DEVELOPMENT OF A MICROSCOPIC CROWD DYNAMIC MODEL: INCORPORATING DECISION MAKING CAPABILITY INTO THE SOCIAL FORCE MODEL

by

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LIST OF ABBREVIATIONS

CA model	Cellular Automata model
EGRESS	A dynamic computational simulator for the analysis and design of safe egress
EXODUS	An evacuation model for mass transport vehicles
FDS+EVAC	Fire Dynamics Simulator for Evacuation
HMFV	Helbing, Molnár, Farkas, and Vicsek
LKF	Lakoba, Kaup and Finkelstein
Q model	Queue model
SFM	Social Force Model
SGEM	Spatial-Grid Evacuation Model
SIMULEX	A simulator designed to simulate the escape of huge number of individual people through large building
VISSIM	A microscopic simulator based on Social Force Model that all vehicles and pedestrians are simulated individually

PEMBANGUNAN SUATU MODEL DINAMIK KERUMUNAN MIKROSKOPIK: MENGGABUNGKAN KEUPAYAAN PEMBUATAN KEPUTUSAN KE DALAM MODEL DAYA SOSIAL

ABSTRAK

Model daya sosial adalah salah satu model pejalan kaki mikroskopik yang paling berjaya yang mewakili fenomena dirancang dengan baik bagi aliran pejalan kaki. Bagaimanapun, keupayaan pejalan-pejalan kaki untuk membuat keputusan dalam situasi-situasi kecemasan dan normal tidak digabungkan dengan betul ke dalam model. Dalam situasi biasa, pejalan-pejalan kaki telah didapati tidak berpandangan jauh dalam mengelakkan beberapa situasi-situasi terhalang yang dijangka. Dalam situasi-situasi kecemasan, beberapa mekanisme-mekanisme realistik bagi keupayaan pembuatan keputusan tidak kelihatan dalam simulasi-simulasi berkaitan. Dalam penyelidikan ini, keupayaan pembuatan keputusan bagi pejalan-pejalan kaki bebas ditingkatkan. Pertama, satu perluasan model dengan membenarkan pejalan-pejalan kaki keupayaan menyiasat kelakuan melebihi kawasan-kawasan tanggapan mereka sendiri dilakukan. Model baru menganggap faktor ketumpatan di dalam kawasan tersebut dan memodelkan kesannya pada keputusan pejalan-pejalan kaki untuk menghapuskan tingkah laku tidak realistik. Kedua, dalam situasi-situasi pemindahan, satu peningkatan bagi memilih sebuah pintu keluar dari set pintu keluar yang ada di persekitaran fizikal dibuat dengan menyediakan pejalan-pejalan kaki dengan keupayaan penilaian persekitaran fizikal mereka dan tingkah laku dinamik pejalan kaki yang lain. Simulasi situasi-situasi kecemasan dan normal dipersembahkan untuk menyahihkan kerja secara kualitatif dengan menyurih tingkah laku pejalan-pejalan kaki yang tersimulasi dan mengkaji kesan tingkah laku ini pada realisme model asal. Satu perbandingan antara model diperluas dan model asal dibuat. Kerja selanjutnya untuk menyelaras parameter-parameter berkaitan dengan kerumunan untuk menghasilkan data empirikal juga dilakukan.

