EXTENDED CELLULAR AUTOMATA SIMULATION MODEL FOR FIRE CROWD EVACUATION

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EXTENDED CELLULAR AUTOMATA SIMULATION MODEL FOR FIRE CROWD EVACUATION

by

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بسم الله الرحمن الرحيم

{نَرْفَعُ دَرَجَاتٍ مَّن نَّشَاءُ وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ} (76- سورة يوسف)

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LIST OF ABBREVIATIONS

ABM	Agent Based Model
CA	Cellular Automata
CO_2	Carbon dioxide
CO	Carbon Monoxide
CPU	Central Processing Unit
CF_{ij}	Congestion Parameter
DPM	Dynamic Parameters Model
D_{ij}	Distance Parameter
E_{ij}	Empty Parameter
FIFO	First-In, First-Out
F_{ij}	Fire Spreading Parameter
GIS	Geographic information system
GPS	Global Positioning System
V_{max}	Maximum Velocity
M	Matrix
M/S	Metre Per Second
N	Newton
PDEs	Partial Differential Equations
PC	Personal Computer
R_{ij}	Path Parameter
QN	Queuing Network Model
RCA	Real Coded Cellular Automata
RBM	Rule Based Model
RFID	Radio Frequency Identification
R	Radius
SA	Simulated Annealing
SFM	Social Force Model
P_{ij}	Transition Payoffs
2D	Two Dimensional
3D	Three Dimensional
VO	Velocity Obstacles

MODEL SIMULASI AUTOMATA SELULAR DIPERLUAS UNTUK EVAKUASI GEROMBOLAN SITUASI KEBAKARAN

ABSTRAK

Beberapa tahun kebelakangan ini, pemindahan orang ramai apabila berlaku kemalangan kebakaran telah menarik perhatian. Kemalangan kebakaran yang berlaku di bangunan sesak boleh menyebabkan korban jiwa. Kajian mengenai evakuasi orang ramai adalah perlu untuk meminimumkan kehilangan nyawa dan harta benda. Kebakaran besar menimbulkan bahaya; oleh itu, simulasi komputer dijalankan sebagai alat alternatif untuk mengatasi kekurangan dalam menjalankan eksperimen evakuasi kebakaran yang sebenar. Para penyelidik telah mensimulasikan pergerakan pengungsi dalam situasi panik, seperti kebakaran, menggunakan model automata selular (CA) untuk meramalkan dan menganalisis tingkah laku pengungsi semasa situasi panik ini. Ini dapat membantu mengurangkan kemalangan dan menyelamatkan nyawa. Walau bagaimanapun, para penyelidik tersebut telah menyiasat kemalangan kebakaran dalam senario statik atau menyebarkan bentuk depan bulat api yang tidak tepat, seperti penggunaan bentuk depan api persegi. Mereka juga telah menerapkan banyak batasan pada faktor lingkungan dan kemalangan, seperti lokasi kebakaran, kecepatan penyebaran api, rintangan, yang dapat menunjukkan pergerakan pengungsi tampak tidak realistik. Di samping itu, model-model yang digunakan oleh para penyelidik itu mengabaikan kesan tekanan orang ramai yang berlaku pada pengungsi di sekitar pintu keluar yang sesak semasa evakuasi kebakaran. Dalam penyelidikan ini, teknik pergerakan api spiral diadopsi menggunakan model CA untuk mensimulasikan bentuk penyebaran permukaan lingkaran api, yang menunjukkan tingkah laku penyebaran api non-statik yang dapat menganggarkan jumlah mangsa yang cedera atau cedera akibat

kebakaran. Sebagai tambahan, parameter CA yang diperluas (penyebaran api, kesesakan dan laluan), set formula matematik, diperkenalkan untuk mensimulasikan keputusan yang diambil para pengungsi dari segi pergerakan dan pertimbangan serta pilihan tindakan mereka. Teknik baru untuk meramalkan tekanan orang ramai dalam kumpulan yang ramai juga dicadangkan. Teknik ini dapat membantu dalam mengukur purata jumlah mangsa semasa pemindahan mangsa apabila berlaku kebakaran. Hasil eksperimen menunjukkan bahawa purata masa evakuasi, waktu evakuasi unit dan jarak perjalanan ketika pengungsi adalah 201.20 langkah masa, 0.50 langkah masa dan 28204 langkah, masing-masing dibandingkan dengan Yue et al. (2011) (201 langkah masa, 0.50 langkah masa dan 34994 langkah), yang dianggap sebagai hasil terbaik dalam literatur. Di samping itu, hasil eksperimen juga menunjukkan bahawa purata kematian orang ramai adalah 20.72 orang apabila parameter yang dicadangkan diaktifkan dibandingkan dengan model Yue et al. (2011) (104.76 orang). Hasil ini menunjukkan model yang dicadangkan dengan parameter yang ditambah lebih baik untuk mengurangkan jumlah kematian orang ramai dalam keadaan yang padat semasa proses evakuasi kebakaran.

