" time) simulation system for evaluation. The graphic engine of the simulation system is built upon Microsoft XNA framework 4.0. The simulation system is working at 60 frames per seconds (to accommodate the default behaviour update interval of the proposed model). The environment representation has the scale of 1:0.05 (i.e. 1 pixel on the screen represents 0.05 metre in the real world). The agents are represented by circles with dots to indicate their orientations (see Figure 6 for illustrations).

As a summary, Figure 5 outlines the overall structure of the crowd simulation system based on the proposed crowd model.

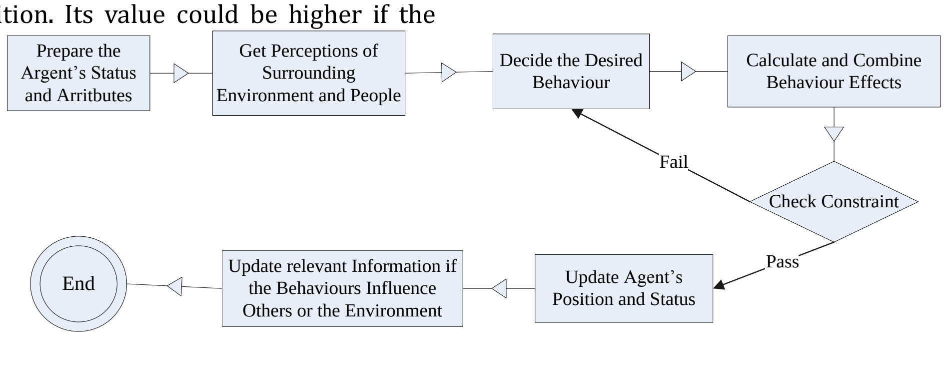

Figure 4. The action process of the agent. Modified from previous work (Sun & Wu 2011).

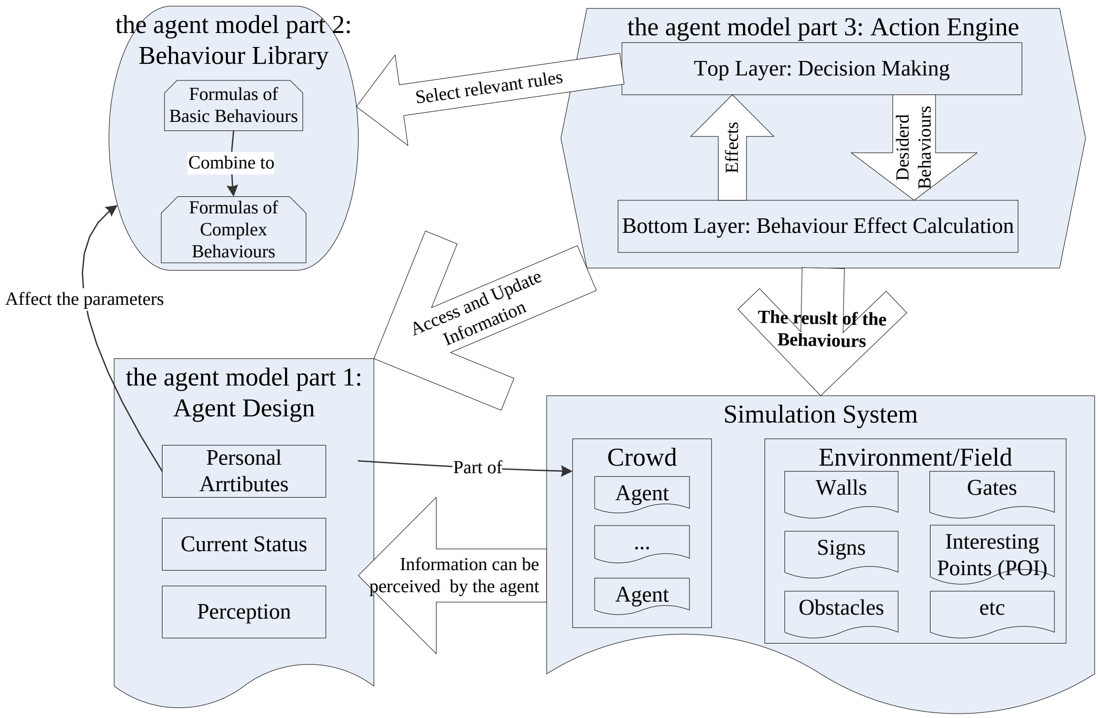

Figure 5 Crowd Model. Based on previous work of a conceptual crowd model (Sun & Wu 2011).