DEVELOPMENT OF A MICROSCOPIC CROWD DYNAMIC MODEL: INCORPORATING DECISION MAKING CAPABILITY INTO THE SOCIAL FORCE MODEL

ABSTRACT

The Social Force Model is one of the most successful microscopic pedestrian models that represent the well-organized phenomena of the pedestrian flow. However, the pedestrians’ abilities to make decisions in normal and emergency situations have not been incorporated properly into the model. In normal situations, the pedestrians were found to be short-sighted in avoiding some anticipated blocked situations. In emergency situations, several realistic mechanisms of the decision making capability do not appear within relevant simulations. In this research, the decision-making capability of the independent pedestrians is enhanced. First, an extension of the model by granting the pedestrians the ability to investigate the behaviors beyond their own perception areas is made. The new model considers the density factor inside such areas and models its effect on the pedestrians' decisions to eliminate the unrealistic behavior. Second, in evacuation situations, an improvement of selecting an exit from the set of exits available in the physical environment is made by providing the pedestrians with an assessment ability of their physical environment and the corresponding dynamic behavior of the others. Simulation of normal and emergency situations are performed to validate the work qualitatively by tracing the behavior of the simulated pedestrians and studying the impact of this behavior on the realism of the original model. A comparison between the original and the extended models is done. Further work to calibrate crowd –related parameters to reproduce empirical data is also made.

CHAPTER 1

INTRODUCTION

1.1 Microscopic Pedestrian Studies

The need for pedestrian facilities to solve many environmental problems has increased with the growth rate of populations where one of the major environmental problems is congestion. In some occasions, congestion has resulted in disasters and crowd stampedes which resulted into injuries and loss of lives (Keating, 1982; Elliott and Smith, 1993; Helbing et all. 2007). As a consequence of these, long-term negative effects have been recorded by survivors, the victims' families and the local communities; which have motivated researchers to make concerted efforts to seek for solutions to alleviate these consequences of congestion. Two common solutions proposed over the years to this environmental problem are: offering better pedestrian facilities and understanding the behaviors of pedestrians, in order to eliminate the undesirable ones. The latter solution has influenced the former, as shown in the example illustrated in Fig. 1-1 and vice versa. A wide range of applications and benefits are expected from these solutions. Pedestrian studies as explained in details (Teknomo, 2002), have a major role to play in establishing the benefits of these solutions and to determine the efficiency of their application. The advantage of achieving progress in a specific crowd situation in one area is such that its applications are transferable to other crowded areas (Helbing, 1997).

Pedestrian studies could be separated into two levels, as proposed by May (1990). The first level is the macroscopic studies which is more concerned with the macroscopic behaviors of the whole crowd. Macroscopic variables resulting from these behaviors are the density, average velocity and flow.

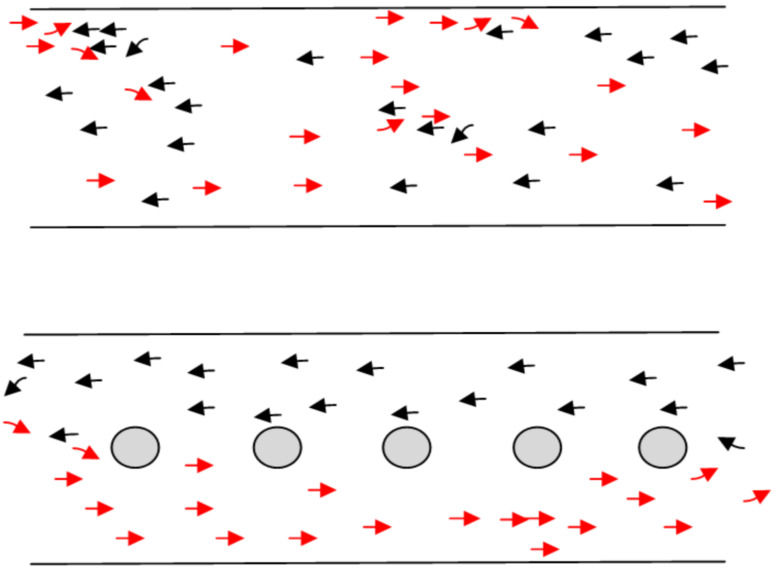

Figure 1-1: Two walkways with opposite walking directions. Each arrow represents the actual velocity of one pedestrian. The lower walkway contains columns built in the middle along the walkway which help in emerging two separated lanes. The interaction between the pedestrians in the above walkway is higher than the one below. The aim of this figure is to show that the self-organized phenomenon (lane formation) inspired the designers to build such columns to exhibit this phenomenon.