EXTENDED CELLULAR AUTOMATA SIMULATION MODEL FOR FIRE CROWD EVACUATION

ABSTRACT

In recent years, crowd evacuation in case of fire accidents has attracted considerate attention. Fire accidents occur in crowded buildings may cause heavy casualties. The study of fire crowd evacuation has become extremely necessary to minimize the loss of life and property. Large fires pose dangers; hence, computer simulations are conducted as alternative tools to the deficiencies in conducting actual fire evacuation experiments. Researchers have simulated evacuees' movements in panic situations, such as fires, using the cellular automata (CA) model to predict and analyze evacuees' behaviors during these panic situations. This could help minimize accidents and save lives. However, those researchers have either investigated fire accidents in a static scenario or propagate inaccurate fire circular fronts shape, such as the adoption of a square fire front shape. They have also applied a lot of constraints on the environmental and accident factors, such as fire location, fire spread speed, obstacles, which could show evacuees movements appeared unrealistic. In addition, the models used by those researchers ignored the effects of crowd pressure applied on evacuees around overcrowded exits during fire evacuation. In this research, the spiral fire movement technique was adopted using CA model to simulate the fire circular surface propagation shape, which presents a non-static fire-spreading behavior that able to estimate the average number of evacuees could be injured or killed by fire. In addition, the new extended CA parameters (fire spreading, congestion and path), the set of mathematics formulas, were introduced to simulate the decision-making of evacuees in terms of movements and judgments and their choices of actions. A new

technique to predict of the crowd pressure in a dense crowd was also proposed. This technique could help in measuring the average of crowd victims during fire evacuation. The experiment results showed that the average of evacuation time, unit evacuation time and travel distance when evacuees were 201.20-time steps, 0.50-time steps and 28204- steps, respectively compared to Yue et al. (2011) (201-time steps, 0.50-time steps and 34994-steps), which considered the best result in literature. In addition, the results also showed that the average of crowd deaths is 20.72 persons when the proposed parameters were activated in comparison with Yue et al. (2011) model (104.76 persons). Such results indicate the proposed model with extended parameters is effectively better in reducing number of crowd deaths in a dense crowd during fire evacuation.

CHAPTER 1

INTRODUCTION

1.1 Problem Background

Crowd can be defined as a group of evacuees gathered in a place for similar or sometimes different purposes. Crowds are present in most of the public places, such as shopping malls and stadiums as well as open areas like parks and they have become an inseparable part of our daily life. In such places, size and density are considered other important specifications of crowd Li et al. (2020c). In fact, larger crowds are harder to manage and because of the collective forces of the evacuees in such a crowd, dangerous accidents are more likely to happen, which will cause numbers of injuries and deaths (Lu et al., 2016).

In accidents (e.g. fire, earthquake, flood or a terrorist attack), where decisions should be made quickly under duress it is likely for evacuees to lose their ability to act logically and decide the appropriate mode of behavior on their own (Stroehle, 2008). Evacuees, therefore, may show different behaviors pertaining to critical situations. Crying, yelling, pushing, and shoving are examples of such behaviors. In such a situation, evacuee may be tried to find the escaped exit by own self or tend to follow others resulting to some of crowd behaviors, such as followers and leader, herd and clustering behaviors, faster-is-slower or arching formation (von Schantz and Ehtamo, 2019). These behaviors sometimes drive evacuees to escape fast. Yet, it will cause an over-crowded situation around some exits, in return. Meanwhile, other exits will be ignored and unutilized efficiently (Helbing et al., 2002). Subsequently, the congestion and physical interactions among evacuees expand around some exits more than others, which will cause numbers of injuries and death during evacuation (Helbing and Johansson, 2013).

In recent years, crowd evacuation in case of fire accidents has attracted considerate attention. This is because the fire includes factors (e.g. fire temperature, fire spread rate and smoke) should be considered alongside with crowd behaviors during evacuation. Smoke, for instance, can affect evacuees in two ways: first, smoke contains some poisonous products, such as carbon monoxide (CO), which are harmful to evacuees' health (Cao et al., 2014, Yamamoto and Takeuchi, 2019). Second, smoke soot reduces the visibility significantly, delays escape of the evacuees in comparison with normal environment and driving them to be exposed to the products of combustion for an unacceptably long period of time, which often leads to high mortality (Nguyen et al., 2013, Richardson et al., 2019). Factually, most of fire victims die from the poisonous smoke, not from the flames. It has been reported that inhalation injury from smoke and the noxious products of combustion in fires may account for about 60% –80% of fire-related deaths (Stamyr et al., 2012). Table 1.1 provides a list of well-known severe fire accidents in history along with the corresponding casualties and losses.

Table 1.1 List of Notable Fire Accidents that Occurred from 2000 through 2019

Year	Casualties	Condition	Location	Reference
2000	235	Kanungu church fire	Kanungu, Uganda	(Services, 2000)
2001	291	Fire in Mesa Redonda shopping Center	Lima (Peru)	(Nguyen, Ho, & Zucker, 2013)
2002	1100	Lagos armory explosion	Lagos, Nigeria	(Siollun, 2013)
2003	192	Daegu subway fire	Daegu, South Korea	(Hong, 2004)
2004	370	Ycuá Bolaños supermarket fire	Asunción, Paraguay	(Benson, 2004)
2005	122	Eyre Peninsula bushfire	South Australia	(List of fires, 2016)
2006	100	A fire that swept through large tents packed with consumers visiting a trade fair in Victoria park	Meerut, India	(Kumar, 2006)
2007	101	Methane explosion in Zasyadko coal mine	Donetsk, Ukraine	(News Agency, 2017)
2008	100	NNPC oil pipeline explosion, which blasted a primary school at Ijegun	Ijegun, Nigeria	(Esiri, 2008)
2009	156	Perm Lame Horse club fire	Perm, Russia	(Valentine, 2009)
2010	117	A fire in the city of Dhaka	Dhaka (Bangladesh)	(Nguyen et al., 2013)
2011	94	AMRI hospital fire	Kolkata, India	(Polgreen & Kumar, 2011)
2012	361	Comayagua prison fire	Comayagua, Honduras	(Moran, 2012)
2013	233	Nightclub fire	Brazil	(Darlington, Brocchetto, & Ford, 2013)
2014	340	Soma mine disaster	Manisa, Turkey	(Lowen, 2015)
2015	173	Tianjin explosions	Tianjin, China	(JING, 2016)
2016	111	Puttingal Temple Fire in Paravur	Kollam, India	(Surendran, 2016)
2017	126	Fire at the Philippine factory complex	Manila, Philippine	(Associated Press, 2017)
2018	137	Fire at fire at the Sejong Hospital in the South Korean city of Miryang	Miryang, South Korea	(Taehoon, 2018)
2019	75	Cairo train station fire	Cairo, Egypt	(Lewis & Saba, 2019)

