GAME THEORETIC SPATIAL EVACUATION SIMULATION MODELS TO PREDICT CROWD DISASTER

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GAME THEORETIC SPATIAL EVACUATION SIMULATION MODELS TO PREDICT CROWD DISASTER

by

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
AIS	Artificial Immune System
ANFIS	Adaptive Network based Fuzzy Inference System
ANN	Artificial Neural Network
App	Application
BN	Bayesian Network
BP	Back-propagation
C	Cooperate
CA	Cellular Automata
D	Defect
DE	Differential Evolution
E	Evaluator
EA	Evolutionary Algorithm
EC	Evolutionary Computing
ESS	Evolutionary Stable Strategy
FL	Fuzzy Logic
GA	Genetic Algorithm
GBN	Gaussian Bayesian Network

GIS Geographic Information System

GPS Global Positioning System

HURAM Human Risk Analysis Model

ISM Industrial, Scientific and Medical

MLP Multilayered Perceptron

NE Nash Equilibrium

PDA Personal Digital Assistant

PD Prisoner's Dilemma

PSO Particle Swarm Optimization

R Retaliator

RFID Radio-frequency Identification

SC Soft Computing

SIA Swarm Intelligence Algorithm

WISP Wireless Identification and Sensing Platform

MODEL SIMULASI PEMINDAHAN RUANG BERASASKAN TEORI PERMAINAN UNTUK MERAMALKAN BENCANA ORANG RAMAI

ABSTRAK

Dinamik orang ramai berperanan penting dalam sistem pengurusan pemindahan yang relevan untuk menganjurkan perhimpunan skala besar yang lebih selamat. Merancang tugas kawalan orang ramai melalui simulasi pemindahan pergerakan dan perlakuan orang ramai semasa proses pemindahan boleh mengurangkan kemungkinan untuk berlakunya bencana orang ramai. Kajian terdahulu tentang pemindahan model tidak menggambarkan ketidakpastian yang dihadapi oleh agen dalam membuat keputusan apabila konflik dalam kalangan agen berlaku. Kebanyakan kajian terdahulu telah mencadangkan model pemindahan dalam ruang diskret dan telah mengandaikan bahawa fungsi kos agen yang menggambarkan bagaimana agen melihat pentingnya senario pemindahan adalah malar. Tesis ini mencadangkan model yang berkaitan dengan gerakan orang ramai yang tertakluk kepada kesesakan ketika pemindahan di bawah keadaan ketidakpastian dan kepastian dalam ruang yang berterusan melalui simulasi komputer. Perlakuan agen dimodelkan berdasarkan tindak balas yang terbaik, tingkah laku yang suka terhadap risiko, tingkah laku yang menjauhi risiko dan tingkah laku yang berisiko neutral melalui teori permainan tertentu. Pertama, fungsi kos agen yang dinamik dicadangkan. Kemudian, kaedah baru untuk mengenal pasti konflik dalam kalangan agen dan menyelesaikan konflik tersebut dicadangkan supaya hanya satu pemenang yang dapat bergerak. Dalam menyelesaikan konflik dalam kalangan agen, matriks permainan baru dicadangkan dengan mengambil kira kos kelewatan masa disebabkan konflik dan juga saiz agen. Seterusnya, model pemindahan berdasarkan ruang yang automatik dibangunkan yang mana agen mengemas kini kelajuan pilihan mereka

berdasarkan paras ancaman. Akhirnya, simulasi komputer dengan populasi homogen dan heterogen dilakukan untuk mengkaji kesan agen ke arah aliran keluar. Hasil simulasi menunjukkan bahawa purata jumlah masa pemindahan lebih cepat apabila populasi agen yang bertindak balas terbaik, agen yang menjauhi risiko dan agen yang berisiko neutral meningkat. Selain itu, kes terpantas diperhatikan apabila populasi agen yang menjauhi risiko meningkat. Hasil simulasi juga menunjukkan hubungan antara tekanan terhadap orang ramai dan bilangan agen yang cedera. Berdasarkan hasil simulasi, dapat disimpulkan bahawa bencana orang ramai dapat dicegah jika populasi agen penuh dengan agen yang menjauhi risiko dan agen yang berisiko neutral meskipun dalam keadaan yang bahaya.