3 SIMULATIONS AND DISCUSSIONS

In order to validate and evaluate the proposed crowd model, several simulations have been carried out. The testing simulations can be divided into three categories:

- Reproduce the crowd behaviours that have been achieved by existing crowd models.
- Demonstrate the model application in a building evacuation scenario.
- Represent the crowd phenomenon from real life experiments which have not been represented by any other crowd model.

(All the simulations were running in real-time on a laptop of 2G RAM and inter i5 CPU)

Section 1 - reproduce existing simulations

In this section, the proposed crowd model is tested in two simulations which reproduce the crowd phenomena that have been represented by different models.

Phenomenon 1 - arch formation at small exit

Helbing et al. (2000;2002) demonstrated the crowd can form an arch-like formation while exiting through a small door. In this study, a series of simulation were conducted with the crowd only have three basic behaviours: exit through the door; keep distance from others in the crowd; keep distance from the wall. Similar phenomenon (Figure 6) has been observed in the simulations with crowd average speed from 0.1 - 3.0 m/s. The simulation shows such phenomenon would exist irrelevant to the crowd speed if only basic movement behaviour were considered (We note, however, Helbing et al.'s work had included a lot of social psychological issues and showed crowd blocking when speed was over 1.5 m/s, which is not reflected in our simulations).

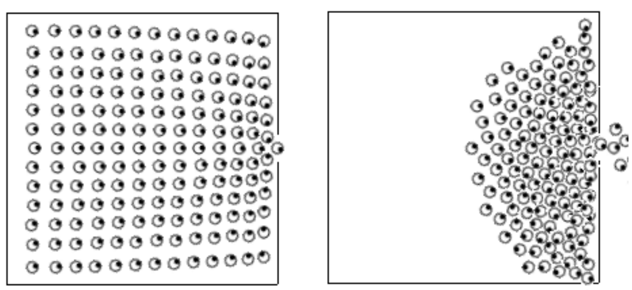

Figure 6. The crowd transit into an arch-like formation at the exit.

Phenomenon 2 - lane formation in bi-directional crowd

It has been observed that in counter-flow situations (e.g. in a corridor), pedestrians tend to move in the same lane when walking in the same direction. Such spontaneous lane formation of bi-directional pedestrian flows was successfully presented many crowd models (Yue et al. 2010; Tajima et al. 2002; Jian et al. 2005; Lam et al. 2003; Helbing & Molnar 1995; Wang et al. 2012) via various methods. By using the author's model, the lane formation were observed (Figure 7) with no additional rules or direction preferences required.

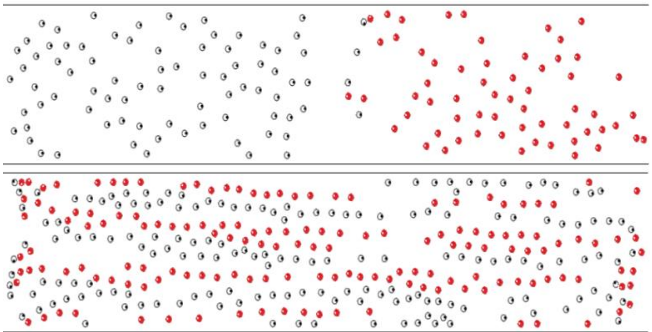

Figure 7. Spontaneous lane formation in a bi-directional crowd.

Figure 7 showes screenshots of the simulation about 400 pedestrians walking in a corridor (dimension: 45m×10m) at speed of average 1.5 m/s. The empty circles represent the individuals walking from left to right. The solid (red) circles represent the individuals walking from right to left. The agents in the crowd only have three behaviours during the movement: cross the corridor; keep distance from others in the crowd; keep distance from the wall.

By successfully reproducing the proven crowd phenomena, the reliability of the proposed crowd model has been demonstrated. The model foundation of using a unified behaviour effect representation and the approach of combining of simple behaviours were working well in the given scenarios.

Section 2 - evacuation from a shopping mall

In this section, an evacuation scenario from a shopping mall was selected to demonstrate how this crowd model can represent heterogeneous crowd, the effects of different individual decisions, as well as the influence of the environment on crowd behaviour (*high level artificial intelligence was kept simple as this section aimed to demonstrate the model application*).