Based on Table 1.1, the study of evacuation has become extremely necessary to minimize the loss of life and property. Large fires pose dangers; hence, real fire evacuation experiments are not possible to be conducted. Therefore, with the development of computer technology, computer simulation has become an important and feasible tool. Simulation of evacuee movement in panic situations, such as in fire disasters, will help us predict and analyse evacuee behaviour during these emergency situations. In these situations, careful preparation, procedure and monitoring could help minimize accidents and could possibly save lives.

Over the past few decades, researchers have employed various models to imitate the human behaviour of evacuees during the emergency situations, such as fire disaster. Social forces model, agent-based model, velocity obstacles, rule-based model and cellular automaton models are examples of such models. These models are deemed the most commonly used to simulate the decision-making of evacuees in terms of movements and judgments on their surrounding conditions and their choices of actions (e.g. stepping back, moving ahead, backtracking, switching lanes, waiting, and interaction avoidance with fire and infrastructure such as walls) during evacuation. There are various pros and cons of applying each of the abovementioned models. Based on the specific requirements and simulation scenario, one model can be more suitable than the others.

At present, a significant number of researchers are using the methodology of cellular automaton models (CA), which considers simple, discrete and dynamic mathematical models capable of displaying complicated behaviour by using simple rules. These simple CA rules describe the behaviour of each automaton and can create an approximation of actual individual behaviour. Thus, many collective crowd behaviours (e.g. arching, clogging, herding behaviour, friction effects, competitive egress behaviour, faster-is-slower, counter flow and bi-direction behaviour) can be simulated with a lower computational cost and achieve very good simulation results (Zheng et al., 2009, Wang and Wang, 2017). As such simulations with very large number of evacuees are possible on even normal personal computers (Sarmady, 2014). The CA models also allows users to observe more details about behaviours of evacuees in different situations (e.g. emergency evacuation) and their interactions with fire, obstacles and building elements, as well as flow, density, and speed. A good understanding of the emergent patterns is required to predict how evacuee flow will behave under different panic situations, such as fire disasters. Consequently, a suitable plan enabling the control of fire spreading and providing sufficient time for evacuees to evacuate safely can be proposed.

1.2 Challenges of the Existing Evacuation Models

The challenges of the existing evacuation models are recognized and thoroughly investigated by a critical analysis of literature on the fire front propagation techniques, fire evacuation models, cellular automata dynamic parameters models and crowd pressure modelling in a moving dense crowd. After that, these challenges are classified into the three main categories as follows:

1.2.1 The Existing Fire Evacuation Models

The existing fire evacuation models (Zheng et al., 2019, Choi et al., 2018, Shuaib, 2018) ignored the main elements, including fire spreading nature, fire surface shape, fire spread speed and crowd pressure that should be considered. Thus, a comprehensive understanding of individual behaviours when fire accidents occur is not provided.

As for modelling the fire surface shape, the existing fire evacuation models propagate inaccurate fire circular fronts shape, such as (Zheng et al., 2017, Yamamoto and Takeuchi, 2019) the adoption of a square fire front shape, which is not similar to actual fire spreading. Thus, fire shape is questioned and determining the actual fire shape could demand a significant amount of computer memory and computation time. Researchers who previously simulated the fire-spreading process in their models have depended on either partial differential equation (PDEs) or Rothermel's equations to simulate the fire spreading. These methods demand a high amount of computer memory and computation time (Clymer, 1993). The previous models, therefore, either propagate an inaccurate fire shape or demand staggering amounts of computer memory and computation time (Clymer, 1993, Finney, 1995, Karafyllidis and Thanailakis, 1997). Cellular automata (CA) models can simulate a fire circular fronts shape during the fire spreading more accurately with lesser computer memory and computation time compared with partial differential equation (PDEs) and Rothermel's equations. Unfortunately, the proposed models in (Encinas et al., 2007, Sirakoulis et al., 2005) have not been applied to the fire evacuation scenario. Most of these models have been applied to forest fires to enhance the effectiveness of firefighting strategies.

Further, the previous fire evacuation models, such as (Yamamoto and Takeuchi, 2019, Wang and Wang, 2016) have been applied a lot of constraints on the environmental and accident factors, such as fire location, fire's spreading feature, fire spreading rate, smoke, internal obstacles, the number of exits, exits width and evacuee distribution, which could show evacuees movements appeared unrealistic. These models also have chiefly assumed that evacuees are homogeneous individuals with the same characteristics in term of stamina and durability of body to tolerate the high fire temperature during the fire disaster, which conflict with reality and simulation. Homogeneity in the discussion here means that all evacuees have the same characteristics and available actions at any given state and the actions have the same effects regardless of which evacuees perform them (De Masellis and Goranko, 2020, Pedersen and Dyrkolbotn, 2013). Meanwhile, heterogeneous usually means that a crowd consists of individuals from all ages, gender, and different social and cultural realities, where decisions and actions can vary from one to another and differently influence crowd evolution (Sighele and Lima, 1954, Cassol et al., 2017).