GAME THEORETIC SPATIAL EVACUATION SIMULATION MODELS TO PREDICT CROWD DISASTER

ABSTRACT

Crowd dynamics play an important role in evacuation management systems relevant to organizing safer large scale gatherings. Planning crowd control tasks via evacuation simulation of the movement and behaviours of crowd during egress could mitigate the possibility of crowd disasters that may happen. Previous studies on evacuation models do not describe the uncertainty faced by the agents in making decisions when conflicts among agents occur. Besides, most of the studies have proposed evacuation models over a discrete space and have assumed that the agent's cost function that describe how the agents view the importance of evacuation scenario to be constant. This thesis proposes models pertaining to crowd motion subject to exit congestion under uncertainty and certainty conditions in a continuous space via computer simulations. Best-response, risk-seeking, risk-averse and risk-neutral behaviours of agents are modelled via certain game theory notions. First, this thesis formulates a dynamical agents' cost function. Then, an enhanced method is proposed to identify conflicting agents as well as to resolve the conflicts so that only one winner will be able to move. In resolving the conflicts among agents, a new game matrix is proposed by taking into consideration the conflict time delay and the size of the agents. Next, an automated spatial evacuation model is developed in which agents update their preferred speed based on the level of threats. Finally, computer simulations with homogeneous and heterogeneous populations are performed in order to study the effect of agents' behaviours towards egress flow. Results show that the average escape time tends to be faster whenever the proportion of best-response, risk-averse and risk-neutral agents are

increased. Apart from that, the fastest case is observed when the risk-averse agents' population gets increased. Simulation results also show the relationships that are entailed between the local crowd pressure and the number of injured agents. Based on the simulation results, it can be inferred that crowd disaster could be prevented if the agents' population are full of risk-averse and risk-neutral agents despite circumstances that lead to threat consequences.

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Undoubtedly, there are many positive effects when people congregate together. However, there are also several negative outcomes when the density of people grows too high, such as stampedes, increased crime, severe traffic delays and pollution. Furthermore, densely populated areas could also lead to emergency evacuation where people attempt to move away immediately from the threat place due to the proximity of people and their frequent interactions. Emergency evacuation could also happen due to natural disasters, fire, traffic accidents, building structural failure and so on.

Various researches and developments have been proposed in the modelling of safe and efficient evacuation of human crowd during events such as Hajj pilgrimage, mega festivals, sporting events, as well as regular pedestrian crowded public places such as shopping areas and underground subways. Given that evacuation processes serve as a routine activity in certain planned events, emergency situations which could lead to crowd disaster could arise either due to crowd dynamics or external factors such as incidents of violence, collapse of buildings and unexpected fire accidents. From a broad perspective, this thesis intends to study the dynamics of crowd that may lead to crowd disasters. Table 1.1 portrays several crowd disaster incidents in which the number of deaths are more than 20 persons that happened from 2010 – 2016 (Still, 2017) and occured mainly due to crowd stampede where panicked crowd rush away to escape from the threat.

Table 1.1: Several crowd disasters that happen around the world from 2010 – 2016.

Date	**Place**	**Number of Deaths**
15 October 2016	Lucknow, India	24
26 September 2015	Mina, Mecca	769
14 July 2015	Andhra Pradesh, India	27
10 July 2015	Bangladesh	20
31 December 2014	Shanghai, China	36
13 October 2013	Madhya Pradesh, India	> 50
11 February 2013	Allahabad, India	36
1 January 2013	Ivory Coast	62
22 November 2011	Modibo Keita Stadium, Mali	36
15 November 2011	Kerala, India	102
22 November 2010	Cambodia	375
24 July 2010	Duisberg, Germany	21
4 March 2010	Kunda, India	63
27 February 2010	Timbuktu, Mali	26

Dynamics of crowd are usually complex and can be defined as the study of the crowd movement in a dense area (Still, 2000). Dedicated research is ongoing in several fields, including the area of crowd dynamics, to propose various effective planning strategies to avoid crowd disaster. Research on crowd dynamics from both theoretical (Bellomo and Dogbe, 2011; Burstedde et al., 2001; Helbing et al., 2003; Kirchner and Schadschneider, 2002; Tajima and Nagatani, 2001) and experimental perspectives (Blue and Adler, 1999; Ma et al., 2010; Muramatsu et al., 1999; Seyfried et al., 2009; Takimoto and Nagatani, 2003) involves multi-disciplinary combination of physics, computer vision, optimization, computational mathematics, psychology, sociology, strategic management and so on. Crowd dynamic models can be classified into different types depending upon how the scheme treats the pedestrians, and the level of details of the models are as follows:

(1) Microscopic models (Goldstone and Janssen, 2005; Lo et al., 2004; Pan, 2006; Saloma et al., 2003; Tajima and Nagatani, 2001; Wolfram, 1983) consider in-

dividual agent behaviour separately as a particle. The agent behaviour in these models is often described by their interactions with other agents in the system.

(2) Macroscopic models (Colombo and Rosini, 2005; Hughes, 2002,0) neither make distinctions between individual agents nor describe their individual behaviour but consider the whole agents flow in terms of density, average velocity and flow patterns.

(3) Mesoscopic models (Helbing et al., 2000b; Klar and Wegener, 2000) model a small group of people in the same environment where every group has its own identical behaviour. Mesoscopic models combine the properties of the macroscopic and microscopic by considering a crowd as a whole and at the same time considering internal forces of each group as well.