This scenario describes the customers exit from a shopping mall (dimension: 40m ×30m). The distribution of the agents is demonstrated in Figure 8: (a) shows 364 people distributed in shops before the evacuation (case B); (b) shows 650 people distributed in shops and corridor (case C). In order to demonstrate how the agents and environment can affect the crowd behaviour, several sets of simulations with different configuration have been carried out (All simulations have been repeated 50 times and the results in the paper represent the average result). The crowd has 1.5 m/s average movement speed by default.

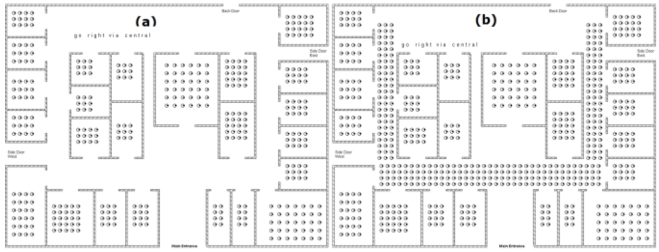

Figure 8. Shopping mall plan and crowd distribution.

Set 1 – Normal evacuation circumstance

This set tested evacuation time at various walking speeds of the crowd. It contains three cases with different crowd amounts. Case A only has 2 people in the top shops (left and right each), which can provide the evacuation time purely determined by walking speed. Case B and C have a larger crowd, in order to find out the effects of interactions between individuals on evacuation time. The individuals are considered as homogenous so the results represented overall group behaviour.

Figure 9 shows congestion occurred as people from two directions were merging into one direction. It can be seen some people were pushed in to the centre before they can turn down to the exit and such phenomenon become more prominent with larger crowd ((a) shows the congestion in Case B and (b) shows the congestion in case C).

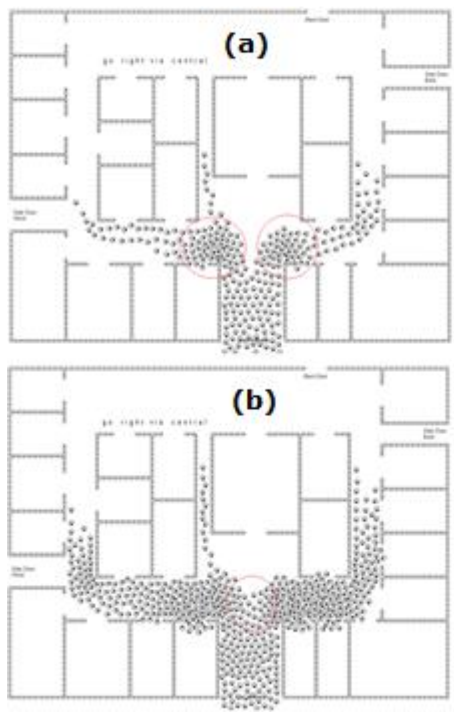

Figure 9. Congestions during the evacuation.

The overall evacuation times are shown in Figure 10. The figure illustrated that the evacuation time increases as the total number of the crowd increase. The slower the walking speed is, the larger differences in evacuation time between the cases are. Figure 10 also reveals despite the congestion become more serious with larger crowd, the relation between walking speed and evacuation time remains approximately the same, as all three cases have the similar curves (To avoid confusion, it needs to point out that this concluion is not contradictory to the “faster-is-slower” phenomenon (Helbing et al. 2000; Guy et al. 2011). In this simulation the crowd does achieve a higher actual speed while the “faster-is-shower” refers to the crowd tries to move faster but ends up with a slower average speed because of the congestion).

In a further simulation with speed variations, the simulation results suggests a small variation on walking speed (±10%) cannot produce a corresponding difference on the evacuation time. The simulation tested the walking speeds of the agents that are randomly assigned to 1.5 ± 10% metres/second. The result shows the mean time of exit the building is 31.5 ± 0.04 second (95% Confidence Level, based on 400 simulations).