In addition, most of the existing fire evacuation models (Yamamoto and Takeuchi, 2019, Zheng et al., 2019) have ignored effect of crowd dense forces and pressure applied on evacuees around congestion exits in a moving dense crowd. As a result, the average number of crowd victims during the fire evacuation will not be measured accurately. These factors also play a major role in estimating and computing the following variables accurately: fire and crowd death toll, crowd pressure, congestion points, evacuation time, unit evacuation time; and travel distance during fire evacuation in overcrowding situations.

Lastly, some of the existing fire evacuation models (Boonngam and Patvichaichod, 2020, Hennemann et al., 2018) considered evacuation time, unit evacuation time or travel distance as main measures of performance when assessing the evacuee evacuation or quality of layout design during the evacuation. They have ignored other fire variables, such as number of evacuees who escaped safely, number of evacuees injured and killed by fire or crowd pressures and number of evacuees stuck inside layout. Resultantly, the evacuee evacuation process and quality of layout design will not be assessed accurately during fire the evacuation.

In real scenarios, a fire inside a room could kill most of the evacuees inside. Few, for instance, will be able to escape and evacuate safely. Following the previous models, if such an accident is simulated, the evacuees' flow rates will be satisfactorily smooth and evacuation time will be markedly short. Such results contradict with reality as the average number of fatalities are very high. Subsequently, evacuees' evacuation time, unit evacuation time and travel distance will be decreased in response to the reduction in the total number of evacuees during the accident. As well, the average of evacuees' flow rate could be increased due to the limited number of remain evacuees existing inside the room. The evacuation time, unit evacuation time, travel distance and flow rate, therefore, cannot be estimated and computed accurately. As a consequence, the quality of design layout configuration and overall movement of evacuees will not be evaluated accurately during fire evacuation.

1.2.2 Evacuation Simulation based on Cellular Automata Dynamic Parameters Models

The existing evacuation simulations relied on cellular automata dynamic parameters models (DPM), such as (Zhu, 2018, Zhu et al., 2018, Yue et al., 2011, Hao et al., 2014) cannot avoid congestion around exits inside room with internal obstacles in the fire evacuation scenario. This is mainly because if the fire accident point happens near any exit and killed all evacuees around that exit then the evacuees who gathered around alternative ones are either will change their directions moving toward the burnt exit ignoring effects of the fire burning area, where all of them will be caught and killed by the fire. Or they will keep moving in their positions reflecting their hesitations and oscillations fearing the danger of fire around the burnt exit. While fire keeps on spreading, hesitations and oscillations of evacuees around alternative exits will be increased. Such simulation results may indicate negatively to the evacuation process in a way that contradicts reality.

The existing cellular automata dynamic parameters models also cannot prevent stuck cases of evacuees within dead-end route (i.e. cul-de-sac) inside layout with internal obstacles during evacuation (Yue et al., 2012b). In this regard, these models have been applied constraints on obstacles shapes, sizes, locations, and arrangement inside the layout (Yue et al., 2012b, Zhu et al., 2018). By doing so, the cul-de-sac areas caused by the bad configuration of these obstacles will not be created. This is because these models lacking to any mechanism or technique to make evacuees to determine the locations of these cul-de-sac areas and avoid evacuees to stuck within these areas during the evacuation. Consequently, if one or two of evacuees being stuck within these cul-de-sac areas for an unacceptably long period. Then, the average of evacuation time, unit evacuation time, travel distance, and congestion points will be greatly increased. Following the previous models, such as (Hennemann et al., 2018, Zuriguel et al., 2020, Zhu, 2018) when the average of evacuation time, unit evacuation time, and travel distance are long that mean the agents flow is not going to be smooth. Arching and jamming around exists will create a lot of congestion points decreasing the average of agents who may escape safely. In addition, a significant increase of unnecessary movements will take place. These movements are consequences of hesitations and oscillations around overcrowded exits demonstrated by the panic egress behaviours. Such a finding may indicate negatively to the evacuation process in a way that contradicts reality as only few evacuees being stuck inside layout during the evacuation (see Section 4.4.4.2 for a detailed clarification).

1.2.3 Simulation of Crowd Contact Forces and Pressure in a Moving Dense Crowd

Most of crowd pressure models (von Schantz and Ehtamo, 2019, Haghani et al., 2019, Wang et al., 2015, Henein and White, 2004, Wang et al., 2019, Li et al., 2019b, Jebrane et al., 2019) support few dense crowd features like pushing in dense crowds that result into falling, trampling and possibly stampede without considering other crowd features, such as shockwave effects, crushing and overtaking behaviours, competitiveness, durability and stamina of body to tolerate the high pressure in a moving dense crowd. They also cannot properly take fully high-pressure and shockwave propagation characteristics into account (Zheng et al., 2009, Li et al., 2019b, Wang et al., 2019), in a moving dense crowd during the evacuation. Thus, the following variables will be affected: crowd death toll, crowd pressure, evacuation time, unit evacuation time; and travel distance during the evacuation. Finally, none of previous crowd pressure models have been applied to fire evacuation scenarios. In fire evacuation, the crowd behaviour around congestion exits (e.g. crushing, pushing, shuffling, trampling, arching, clogging, and simultaneously rushing toward exits) itself may cause killings or injures (Zheng et al., 2009).

Further, most of the previous models carried out in empty layouts without considering the effect of obstacles during evacuation (Jebrane et al., 2019, Cornes et al., 2017). These simulations, therefore, neglected the significant role of obstacle shape along with its size, resistance and location in front of exits in conjunction with evacuees' speed during evacuation. This is because unsuitable shape of the obstacles (e.g. rectangle, square and longitudinal shapes) along with unsuitable size and location (e.g. in front of exits) may lead to increase the average of crowd pressure applied on evacuees around these obstacles, which enhances the possibility of getting crushed to death during the evacuation.