Modelling and simulation of crowd evacuation, which has been an active research topic amidst a diverse range of research communities, can be broadly classified into three categories (Pan et al., 2007) as follows:

(1) Individual agents: Each of the agents have a certain preference to follow when they are subject to an evacuation scenario. As such, each agent will try to maximize their own utility.

(2) Interaction among individuals: This could also contribute to the smoothness of the evacuation process. During emergency evacuation, usually some sort of interaction happens among agents. Some of the agents would tend to follow the majority, while others would rush towards the direction of exits which could slow down the evacuation time which in turn may lead to a stampede.

(3) Group movements: The movement of several agents as a group could also affect the evacuation process. For example, constraints in the environment such as a narrow exit can restrict the movement of a group of agents. It could increase the tension perceived among group members which in turn may lead to uncoordinated movement of agents.

Evacuation simulation of the movement and behaviour of a crowd during egress could reduce the possibility of crowd disasters (Still, 2000). It is an undeniable fact that behaviour of a crowd is intrinsic and could be influenced by external factors such as clogging, counter flow, narrow path and congestion. However, systematic modelling and simulation of crowd behaviour could lead to minimal evacuation time and safer evacuation. The method proposed in this thesis essentially intends to analyse the behaviour of the crowd through evacuation simulation in order to provide safe and better evacuation flow. In this thesis, crowd evacuation modelling will be focused at the microscopic level which is comprised of individuals, and interaction among individual levels. This is because the proposed work is based on agent based modelling which is to model and simulate the actions and interactions of autonomous agents in order to study their consequences towards the movement of the whole crowd. This thesis intends to characterize the behaviour of crowd during evacuation scenarios with the aid of game theory oriented simulations. Game theory investigates and formulates mathematical models that deals with the decision making of interacting players (agents). The reasons why the notion of game theory has been utilized is elaborated in the following chapter.

1.2 Problem Statement

The main problem in performing research pertaining to crowd emergency is that people cannot be exposed to real emergencies in order to analyse their behaviours and reactions. Hence, numerous research have been proposed in theoretical perspectives by modelling and simulating the evacuation scenarios in order to study the various problems during evacuation (Still, 2000).

As evidenced by the literature most of the previous research have assumed the whole crowd as a single entity and somehow the importance of the behaviours and characteristics of individual agents (Chen, 2006) are not given adequate attention when considering the movement of the whole crowd. There exists a research gap to study the effect of the interactions among different types of crowd behaviours towards crowd flow. Hence it is important to model in detail different types of crowd behaviours by utilizing other types of notions (Ma, 2013). Besides, previous works (Hao-Nan et al., 2014; Heliövaara et al., 2013; Pärnänen, 2015; von Schantz and Ehtamo, 2015) have treated evacuation models using discrete space which is not realistic. This is because evacuation model using discrete space assumes the equal size for all agents and also simulates the crowd movement via probabilistic theory. Furthermore, previous works (Bouzat and Kuperman, 2014; Shi and Wang, 2013; Zheng and Cheng, 2011) have assumed that the agent's cost function that describes how the agents' view the importance of evacuation scenario, to be constant. Importantly, the agents' cost function is to be addressed according to the spatial and temporal evacuation situations so that we can understand how agents would respond in different situations. Hence, there is a need to build a dynamical agents' cost function which will take into account the continuous space, dynamic changes of escape time, conflict cost and conflicting neighbouring agents.

Furthermore, there is a need to build a model that explains the different types of crowd behaviours that could be observed during evacuation scenarios. Wirz et al. (2013) have recommended that it is important to apprehend the behaviours of the crowd. Besides, the relation of crowd behaviours and evolution of different types of behaviours towards egress flow remain unexplored in previous works (Hughes, 2003; Wirz et al., 2013). Therefore, it is imperative to examine the effect of various crowd behaviours towards egress flow and the relationship between evolution of crowd behaviours and the occurrences of the crowd disaster. The proposed model should be able to explain how and why agents could be injured during evacuation. Hence, with the aid of evacuation simulation of different types of crowd behaviours, we may understand how the crowd safety could be affected.

1.3 Research Objectives

The overarching aim of this thesis is to achieve a realistic spatial evacuation model supported by relevant simulations that would be able to describe how the evolution of different types of crowd behaviours could affect the egress flow that could gradually lead to possible crowd disasters. Besides, this thesis also aims to enhance the agents' decision making abilities during evacuation scenarios. To achieve these goals, this thesis seeks to fulfill the following objectives:

(1) To formulate the dynamical cost function for individual agents and the interaction among different types of agents' behaviour by utilizing classical notions of

game theory.

(2) To formulate the spatial evacuation model in a continuous space that intends to encompass how the agents' neighbourhood can be identified and resolved subject to exit congestion under typical uncertainty and certainty conditions.