A graphical representation (such as the fundamental diagram) to describe the relationship between two of these macroscopic variables, forms an essential tool for the assessment of the models; as to whether it can describe the pedestrian stream appropriately, with respect to the empirical studies. Furthermore, this graphical representation has a lot of benefits to optimize some parameters of the model in consideration for the calibration process. Examples of macroscopic studies are (Fruin, 1971a and 1971b) and (Institute of Transportation Engineers, 1994). The second level is the microscopic studies, which is more concerned with the detailed interactions among the pedestrians and their effect on motion. A variety of models have been proposed in microscopic studies, among which are the Cellular Automata Model (Wolfram 1986); (Blue and Adler, 1999 and 2000); (Burstedde et al., 2001), (Klüpfel, 2003) and (Schadschneider, 2001), the Magnetic Force Model (Okazaki, 1979) and (Okazaki and Yamamoto, 1981) and the Social Force Model (Helbing, 1991); (Helbing and Monlar, 1995); (Helbing et al. 2000; 2002; 2005 and 2007); (Lakoba et al. 2005) and (Yu and Johansson 2007).

For emergency situations, the modification of the evacuation model-based simulators has become the main goal of researchers, to provide protection to pedestrian facilities, such as fire safety protection (Lo, 1999) and (Zhao, et al., 2004). Generally speaking, these systems on the one hand, have mostly focused on modeling the evacuation flow but paying less attention to the psychological behavioral reactions resulting from the interactions among the fleeing pedestrians and the effects on their decision making. On the other hand, conducting real-life experimental studies for validation and verification are mostly difficult and could lead to dangerous consequences. To overcome the former shortcoming, researchers such as Lo et al. (2006), Ehtamo, et al. (2008) and Guo and Huang (2010) have devoted most of their efforts in modifying models for exit choice, which is an essential decision making aspect in the evacuation process. This was achieved by incorporating psychological rules based on psycho-architecture studies such as those proposed by Passini (1984), Canter (1985), and Proulx, (1993). Considering the rules previously mentioned on one hand, independent exit choice models were incorporated into evacuation models. On the other hand, modifying microscopic models to take into account the aspects of the evacuation process was also proposed by many researchers.

Based on the consideration that pedestrians are self-driven particles, The Social Force Model has been considered as the most realistic model that expresses the motivations of pedestrians to act as forces. Furthermore, the successful introduction of self-organization phenomena of pedestrian dynamics in normal and panic situations (Helbing et al., 1997; 2000; 2002 and 2005) has rendered the Social Force Model one of the most important models in microscopic studies. Some of the interesting phenomena captured by this model are: (1) lane-formation, (2) oscillations at bottlenecks, (3) crowd transition to in-coordination due to clogging, and (4) ‘faster-is-slower’ due to impatience (i.e., moving faster likely causes clogging).

Lately, the model has gone through a series of advancement, corresponding to how much its parameters are realistic and the possibility of obtaining real-life data (Lakoba, 2005); (Seyfried et al. 2006); (Yu and Johansson, 2007) and (Parisi et al. 2009). For evacuation situation, the model has been modified in (Helbing et al. 2000) by incorporating physical forces which emerge in situations when contact exists. An open source implementation FDS+EVAC (Korhonen et al. 2008) as well as a professional simulation framework VISSIM (Kretz et al. 2008) were developed in cooperation with the original authors.

According to (Hoogendoorn et al. 2001), the pedestrian's behavior could be theoretically divided into three inter-related levels: 1) the strategic level, where the pedestrian's activities and order are determined; 2) the tactical level, where decisions are made while performing activities (e.g., choosing a route to an intermediate target among alternative routes based on utility maximization); and 3) the operational level, where the instantaneous behaviors which involve most activities resulting from the interactions among pedestrians are described; such as avoiding collisions, deviations, acceleration and deceleration. All aspects of the last level are examples of pedestrian dynamics, based on the Social Force Model. The definition of the destination, which was an exogenous input from most related studies, is the only aspect of the tactical level belonging to the Social Force Model.