Finally, none of previous crowd models have been applied to fire evacuation scenarios. A number of studies, however, has been conducted on fire evacuation scenarios in inhabited areas assessing the panic feelings among the involved evacuees. Nevertheless, these studies have not examined the important role of crowd pressure applied on evacuees around overcrowding exits during a fire evacuation. In emergency situations, the crowd behaviour (e.g. crushing, pushing, shuffling, trampling, arching, clogging, and simultaneously rushing toward exits) itself may cause killings or injures (Zheng et al., 2009). In fire disaster, therefore, evacuees could be caught and killed by the fire, suffocation by the smoke poisonous gases like CO_2, or they are getting crushed to death around congestion exits during the evacuation.

1.3 Problem Statement

The challenges discussed in Section 1.2 revealed the factors impacting fire evacuation modelling during the emergency which mainly focused on modelling the fire surface shape, crowd dense forces and the decision making of evacuees and judgments on their surrounding conditions and their choices of actions during the fire evacuation. These actions include stepping back, moving ahead, switching lanes, waiting, exit selection behaviour evacuation and interaction avoidance with fire, obstacles and walls. Driven by the challenges discussed in Section 1.2, the deficiencies in current evacuation models can be classified as follows:

The existing fire evacuation models propagate inaccurate fire circular fronts propagation shape, such as (Zheng et al., 2017, Yamamoto and Takeuchi, 2019) the adoption of a square fire front shape, which is not similar to actual fire spreading. Cellular automata (CA) models can simulate a fire circular fronts shape during the fire spreading process accurately (Encinas et al., 2007, Sirakoulis et al., 2005). Unfortunately, the proposed CA models have not been applied to the fire evacuation scenario. Most of these models have been applied to forest fires to enhance the effectiveness of firefighting strategies. Thus, a suitable evacuation plan that enables the control of fire spreading and provide enough time for evacuees to evacuate safely during the fire cannot be proposed. The greater the impact is, of course, the number of fire injuries and deaths will be markedly increased during the evacuation.

Next, researchers have modelled evacuee evacuations in different emergency situations based on the cellular automata dynamic parameters models (Zhu et al., 2018, Yue et al., 2011, Hao et al., 2014, Zhu, 2018). These models involves several dynamic parameters reflecting various considerations of evacuee movement (e.g. destination of movement, crowdedness of the neighbourhood etc.), evacuees choose to move to one of their neighbouring cells in the following time step based on the value of a quantity called transition payoff, which is the summation of several dynamic parameters considering of direction of movement, configuration of the vision conscious field etc. These parameters, therefore, have an important role in simplifying the decision making of evacuees and judgments on their surrounding conditions and their choices of actions (e.g. selecting the safe exit, which has the lowest jam levels) during the evacuation. However, the existing cellular automata dynamic parameters models unable to prevent stuck cases of evacuees within dead-end route (cul-de-sac) inside the room with internal obstacles during the evacuation. Consequently, evacuation simulations relied on cellular automata dynamic parameters models are either carried out in empty layouts or applied different constraints on obstacles or cul-de-sac areas inside layout (Yue et al., 2012b, Zhu et al., 2018), which could show evacuees movements appeared unrealistic. As a consequence, the following variables will be affected: evacuation time, unit evacuation time; and travel distance during the evacuation. Finally, the previous cellular automata dynamic parameters models, such as (Zhu, 2018, Hao et al., 2014, Yue et al., 2011) have not been applied to fire evacuation scenario. In fire evacuation, the congestion around overcrowding exits itself may cause killings or injures (Zheng et al., 2009).

Lastly, most of the previous crowd pressure models, such as (Henein and White, 2004, Cornes et al., 2017, Jebrane et al., 2019, Wang et al., 2019, von Schantz and Ehtamo, 2019) carried out in empty layouts without considering the effect of obstacles during evacuation. These models, therefore, neglected the significant role of obstacle shape along with its size, resistance and location in front of exit in conjunction with evacuees' speed during evacuation. They also have chiefly assumed that evacuees are homogeneous individuals with the same characteristics includes age, speed, competitiveness, pushing forces, resist forces, stamina and durability of body to tolerate high crowd pressures in a moving dense crowd. This assumption conflicts with reality and simulation. That is, the real crowd consists of individuals from all ages, gender, and different social and cultural realities, where decisions and actions can vary from one to another and differently influence crowd evolution. Further, the previous crowd pressure models, such as (von Schantz and Ehtamo, 2019, Haghani et al., 2019) support few dense crowd features like pushing in dense crowds that result into falling, trampling and possibly stampede without considering other crowd features, such as human and obstacles resistances, shockwave effects, crushing and overtaking behaviours, competitiveness, durability of body to tolerate the high pressure in a moving dense crowd and stamina. They also cannot properly take fully high-pressure and shockwave propagation characteristics into account (Zheng et al., 2009, Li et al., 2019b, Wang et al., 2019) in a moving dense crowd during evacuation. For instance, the crowd pressure model proposed by Henein and White (2004) relied on the Von Neumann configuration that offers limited movement options for evacuees (four neighbourhoods) that make evacuees walk in long routes to reach exits located on the opposite sides, which show evacuees movements appeared unrealistic. Such a movement will lead to create lot of empty spaces within arching around congestion exits. These empty spaces may have negative impact on propagation characteristics of evacuee shockwave in a dense crowd. Thus, the following variables will be affected: crowd death toll, crowd pressure, evacuation time, unit evacuation time; and travel distance during the evacuation. Finally, none of previous crowd pressure models have been applied to fire evacuation scenarios. In fire evacuation, the crowd behaviour around congestion exits (e.g. crushing, pushing, shuffling, trampling, arching, clogging, and simultaneously rushing toward exits) itself may cause killings or injures (Zheng et al., 2009).