(3) To validate the effect of crowd behaviours towards the egress flow and the critical conditions of the crowd by designing an automated spatial evacuation model and by performing computer simulations of evacuation scenarios under normal and threat conditions.

1.4 Research Scope

The scope of this thesis is to develop the realistic spatial evacuation model and simulate different features of human escape behaviours in crowded environments with a single exit, including, but not limited to, discotheques, stadia, lecture halls or rooms in general and other event areas. The scope of this thesis is set to examine the crowd escape behaviours in environments with a single exit because the critical conditions during emergency scenarios may arise due to the crowding and movement at vulnerable locations such as at exit doors, gates, and passages (Friberg and Hjelm, 2015). Bottleneck frequently occurs at the point when hindrances cause disturbances or when the spatial space limits the flow. Critical conditions of the crowd could happen when densely packed crowd move through the bottleneck. This is because of the high pressure that spread and transmit among the crowd. Furthermore, agents also could fall due to the forces that spread among the crowd (Friberg and Hjelm, 2015).

This thesis also attempts to improve the way that agents' behave or decide during emergency evacuation by modelling and simulating different types of crowd behaviours. This thesis classifies the potential crowd behaviours as risk-seeking, risk-averse, risk-neutral and best-response agents. Different types of agents have the same cost function but may have different preferences or strategies. These different strategies of the agents are owing to the different risk attitude of the agent types. These agents' behaviours and their set of strategies are discussed further in Chapter 4.

1.5 Research Contributions

The main contributions of this research are as follows:

(1) Agents neighbourhood is treated in the continuous space which attempts to intuitively emulate pedestrian interactions that occur during mass gatherings.

(2) Formulation of the dynamical cost function for individual agents with the incorporation of a novel parameter conflict time delay and the development of a spatial evacuation model based on this cost function.

(3) Formulation of an automated spatial evacuation model.

(4) Study of the effect of crowd behaviours towards the egress flow and the critical conditions of the crowd via game theory oriented simulations under normal and threat conditions.

(5) Study of the equilibrium strategies of the crowd. This has lead to the important findings on how a typical crowd should decide and behave in order to prevent crowd disasters.

1.6 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 describes the previous works pertaining to this research area. In Chapter 3, research methodology of this research and background analysis on crowd evacuation models with static cost functions are presented. Chapter 4 further enhances the spatial evacuation model and then elaborates the development of an automated spatial evacuation model and the effect of crowd behaviours toward critical conditions of the crowd. Chapter 5 basically validates the proposed evacuation model. Finally, Chapter 6 concludes the thesis and also sets up the direction for future avenues.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Evacuation processes serve as a routine activity in certain planned events, crowd management authorities are also expected to take immediate evacuation steps during emergency situations such as unexpected fire accidents, bomb blasts, stampedes due to crowd panic, incidents of violence, collapse of buildings, natural calamities like earthquakes, and so on.

The prevailing evacuation management systems depend mainly on human power to assist the evacuees during an emergency evacuation scenario. However, the absence of information, especially pertaining to crowds such as the location, the seriousness of the disaster, and safer evacuation exits may worsen a crowd calamity circumstance, thus rendering the job of safe evacuation difficult. Besides, blockage conditions amidst an emergency evacuation cause a great challenge for any evacuation management system. Traffic and blockage during emergency evacuation occur when the demand for travel exceeds the available path.

Although the organisers of large gatherings might have done the necessary preparation, it is difficult to anticipate the behaviour of a crowd during an event that may lead to a possible crowd disaster. Uncertainty nature during evacuation scenarios be the cause of complexity for the evacuation management to react properly. For instance, three million people run away on account of Hurricane Floyd which struck the east coast of the United States. This evacuation is considered as one of the largest evacuations depicts the complicatedness faced by evacuation management authorities (Chen, 2006). Early mitigation of crowd disaster could open the way for the authorities to direct and provide a safe evacuation path for the crowd. To give an example, late evacuation is one of the reasons for the crowd disaster of the Love Parade 2010 in Duisburg, Germany where 21 visitors died in a stampede. It is reported that the first attempt by the police to direct the crowd for safe evacuation during the crowd disaster of Love Parade 2010 started around 16:40, while crowd turbulence had already started at least at 16:34 (Helbing and Mukerji, 2012). It is vital to predict the area where the crowd congestion may occur during any particular event in order to provide safety measures (Helbing et al., 2007). Crowd dynamics have important applications in evacuation management system relevant to organizing safer large scale gatherings. Crowd dynamics have been studied from both experimental and theoretical perspectives.