Set 2 - Evacuation with some elderly people

In this set of simulations, it tested whether the agents with different physical characteristics would have an impact on the evacuation time. Eight elderly people are added into the corridor which is showed in Figure 12: (a) case A; (b) case B. As a result, for case A, the evacuation time was 42.9 seconds which was 0.9 second more than the normal case (without elderly people). For case B, the evacuation time was 48.2 second which was 8.2 seconds more than the normal case. The results reveals although same amount of the elderly people is added into the simulation, their effects on others are largely dependent on their initial positions. In other words, the layout of environment needs to be taken into account. Figure 12 (c) shows in case A, the normal people’s movement are not affected much because they can overtake the elderly one by one easily. But in case B, because the elderly people started as a group, their slow movement actually blocked the way of others and reduced the effective width of the corridor. It can be observed in Figure 12 (d) that the evacuation rate of the left side was slower than the right side due to the blockage effect by the elderly group.

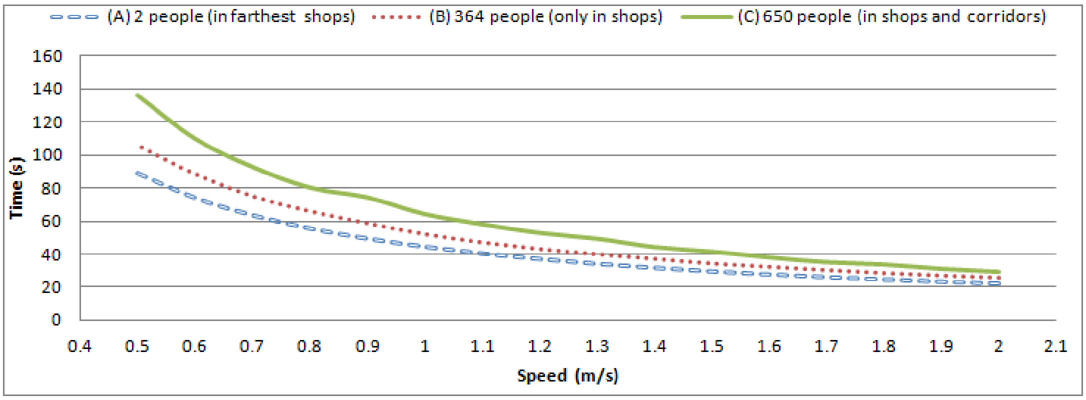

Figure 10. Evacuation times at different walking speeds (3 scenarios)..

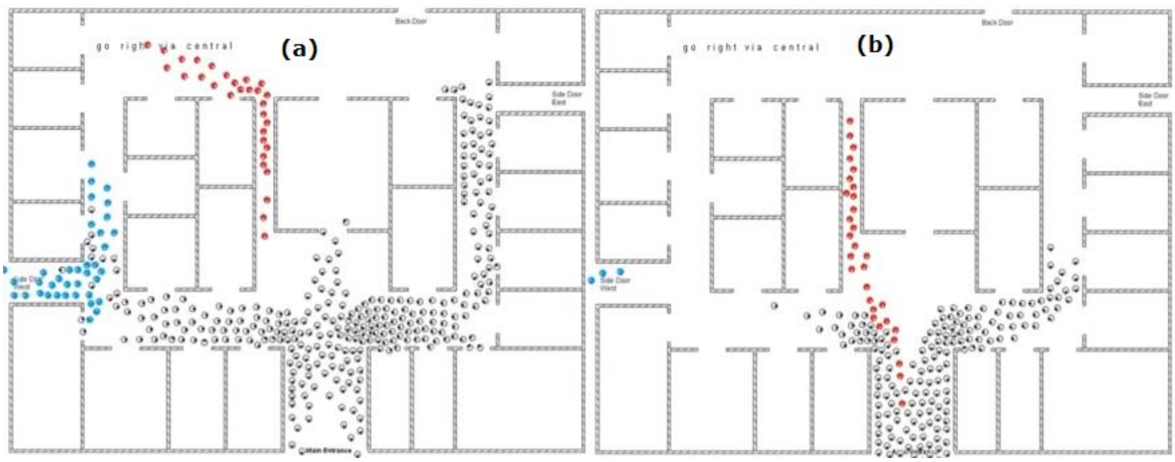

Figure 11. Simulation of some agents make use of the fire (west) exit.

Figure 12. Simulations contain elderly group.

Set 3 - Different exit routes

In the set of simulations, the effects of individual decisions were tested: the people in the left side corridor would randomly use the fire-exit (west) or the main entrance (A sign indicates the first exit but overall 50% of the crowd can make use of it.