1.4 Research Objectives

The key objectives of this research are outlined as follows:

1. To propose fire crowd evacuation model for circular shape fire spreading surface propagation on cellular automata model using homogenous evacuee simulation.

2. To propose extension of cellular automata parameters for an improved homogenous evacuees' movement for fire crowd evacuation models.

3. To propose dense crowd forces and heterogenous evacuees' movements for a better crowd victims estimation during fire evacuation.

1.5 Research Contributions

The key contributions of this research are outlined as follows:

1. The spiral movement technique for simulating a fire circular fronts propagation shape on cellular automata model using homogenous evacuee simulation.

2. The new three parameters (fire spreading, congestion, and path) are introduced to simplify the decision making of evacuee movements and chaotic behaviours during the fire evacuation in a moving dense crowd.

3. A new crowd dense forces model to predict of the crowd pressures acting on heterogeneous evacuees during collisions in a moving dense crowd under fire by incorporating the main dense crowd features based on cellular automata model.

1.6 Study Scope and Significance

Modelling fire evacuation involved numbers of various environmental and accident factors, which pose a challenge in solving the respective problem. Thus, the scopes and limitations have to be made transparent to ensure the study to be manageable. The scopes and limitations of this study are given as follows:

- This study assumes that the space of the floor plan (i.e. room, corridor, etc.) on a discrete $W \times W$ cells of a grid in a two-dimensional system. Thus, the fire evacuation simulation components, such as agents (evacuees), obstacles, walls, and fire are mapped out on a discrete $W \times W$ cells of a grid in a two-dimensional system.
- This study considers only effects of fire temperature and smoke poisonous toxic gasses, while neglecting the effect of smoke soot in reducing the visibility of evacuees leading them to wait for long time that enables the fire to catch and kill them or cause asphyxiation.
- This study considers only three shapes of obstacles that are square, rectangle and longitudinal shapes without considering other shapes (e.g. circular and elliptical shapes) and its effects in decreasing resistance against evacuee flow during evacuation in overcrowding situations.
- This study assumes that evacuees have same body size without considering the difference among evacuees' body sizes and its role in predicting of the

pressure and the crowd forces generated during collisions of evacuees in a moving dense crowd.

- This research does not consider other factors, such as heights, slopes, and winds on increasing/decreasing of the fire rate of spread during evacuation.

This research is considered crucial as it attempts to bridge the gaps in understanding, predicting and preventing dangerous crowd phenomena and possibly saving lives. The outcome of the proposed fire evacuation model can help managers, planners, and architects understand, predict and prevent possible risks during the fire evacuation in large gathering buildings early in the planning of such facilities. Managers of large events can also use simulations to enhance their understanding of how to control crowd movements in different emergency situations. In these situations, careful preparation, procedure and monitoring can help minimize accidents and possibly save lives.

1.7 Outline of the Thesis

This thesis is organized into six chapters. Brief descriptions of the content of each chapter is given as follows:

(I) Chapter 1 of the thesis begins with a discussion of the problem background, challenges, objectives, contributions, scopes, and significance of the research topic in general.

(II) Chapter 2 outlines the state-of-the-art and challenges posed in the domain problems. This chapter also provides some insight of the theoretical background of the focused domain problems trends, and directions that motivate the pursuit of this study.

(III) Chapter 3 describes the research methodology employed in this research including the research framework, CA-based agents simulation model, the new extended cellular automata parameters (i.e. fire spreading, congestion and path), the proposed crowd dense forces model, performance measures and experimentation conducted in the study.

(IV) Chapter 4 elaborates the key role of the new extended cellular automata parameters (i.e. fire spreading, congestion and path) in simulating the decision-making of agents in terms of movements and judgments on their surrounding conditions and their choices of actions, while considering the various environmental and accident factors namely, crowded exits, internal obstacles, exit configurations, exit location, exit width, cul-de-sac areas, agent density, jam degree, fire location and the acceleration of the fire rate of spread during evacuation. The spiral fire movement technique as compared with other fire models adopting a square fire front shape or investigating the fire in a static scenario is also discussed. The experimentation and numerical results of the new extended cellular automata parameters and fire spiral movement technique are summarized, evaluated and compared against the previous literature methods.

(IV) Chapter 5 elaborates in detail a significant role of incorporating the proposed crowd contact forces model with the new extended cellular automata parameters (i.e. fire spreading, congestion and path) through several evacuation scenarios, while considering the various environmental and accident factors namely, crowded exits, crowd pressures, crowd forces, internal obstacles, exit configurations, cul-de-sac areas, agent density, jam degree around exits, fire location and the acceleration of the fire rate of spread during evacuation. As well as discussing the effects of fire death toll, crowd death toll and agents being stuck inside cul-de-sac areas on estimating variables, including evacuation time, unit evacuation time, travel distance, unit travel distance, congestion points and crowd pressure during evacuation.

(VII) Finally, Chapter 6 provides the concluding remark regarding the overall findings and contributions, potential future works and the outcome of the research in detail.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter outlines the background study of the problem domains considered in this thesis by reviewing the related works of the various aspects, problems, techniques and approaches in the field of simulation of a moving dense crowd during the emergency situations, especially fire disasters. Throughout this chapter, the outlook of the domain problems will be identified from a top-down perspective of emergency evacuation which will be elaborated in detail, whereas the potential gaps will also be highlighted. To get a clear view of the main content, the organization of this chapter is given as in Figure 2.1.