2.2 Evacuation Studies via Experimental Perspectives

For experimental perspectives, field reviews have been conducted for better understanding of crowd dynamics (Daamen and Hoogendoorn, 2007; Fruin, 1971; Kholshevnikov et al., 2008; Pauls, 1984; Seyfried et al., 2005). Furthermore, numerous studies have utilized sensors such as Global Positioning System (GPS), Bluetooth, Radio-frequency Identification (RFID) and video based in order to monitor the agents (pedestrians) for studying on their trajectories, behaviours, flow, density and so on. This section gives brief reviews on previous works pertaining research on crowd dynamics monitoring via these aforementioned sensors.

2.2.1 Via GPS

The deployment of smartphones for crowd monitoring has been increasing recently, mainly because of the fact that smartphones are embedded with GPS receivers. Blanke et al. (2014) monitored the crowd behaviour by tracking the location of attendees' smartphones. In order to collect the attendees' location, it is important to have a dedicated application installed by users on their smartphones. Here, the authors built an official application (app) for the Zuri Fascht 2013 town festival in Switzerland, which is attended by hundreds of thousands of people. The app is able to gather 25 million GPS data during the 3-day festival. Since the deployed app needs the user's cooperation, the data collection was performed after getting the user's consent.

Natural disasters could lead to several hazardous effects. Rahman et al. (2012) developed a system for evacuation preparation purposes during disasters (especially that affect Bangladesh). In the event of a user being in any calamity zone, the application utilizes GPS to recognise the user's present position and sends this information to the system for evacuation. Likewise, Soni et al. (2014) proposed a location based early disaster warning system using Google Maps and GPS technology.

Meanwhile, Koshak and Fouda (2008) analysed pilgrims' movement during Hajj Tawaf of $1424H$ (2004 in the Gregorian calendar) by utilizing GPS and Geographic Information System (GIS). Here, the GPS devices are used to fetch the location of the movement of pilgrims at intervals of $15s$. The other related works in crowd monitoring via GPS devices can be found in Ramesh et al. (2012) and Zheng et al. (2010).

2.2.2 Via Bluetooth

Bluetooth is a low-power, short-range, cost-effective, and open protocol wireless technology for exchanging data over short distances by using short wavelengths. It works using the Industrial, Scientific and Medical (ISM) frequency band of $2.4GHz$. Since numerous individuals have Bluetooth transceivers in their smartphones, laptops, and Personal Digital Assistants (PDA) in the discoverable mode as default setting, Bluetooth technology is currently being researched for the purpose of crowd monitoring. Versichele et al. (2012a) utilized Bluetooth technology to track the crowd at the Ghent Festivities in Belgium, which is a 10 day cultural and theatre festival. They placed the static Bluetooth scanning devices in the related bounded area to extract the information of the attendees. They were able to track $152,487$ trajectories generated by $80,828$ detected attendees. Versichele et al. (2012b) also presented a technique that aided in the mobile mapping of spectators along the track of a road cycling race using Bluetooth sensors, during the "Tour of Flanders," which is a large sporting event, a road cycling race held yearly in Flanders, Belgium. Here, they utilized a vehicle furnished with two Bluetooth sensors that moved along the track, searching Bluetooth gadgets passing by them in order to map the attendees.

Besides, Weppner and Lukowicz (2013) monitored the crowd by scanning the Bluetooth devices using smartphones. They discovered the crowd density in an area of $2,500m^2$ by integrating the information from several mobile phones carried by different stationary and dynamic users. They extracted the crowd density information by analysing the collaborative features based on the ratio between values observed by different devices with a granularity of $40s$. The system was tested during the European soccer championship public viewing event in Kaiserslautern and the system is reported to achieve more than 75% recognition accuracy. Another related work can be found in O'Neill et al. (2006), in which they proposed crowd density estimation techniques by utilizing the Bluetooth scanning gadget. They fixed the Bluetooth scanning device near a narrow exit or gate in order to find the cumulative crowd density in a bounded area.

2.2.3 Via RFID

RFID is a small electronic device that consists of a small chip and an antenna. The RFID device does not need to be positioned relative to the scanner. In contrast, a RFID device can operate within a range of a few feet of the scanner. Recently, RFID is being used for coordinating universal computing and physical objects such as products, vehicles, and people. A RFID framework comprises four principal components: RFID tags, RFID readers, antennas, and a computer network used to connect the readers.

Mitchell et al. (2013) tracked the pilgrims during Hajj via RFID technology. They proposed that each of the pilgrims is given a RFID tag. Then, the RFID readers are divided into a number of regions and placed around the Hajj area. When a pilgrim passes near an RFID reader, the pilgrim's tag will be read and sent to the system in order to update the pilgrim's location. Similarly, Nair and Daniel (2014) also tracked pilgrims during Hajj using a RFID system. However, here, the authors used a micro-controller and a Zigbee transceiver (a low-cost, low-power wireless communication protocol) together with RFID readers. In addition, they proposed a heartbeat monitoring system in which they detect the heartbeat of each pilgrim in order to monitor the medical condition of the pilgrims.