Figure **11**a shows the agent use the west exit in bule (solid) colour). Surprisingly, the evacuation time was only improved by 0.2 second in this case than the case of using only one exit. However, when watching the evacuation process of the simulation, clear difference can be observed. The people choose the closer exit (which is the west exit) did evacuate much quicker than the others (

Figure **11**b shows after around 20 seconds, the agents near the west exit have almost evacuated). The overall evacuation time did not improve as the remaining crowd were still queuing at the south main entrance while the west exit was already cleared.

Section 3 - simulate un-modelled crowd behaviour

Real life experiments (Dyer et al. 2009) showed the crowd could reach the target position together without the internal communications if more than ten percent of crowd know (informed) the position of target. Such phenomenon is known as consensus decision making in group. Similar results were produced by Pelechano & Badler (2006) but explicit leadership and communications were enabled in the crowd. However, to the authors' knowledge, there are no crowd model can simulate Dyer et al.'s finding with identical instructions. The authors designed a series of simulation to test whether the proposed crowd model could produce the phenomenon with the same instructions used in Dyer's experiment.

Two categories of agents have been implemented: one will try to move to the target as "informed" agents while the other one moves randomly as long as remaining in the group. The behaviour of "remain in the group" is defined as the combination of the "walk towards the group" behaviour and the "align direction with the group" behaviour, each has 50% weighting (the group range was defined as 5 metres). The other behaviours used in the simulation were: "seek to target", "move randomly", and "keep distance from others". No communication is enabled during the simulation. The simulation tested the amount of 200 people (the "informed" agents were randomly chose). The target was located 25 metres to the west of the group which is only visible to the "informed" agents.

The simulations have been tested at four proportions of informed individuals: 2.5%, 5%, 10%, and 15%. It can be seen (Figure 13) that the group can achieve reasonable arrival accuracy when the proportion of informed agent is more than 10%. Each configuration has been repeated 100 times and results represented the average.

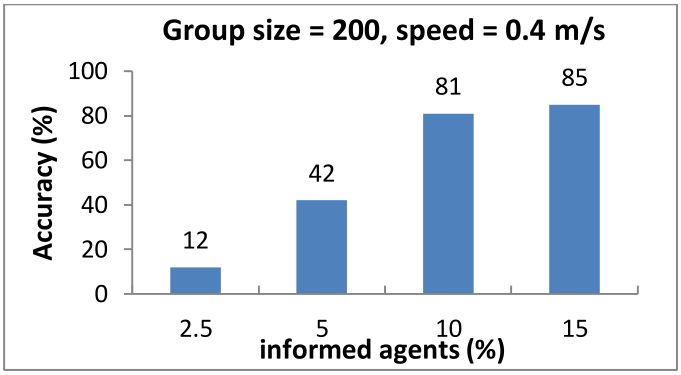

Figure 13. Successful rate of reaching the target with various percentages of informed agents.

4 CONCLUSION AND FUTURE WORK

To conclude, this paper introduced a generic crowd model which can represent different individual behaviour effects under a unified mathematic model. A core formula with seven generic parameters was proposed to form the foundation of behaviour representation in this model. The agent-based modelling approach was adopted to create the heterogeneity in the crowd. A Behaviour Library was introduced as a collection of behaviour rules and their configurations and calculations using the core formula have been demonstrated. This model then was implemented into a real-time simulation system and several simulations were conducted. Through those simulations, the proposed crowd model has demonstrated its capacity in three aspects:

- The reliability to reproduce several known crowd phenomena.
- The ability to present individual differences, the effects of their decisions, and environmental constraint in a given environment.
- The flexibility to model and simulate new crowd behaviour from real-life findings without modifying the existing model.

Future works are suggested in two aspects:

- The proposed model can be applied to a more realistic environment and include more complex behaviours observed from case study or video analysis (Malinovskiy et al. 2009).
- The graphical representation of the simulation can be expanded to support further analysis, such as the recording of the agents' movement trajectory.
- Complicate agent behaviours and artificial intelligence can be integrated in the high level once the unified behaviour effect representation method was further calibrated.

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REFERENCES

Bandini, S., Federici, M.L. & Vizzari, G., 2007. Situated Cellular Agents Approach To Crowd Modeling and Simulation. *Cybernetics and Systems*, 38(7), pp.729–753.

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(Suppl 3), p.7280.