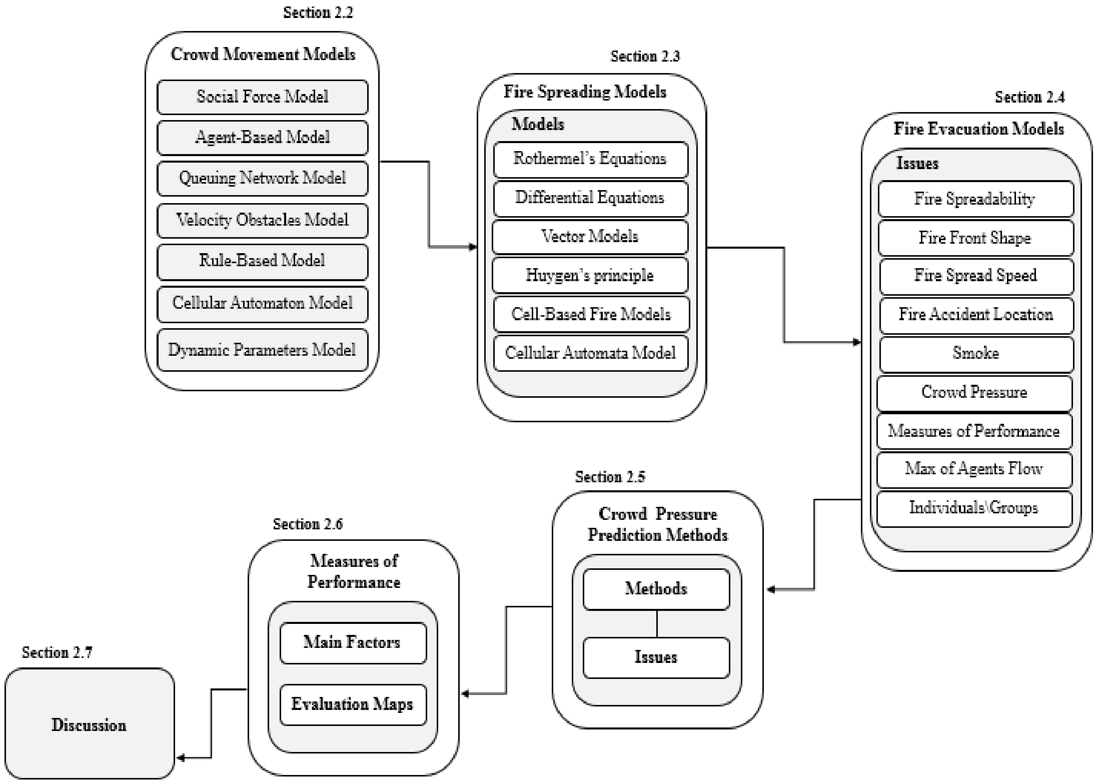

Figure 2.1 The Content Structure of Chapter 2

2.2 Crowd Movement Models

Researchers have modelled agents' behaviours under different emergency circumstances based on various methods, such as social forces model (Shuaib, 2018, Frank and Dorso, 2011, Matsuoka et al., 2015, Jiang et al., 2014, Farina et al., 2017), agent-based model (Shi et al., 2009, Wagner and Agrawal, 2014, Trivedi and Rao, 2018), velocity obstacles (Fiorini and Shiller, 1998, Guy et al., 2009, Paris et al., 2007, Karamouzas and Overmars, 2012), cellular automata model (Georgoudas et al., 2007, Wei-Guo et al., 2006, Yamamoto et al., 2015, Yamamoto et al., 2008) and rule-based models (Reynolds, 1987, Reynolds, 1999). These models are deemed the most commonly used to simulate the decision making of agents in terms of movements and judgments on their surrounding conditions and their choices of action (e.g., moving ahead, backtracking, switching lanes, waiting and interaction avoidance with infrastructure) during evacuation. There are various pros and cons of applying each of the abovementioned models. Based on the specific requirements and simulation scenario, one model can be more suitable than the others. In the next sub-sections, a review of the traditional agents' movement models with their strengths and weaknesses was carried out.