The extended version of RFID, which is referred to as Wireless Identification and Sensing Platform (WISP) is presented by Mowafi et al. (2013) in order to track the crowd during large-scale gatherings. WISP extends the RFID technology by including sensing power, computing power, and enabling the storage of identity and contact information. During large-scale events, WISP readers and writers are placed in several places to collect data of crowd mobility. Other related works of implementing crowd tracking via RFID technology can be found in Mohandes (2010), Yamin and Ades (2009) and Yamin et al. (2008).

2.2.4 Via Video based

Detection of humans in any crowd scenario is the first relevant step of information extraction in video based systems. However, detecting humans in the video is a difficult task because of the intricacies inherent on dynamic human motion. Dalal and Triggs (2005) suggested that detecting humans has proven to be a challenging task because of the wide variability in appearance due to clothing, partial occlusion, and illumination conditions.

Then, the next step is to track multiple objects over time in occluded scenes and to keep a consistent identity for each target object. This is due to the fact that it can give important information about human interactions, relationships between objects of interest, and human behaviours (Li et al., 2008). Examples of video based crowd monitoring can be found in Ali and Shah (2008), Helbing et al. (2007) and Johansson et al. (2008). In addition, reviews on moving object detection and tracking via computer vision approaches can be found in Junior et al. (2010), Li et al. (2013) and Zhan et al. (2008).

2.3 Evacuation Studies via Theoretical Perspectives

In theoretical perspectives, crowd dynamic models has been classified into different types depending on how the scheme treats the pedestrians and the level of detail of the models, viz. macroscopic model, mesoscopic model and microscopic model.

2.3.1 Macroscopic and Mesoscopic Models

Macroscopic model (Colombo and Rosini, 2005; Hughes, 2002,0) consolidates the whole crowd as a single entity, while mesoscopic model (Helbing et al., 2000b; Henderson, 1971; Hoogendoorn and Bovy, 2000; Klar and Wegener, 2000; Wang et al., 2015) considers different small groups with identical characteristics. In macroscopic model, whole movement of the crowd is considered similar to fluid flow where the movement and characteristics of fluid molecules can be ignored. Flow of the whole crowd can be utilized to study the densities scattered in public transport station (Daamen, 2004), airports (Ju et al., 2007; Ma, 2013) and places of worship (AlGadhi and Mahmassani, 1991). Quite similar to macroscopic, mesoscopic model as in Wang et al. (2015) obtains general view of the crowd movement by separating the crowd into different small groups.

2.3.2 Microscopic Model

Microscopic model is considered as a complex system (Helbing et al., 2001) and it involves both physical law and characteristic of each agent in a crowd (Ma, 2013).

Through microscopic model, each agent behaviour can be simulated and emergent behaviour of whole crowd can be observed (Chen, 2006). Microscopic model which is also known as agent-based modelling or as individual-oriented, is a robust model for observing the resulting behaviour of whole crowd in a dynamic system by simulating the agent-agent interactions. Thus, the effect of crowd behaviours towards density, speed, pressure and flow of the whole crowd can only be understood when behaviour of each agent is modelled in the system. Cellular automata evacuation model, lattice gas evacuation model, social force evacuation model and game theoretic evacuation model are examples of microscopic model (Zheng et al., 2009). This sub-section presents a brief review of these models as furnished below.

2.3.2(a) Cellular Automata Evacuation Model

Cellular automata (CA) is defined as a collection of cells arranged in a grid, where the state of each cell at the next time step is decided based on its current state and those of its neighbouring cells (Wolfram, 2002). More specifically, at every time step, a definite rule determines the state of a given cell from the state of that cell and its neighbours at the preceding time step. CA models are simple, discrete, and dynamic mathematical models capable of showing complex behaviours by using simple rules. CA models use relatively simple transition rules (i.e., pedestrian movement between cells). CA model was firstly proposed in Von Neumann (1951) in order to represent the biological systems. Two neighbourhood configurations, namely, Von Neumann neighbourhood and Moore neighbourhood are utilized in CA models (Gwizdałła, 2015; Szabó and Fath, 2007; Tanimoto et al., 2010). Moore neighbourhood comprises eight cells surrounding a central cell on a two-dimensional square lattice, while Von Neumann neighbourhood embraces the four cells orthogonally surrounding a central cell on a two-dimensional square lattice. Recently, dynamics in evacuation scenarios have been investigated via CA models.

Sarmady et al. (2010, 2011) presented a new CA-based model by utilizing fine grid cellular automata in order to attain realistic agents movement. The authors simulated different movements, such as the movements of a crowd on a slope, groups of agents, and moving objects such as wheelchair. Zheng et al. (2011) proposed a CA based evacuation model to investigate how agents evacuate from a room under fire especially during fire spreading case. They studied the effect of fire spreading towards the evacuation dynamics. Their results showed that the increased in spread rate of the fire will make the evacuation process more difficult.