Braun, A. et al., 2003. Modeling individual behaviors in crowd simulation. In *16th International Conference on Computer Animation and Social Agents*. Published by the IEEE Computer Society, pp. 16–21.

Cheng, W. et al., 2008. A modified particle swarm optimization-based human behavior modeling for emergency evacuation simulation system. In *Information and Automation, 2008. ICIA 2008. International Conference on*. IEEE, pp. 23–28.

Chu, C.-Y., 2009. A Computer Model for Selecting Facility Evacuation Design Using Cellular Automata. *Computer-Aided Civil and Infrastructure Engineering*, 24(8), pp.608–622.

Couzin, I.D. et al., 2005. Effective leadership and decision-making in animal groups on the move. *Nature*, 433(7025), pp.513–6.

Dijkstra, J., Timmermans, H. & Jessurun, A., 2000. A multi-agent cellular automata system for visualising simulated pedestrian activity. In *Proceedings on the 4th International Conference on Cellular Automata for Research and Industry*. pp. 29–36.

Drury, J., Cocking, C. & Reicher, S., 2009. Everyone for themselves? A comparative study of crowd solidarity among emergency survivors. *The British journal of social psychology / the British Psychological Society*, 48(Pt 3), pp.487–506.

Dyer, J.R.G. et al., 2009. Leadership, consensus decision making and collective behaviour in humans. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 364(1518), pp.781–9.

Ebihara, M., Ohtsuki, A. & Iwaki, H., 1992. A Model for Simulating Human Behavior During Emergency Evacuation Based on Classificatory Reasoning and Certainty Value Handling. *Computer-Aided Civil and Infrastructure Engineering*, 7(1), pp.63–71.

Guy, S.J. et al., 2011. Simulating heterogeneous crowd behaviors using personality trait theory. In *Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*. New York, NY, USA: ACM, pp. 43–52.

Hamagami, T. & Hirata, H., 2003. Method of crowd simulation by using multiagent on cellular automata. *IEEE/WIC International Conference on Intelligent Agent Technology, 2003. IAT 2003.*, pp.46–52..

He ̈geas, L. et al., 2003. A physically-based particle model of emergent crowd behaviors. In *International Conference Graphicon 2003*. Citeseer, pp. 5–10.

Helbing, D. et al., 2002. Simulation of pedestrian crowds in normal and evacuation situations. In S. Schreckenberg, M and Sharma, ed. *PEDESTRIAN AND EVACUATION DYNAMICS*. pp. 21–58.

Helbing, D., Farkas, I. & Vicsek, T., 2000. Simulating dynamical features of escape panic. *Nature*, 407(6803), pp.487–490.

Helbing, D. & Molnar, P., 1995. Social force model for pedestrian dynamics. *Physical review E*, 51(5), p.4282.

Jian, L., Lizhong, Y. & Daoliang, Z., 2005. Simulation of bi-direction pedestrian movement in corridor. *Physica A: Statistical Mechanics and its Applications*, 354, pp.619–628.

Kirchner, A. & Schadschneider, A., 2002. Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. *Physica A: Statistical Mechanics and its Applications*, 312(1-2), pp.260–276.

Kobes, M., Helsloot, I., de Vries, B., et al., 2010. Building safety and human behaviour in fire: A literature review. *Fire Safety Journal*, 45(1), pp.1–11.

Kobes, M., Helsloot, I., Vries, B. De, et al., 2010. Way finding during fire evacuation ; an analysis of unannounced fire drills in a hotel at night. *Building and Environment*, 45(3), pp.537–548.

Kuligowski, E.D. & Peacock, R.D., 2005. *A review of building evacuation models*,

Lam, W.H.. et al., 2003. A generalised function for modeling bi-directional flow effects on indoor walkways in Hong Kong. *Transportation Research Part A: Policy and Practice*, 37(9), pp.789–810.

Liu, M. & Lo, S.M., 2011. The quantitative investigation on people’s pre-evacuation behavior under fire. *Automation in Construction*, 20(5), pp.620–628.

Luo, L. et al., 2008. Agent-based human behavior modeling for crowd simulation. *Computer Animation and Virtual Worlds*, 19(3-4), pp.271–281.

Macal, C.M. & North, M.J., 2007. Agent-based modeling and simulation: Desktop ABMS. *2007 Winter Simulation Conference*, pp.95–106.