2.2.1 Social Forces Model (SFM)

The social forces model produces smoother movements in comparison to cell-based methods due to its continuous nature. The social force models, therefore, were used to simulate human behaviour in normal, crowd and emergency situations (Helbing et al., 2002, Helbing et al., 2000a, Helbing et al., 2000b). From this point of view, it has been noticed that the social forces model has been used to simulate many of crowd phenomena successfully, such as arch formation at exits, lane formation, counter flow, faster-is-slower, ignorance of available exits, freezing by heating effect and oscillations at bottlenecks under different circumstances (Helbing et al., 2002, Low, 2000, Helbing et al., 2001, Helbing et al., 2000a, Helbing et al., 2000b, Helbing and Johansson, 2011). However, social forces model suffers from many drawbacks. First, this model uses nonlinearly coupled differential equations to simulate movements of agents. It is more difficult to modify and add features to such equations compared with the simple rules of cellular automata (CA) model and other models supporting different crowd scenarios (Shiwakoti et al., 2008, Teknomo, 2002, Zheng et al., 2010). Second, these models require high computing power for the numerical solution of the differential equations. Researchers have only been able to simulate a few hundred agents on a single CPU and thousands of them using parallel processing methods. For example, Sarmady and Sarmady (2008) simulated tens of thousands of agents using a regular PC. In contrast, Quinn et al. (2003) has simulated 10,000 agents on 11 CPUs. He has employed Helbing Model within his simulation. The computational time in this model is of the order of O (N^2) as each agent evaluates the force from every other agent compared to a cellular automaton model, where the number of computations is of the order of the sample size O (N) (Haner et al., 2012). Therefore, if the number of agents is large, it will be practically impossible to use this method unless incorporate parallel processing technique or grid computing technology is utilized. Third, the interaction model does not guarantee that the agents will not collide (overlapping) with each other (For example, see Figures 1, 3 and 4 in (Shuaib, 2018), Figures 8 and 9 in (Farina et al., 2017) and Figure 6 in (Jiang et al., 2014)). It is unrealistic if the agent can enter another agent visually, especially when the agent density is very high. In this regard, another force is needed to avoid collision, similar to the magnetic force model (Teknomo, 2002). Fourth, agents in the social force model tend to adjust their speed of motion inversely proportional to the distance from borders and other agents. In reality, agents may formulate better escape strategies (for example moving between two other agents to find a quieter route) which are not considered by this set of models. Fifth, it is observed that researchers of social force model are more focused on the physical interactions to explain biological and physical behaviours rather than the real agent traffic flow (Teknomo, 2002). Sixth, modifying the social force to support the circular movement (e.g. circular motions of pilgrims around the Kaaba during Tawaf) is more difficult than the other models. It is also difficult to introduce new features and functionalities to the model as changes in the equations and therefore numerical methods being used to solve it will be required. Such amount of changes to the software might be undesirable (Sarmady, 2014, Sarmady et al., 2011).

2.2.2 Agent-Based Model (ABM)

Agent-based model can be viewed as the most natural way of simulating a system with many different components. Agent-based model is characterized by a high level of autonomy of the simulated agents, where each agent is controlled by a set of rules. In this regard, the motion can look very realistic and that the agents can be adaptive and possess a high degree of artificial intelligence (Johansson, 2008). This also make agent-based models suitable for crowd animation (Popović et al., 2003, Treuille et al., 2007). The agent-based model also can be combined well with other kinds of models. For example, when simulating the evacuation of agents in scenarios where poisonous gas spreads in the environment. One can easily couple agent-based models with continuum models, such as gas-kinetic or fluid-dynamic models (Helbing, 2012). A disadvantage is that these kinds of models tend to be very complicated, which makes it hard to approach them analytically and they typically also need a lot of computational effort (Johansson, 2008). This is mainly because agent-based models consider systems at a disaggregated level. This level of detail involves the description of potentially many agent attributes and behaviors, and their interaction with an environment. For instance, a system based on human beings will involve agents with potentially irrational behavior, subjective choices, and complex psychology. These factors are difficult to quantify, calibrate, and sometimes justify, which complicates the implementation and development of a model, as well as the interpretation of the simulation outputs (Castle and Crooks, 2006). In practical terms, integrating a large amount of details will make programming the model more challenging, as each model feature needs to be defined and integrated with the other model components in a meaningful way (Eberlen et al., 2017). The major drawback of agent-based model also is the amount of computing power required. Modelling the evacuation of a sports stadium may require over 100,000 agents, each with their own set of rules regarding their interactions (Winter, 2012).

2.2.3 Queuing Network Model (QN)

Queuing network model could be used as evacuation tools from fire in the building (Desmet and Gelenbe, 2013, Hajibabai et al., 2006, Xu et al., 2012, Løvås, 1994, Wang et al., 2018, Hu and Liu, 2018). In this model, each room is denoted as a node and the exit between rooms as links. Each agent will move from one node, queue in a link and arrive at another node in order to find an exit in quickest time and evacuate. Route, which each agent uses, and the evacuation time is recorded in each node. When an agent arrives in a node, he makes a weighted-random choice to choose a link among all possible links. The weight is a function of actual population density in the room. If the link cannot be used, an agent will wait or find another route to follow. The queuing network model has implicit visual interaction. However, the behaviour of the agents is not clearly shown and the collisions among agents are not clearly guaranteed. The FIFO priority rule that is inherent in the model is not very realistic especially in a crowded situation (Teknomo, 2002).

2.2.4 Velocity Obstacles Model (VO)

The velocity obstacles models are categorized as continuous models and produces smooth movements (Curtis et al., 2013, Giese et al., 2014, Fiorini and Shiller, 1998, Guy et al., 2009, Paris et al., 2007, Karamouzas and Overmars, 2012, Sarmady, 2014). In these models, a feasible velocity along with direction are calculated for agents, in a way that they do not collide in a specific time. On the other hand, when there is no collision potential could be predicted. Agents, subsequently, can walk with their free flow speed. In terms of simulation performance and speed, the model has been used for relatively large crowds. However, it is observed that the pushing, trampling and the phenomena of panicky crowds are not supported despite the collision avoidance is applied by controlling speed and movement direction. Consequently, these models cannot be used for evacuation modelling and high dense crowds (Curtis et al., 2011). Furthermore, when dense crowds of higher than 5-6 agents/m^2 agents tend to walk very near to each other and almost collide (Sarmady, 2014). In this regard, the velocity obstacles models might not be very realistic in microscopic scales and dense crowd specific phenomena like arching, pushing, and trampling may not be modelled.

2.2.5 Rule-Based Model (RBM)

The rule-based model introduced specific behaviour-based rules for simulating the movements and interactions of simple creatures like flocks of birds, group of fishes and herds of animals (Reynolds, 1987, Reynolds, 1999). This model was later used to simulate the movements of agents. Three behavioural rules are used in this model.