Besides, Zhang et al. (2013) proposed a CA based evacuation model in a stadium. Here, the agents in the stadium are divided into four types, viz. young male, young female, old male, and old female. The agent movement direction is determined by the distance of the agent to the exits, the number of agents and obstacles, as well as the density within the view field of the agent. The simulation results show the following:

(1) The agents congregate near the exit to form semicircular shapes.

(2) The agents can choose their exit on the basis of number of the agents near the exit.

Hao et al. (2014) presented an improved dynamic parameter model in order to study the mixed strategy of the agents for exit selection. They achieve this mixed strategy by amalgamating the distance-based and time-based strategies through a cognitive coefficient, which is embedded in the computation of the shortest estimated distance in the dynamic parameter model. The simulation model shows that the mixed strategy can be utilized for decreasing the evacuation imbalance which is the result of the asymmetry of exits.

Yang et al. (2014b) proposed a CA based evacuation model in order to investigate the agents' behaviours during fires in public places. Here, the authors simulated the evacuation of agents during a fire by incorporating agents of different speeds, genders and ages, viz. young, middle aged, and old. The presented model is able to demonstrate individual characteristics such as herd and following behaviour, and also the environmental effects towards agents behaviour. Other recent related works on CA evacuation model are Chen and Han (2015), Fu et al. (2012), Hu et al. (2014), Li and Han (2015), Müller et al. (2014), Nam et al. (2016), Pereira et al. (2017), Tissera et al. (2012), Wang et al. (2015a), Yuan and Tan (2011), Zheng et al. (2017) and Zou et al. (2016a).

2.3.2(b) Lattice Gas Evacuation Model

Lattice gases are a type of cellular automata used in fluid flow. Wolfram (1984) in 1980s has popularized this lattice gas model and later in 2002 by (Fredkin and Toffoli, 2002). In lattice gas models, each agent is considered as an active particle on the grid. Lattice gas model can be utilized in order to examine the features of the agents in crowd by the means of probability and statistics.

Several characteristics of the crowd that have been studied by using lattice gas models are as follows:

- Simulation of the crowd exit flow from a hall (Tajima and Nagatani, 2001).
- Simulation of the agent flow at a bottleneck by using lattice gas models of biased-random walkers (Tajima et al., 2001).
- Simulation of the agent flow in the T-shaped channel (Tajima and Nagatani, 2002).
- Simulation of the counterflow of crawlers in a different floors (Nagai et al., 2005).
- Simulation of the egress process through an exit (Takimoto and Nagatani, 2003).
- Simulation of the evacuation of walkers and crawlers from a corridor with an exit (Nagai et al., 2006).
- Simulation of the egress process from a classroom (Helbing et al., 2003).
- Simulation of the egress process from a dark room with a few exits (Nagai et al., 2004).
- Simulation of the egress process from a smoky room (Isobe et al., 2004)

Other recent related works on lattice gas evacuation model are Guo et al. (2013), Yu et al. (2014) and Zou et al. (2016b).

2.3.2(c) Social Force Evacuation Model

Helbing and Molnar (1995) presented social force model for agent (pedestrian) movement. The idea behind social force is to find a set of basic rules based on behavioural aspects. Each agent is affected by four major factors:

- Agent's goal is to arrive at certain preferred destination.
- Agent wants to be not so close with other neighbouring agents.
- Agent also wants to be not so close with wall and borders.
- Agents' each other attractions.

Helbing and Molnar (1995) determined the sum of effect towards agent α by,

$$\mathbf{F}_\alpha(t) = \mathbf{F}^0_\alpha(\mathbf{v}_\alpha, v^0_\alpha \mathbf{e}_\alpha) + \sum_\beta \mathbf{F}_{\alpha\beta}(\mathbf{e}_\alpha, \mathbf{r}_\alpha - \mathbf{r}_\beta) + \sum_B \mathbf{F}_{\alpha B}(\mathbf{e}_\alpha, \mathbf{r}_\alpha - \mathbf{r}^\alpha_B) + \sum_i \mathbf{F}_{\alpha i}(\mathbf{e}_\alpha, \mathbf{r}_\alpha - \mathbf{r}_i, t) \tag{2.1}$$

The first term in Equation 2.1 is the agent's goal to arrive at certain preferred destination. The second and third term in Equation 2.1 are sum of the repulsion forces towards other agents β and borders B respectively, while the fourth term in Equation 2.1 refers to agents' each other attractions.