Malinovskiy, Y., Zheng, J. & Wang, Y., 2009. Model-Free Video Detection and Tracking of Pedestrians and Bicyclists. *Computer-Aided Civil and Infrastructure Engineering*, 24(3), pp.157–168.

Moussa ̈ıd, M., Helbing, D. & Theraulaz, G., 2011. How simple rules determine pedestrian behavior and crowd disasters. *PNAS*, pp.1–5.

Musse, S.R. & Thalmann, D., 1997. A model of human crowd behavior: Group inter-relationship and collision detection analysis. In *Computer Animation and Simulation*. Citeseer, pp. 39–51.

Von Neumann, J. & Burks, A.W., 1966. *Theory of self-reproducing automata*, University of Illinois Press.

Ng, M., Park, J. & Waller, S.T., 2010. A Hybrid Bilevel Model for the Optimal Shelter Assignment in Emergency Evacuations. *Computer-Aided Civil and Infrastructure Engineering*, 25(8), pp.547–556.

Parisi, D. & Dorso, C.O., 2007. Morphological and dynamical aspects of the room evacuation process. *Physica A: Statistical Mechanics and its Applications*, 385(1), pp.343–355.

Pelechano, N., Allbeck, J.M. & Badler, N.I., 2008. Virtual Crowds: Methods, Simulation, and Control. *Synthesis Lectures on Computer Graphics and Animation*, 3(1), pp.1–176.

Pelechano, N. & Badler, N.I., 2006. Modeling crowd and trained leader behavior during building evacuation. *IEEE computer graphics and applications*, 26(6), pp.80–86.

Pelechano, N. & Malkawi, a, 2008. Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches. *Automation in Construction*, 17(4), pp.377–385.

Perez, G.J. et al., 2002. Streaming, disruptive interference and power-law behavior in the exit dynamics of confined pedestrians. *Physica A: Statistical Mechanics and its Applications*, 312(3-4), pp.609–618.

Reynolds, C.W., 1987. Flocks, herds and schools: A distributed behavioral model. In *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*. ACM, pp. 25–34.

Reynolds, C.W., 1999. Steering behaviors for autonomous characters. In *Game Developers Conference. http://www. red3d. com/ ...*. Citeseer.

Santos, G. & Aguirre, B.E., 2004. A critical review of emergency evacuation simulation models. In *In Proceedings of the NIST Workshop on Building OccupantMovement during Fire Emergencies.* Disaster Research Center, pp. 25–50.

Shendarkar, a et al., 2008. Crowd simulation for emergency response using BDI agents based on immersive virtual reality. *Simulation Modelling Practice and Theory*, 16(9), pp.1415–1429.

Sun, Q. & Wu, S., 2011. A Crowd Model with Multiple Individual Parameters to Represent Individual Behaviour in Crowd Simulation. In *2011 Proceedings of the 28th ISARC.* Seoul, Korea, pp. 107–112.

Tajima, Y., Takimoto, K. & Nagatani, T., 2002. Pattern formation and jamming transition in pedestrian counter ow. , 313, pp.709–723.

Wang, Z. et al., 2012. Team-moving effect in bi-direction pedestrian flow. *Physica A: Statistical Mechanics and its Applications*, 391(11), pp.3119–3128.

Wolfram, S., 2002. History of cellular automata. In *A new kind of science*. Wolfram Media, Inc., p. 876.

Wolfram, S., 1983. Statistical mechanics of cellular automata. *Reviews of Modern Physics*, 55(3), pp.601–644.

Wolfram, S., 1986. *Theory and Applications of Cellular Automata*, World Scientific.

Yu, Y. & Song, W., 2007. Cellular automaton simulation of pedestrian counter flow considering the surrounding environment. *Physical Review E*, 75(4), p.046112.

Yue, H. et al., 2010. Study on bi-direction pedestrian flow using cellular automata simulation. *Physica A: Statistical Mechanics and its Applications*, 389(3), pp.527–539.

Zhao, D., Yang, L. & Li, J., 2006. Exit dynamics of occupant evacuation in an emergency. *Physica A: Statistical Mechanics and its Applications*, 363(2), pp.501–511.

Zheng, X., Zhong, T. & Liu, M., 2009. Modeling crowd evacuation of a building based on seven methodological approaches. *Building and Environment*, 44(3), pp.437–445.

FIGURE

FORMULA