Then, Helbing et al. (2000a) extended the social force model in order to be able to simulate the egress panic. The extended social force model is determined by the acceleration equation and will be explained later in Chapter 4. This extended social force model (Helbing et al., 2000a) is further developed by researchers in order to study the problem of crowd evacuation. For example, Parisi and Dorso (2005) have utilized the social force model (Helbing et al., 2000a) in order to examine the egress flow of the room with a single exit; later they modified slightly the social force model for simulating the evacuation process under panic (Parisi and Dorso, 2007). Other recent related works on social force evacuation model are Gao et al. (2016), Li et al. (2015b), Ren et al. (2014), Yang et al. (2014a) and Zeng et al. (2014).

2.3.2(d) Game Theoretic Evacuation Model

Game theory for evacuation model was started by Lo et al. (2006) where the authors implemented game theory model for exit selection during evacuation scenario. They have studied competitive behaviour by assuming that evacuees are selfish in a non-cooperative game. One of the drawbacks of the model is that they have assumed that all evacuees are rational during the fire scenario, while in real cases, most of the evacuees tend to be panic. Ehtamo et al. (2010) also presented exit selection model for evacuation based on agents' best response. They have added the patience parameter in order to study the minimal time for the agents to find the alternate exit. They have found that patience parameter affects the time required to achieve equilibrium.

Another interesting work using game theory for evacuation was done by Zheng and Cheng (2011). They have combined game theory with floor field cellular automata where only one agent can go through the exit and each person can take one of the three possible strategies, *polite*, *normal* and *vying*. The payoff table for these strategies can be seen in Table 2.1. In Table 2.1, b is the benefit for the agent to reach the preferred destination and is set to 1, while c is the conflict cost which represents the degree of emergency. c is set to 0 in order to represent highest emergency degree, while c is set to 10 in order to indicate lower emergency degree. Pure strategy Nash Equilibrium of this game is to play *polite* when the other is playing *vying* and vice versa. Another pure strategy Nash Equilibrium is to play *normal* when the other is playing *vying* and vice versa. A probability of mixed-strategy Nash equilibrium is $(0, 2c/(2c+b), b/(2c+b))$, which means zero for *polite* strategy, $2c/(2c+b)$ for *normal* strategy and $b/(2c+b)$ for *vying* strategy, where b represents the benefit of arriving at preferred destination while c represents the cost of competition.

Table 2.1: Payoff table as in Zheng and Cheng (2011).

Player 1 / Player 2	**Polite**	**Normal**	**Vying**
Polite	$0,0$	$0,b$	$0,b$
Normal	$b,0$	$b/2,b/2$	$0,b$
Vying	$b,0$	$b,0$	$-c,-c$

In Hao-Nan et al. (2014), the authors discussed game theory strategies update in evacuation circumstances. They explored the probability equation of evacuees moving to the next step in cellular automata simulation related to the position of exit. Bouzat and Kuperman (2014) have utilized game theory coupled with lattice gas models in order to analyse characteristic features of agents, viz. cooperative and defective behaviours confined to an indoor evacuation scenario. Their results indicated that under certain conditions, cooperators could evacuate more rapidly due to mutual cooperation. Research work proposed by Heliövaara et al. (2013) and von Schantz and Ehtamo (2015) consider a spatial evacuation game, where the agents interact with their nearest neighbours by choosing either patient or impatient strategic options. Two games are discussed viz. Prisoners Dilemma and Hawk-Dove, which depend on how far the agents are located from the exit. Further, the agents choose their best response strategies depending upon observing the previous strategy chosen by their opponents. Other related work on evacuation modelling and simulation via game theory can be found in

Chizari et al. (2013), Dossetti et al. (2017), Pärnänen (2015), Shi and Wang (2013), Sun et al. (2010), Suryotrisongko and Ishida (2011) and Zheng and Cheng (2011b). Next section provides a brief overview of recent evacuation models under uncertainty that have evolved in the recent decade.

2.4 Evacuation Models under Uncertainty

Evacuation models reviewed here are based on the Soft Computing (SC) approaches, viz. fuzzy logic, neural computing, probabilistic graphical models, and evolutionary computing. This is due to the existence of similarities between evacuation scenario and guiding principles of SC techniques. Ramík (2001) has stated that the guiding principle of SC in order to achieve robust and low-cost solutions is by solving the uncertainty, imprecision, partial truth, and approximation problems. Meanwhile, typical evacuation scenarios inherit these types of limitations. For example, the uncertainty behaviour of crowd is unavoidable during any evacuation scenario, especially during emergency evacuation. We can almost never predict with certainty what will happen during such scenario.

2.4.1 Fuzzy Logic Evacuation Models

Fuzzy Logic (FL) based approaches intend to counter uncertainties inherent in subjective domains such as crowd dynamics and crowd evacuation by making use of intuitive decision rules that are otherwise hard to express using the conventional Boolean logic. This sub-section will describe some typical FL based approaches relevant to the evacuation mechanisms of human crowd. Zhu et al. (2008) have proposed a fuzzy modelling approach to simulate and analyse potential factors such as evacuation time