1.2 Research Problem

The Social Force Model has attracted significant criticisms from other researchers (Still, 2000 and Lakoba, et al., 2005). Most of the criticisms involve the psychological and social facts, such as the following:

1- The pedestrians are intelligent people with the ability to make more far-sighted decisions than simply reacting to the immediate surrounding pedestrians. Therefore, several realistic mechanisms of the tactical level do not appear within relevant simulations. Given a normal traffic situation (i.e., a non-panic situation), this is an obvious fact and as such, depriving the pedestrians (especially those who are independent on others) of any intelligence therefore limits the ability of the simulation to capture the real behavior of pedestrians.

2- According to psycho-social studies (Mintz, 1951 and Brown, 1965), which show the fundamental aspect of the independence state of the pedestrian's decision-making aspects, the most essential feature of this aspect is the pedestrian’s ability to make his own decision even under perceived dangers. Within the simulations based on the Social Force Model, the variety of pedestrian’s abilities to make decisions in emergency situations has not been properly incorporated. Many aspects of the independent and dependent pedestrians have not been taken into consideration in the model.

Furthermore, reproducing the fundamental diagram (velocity vs. density) based on the Social Force Model to fit the available experimental data for the pedestrian traffic flow (the flow rate and the fundamental diagram) has also been done in different studies (Seyfried et al. 2006; Parisi et al., 2009). However, these studies have provided the pedestrians in the model with certain artificial aspects and imposed constraints to obtain the empirical data. Indeed, the fundamental diagram could be reproduced without changing any of the principles of the model. Some related parameters need to be modeled with respect to the crowd, to help in reproducing the appropriate experimental data.

1.3 Research Objectives

The main objective of this thesis is in developing a model for pedestrian flow, on the basis of the Social Force Model, which provides the pedestrians with several aspects of intelligence in decision making capability, whether in normal or panic situations. Additionally, the other objective involves modeling essential parameters in the Social Force Model, to reproduce experimental data as an aspect of the calibration of the model. The specific measurable objectives derived from the main objectives are:

1) To identify the stages in the development of the Social Force Model
2) To incorporate an investigation capability model into the Social Force Model as a decision making aspect for independent pedestrians
3) To model the investigation and the decision making processes with regards to macroscopic variables in a normal situation
4) To introduce an exit choice model based on the Social Force Model in an emergency situation
5) To perform simulations for the purpose of qualitative validation and comparisons with the original model with regards to quantitative measurements
6) To model crowd-related parameters of the Social Force Model, in order to reproduce experimental data as an aspect of the calibration of the model

1.4 Importance and Significance of the Research

Since congestion is the main reason for the occurrence of disasters such as crowd stampede, there is the essential need to prevent the consequences of this phenomenon from occurring. The need for a powerful simulator to perform a large-scale pedestrian and evacuation simulations with complex geometries and multi-dimensional interactions is extremely important, to deal with this pressing environmental phenomenon.

Essentially, simulators are based on mathematical models of the pedestrian dynamic flow, therefore the progress of establishing a good representative model plays the major role, to obtain a more realistic performance by these simulators. The pedestrian is a major block in congestion. Understanding his behavior, during his interaction with the other pedestrians helps researchers to incorporate the realistic aspects of this interaction into their models and in turn, this helps in obtaining properly developed simulators.

The major beneficiaries of this research are transport stations, shopping centers, crowded buildings, religious ritual areas and designers of buildings for emergency and non-emergency evacuation. The beneficial aspects treated in this research focuses on the Al-hajj crowds, as such the findings are expected to be used on the Al-hajj crowd, which could in turn provide useful suggestions and mitigation measures for the smooth flow of crowds at the ritual areas and prevent the occurrence of disasters.

The output expected from the research is a pedestrian dynamic flow model for developing simulators, for the purpose of transportation and the safety of public places. It could also be useful for serving the community and help to open new fields of research.

1.5 Research Scope

The main concern of this study is the incorporation of decision making aspects into the microscopic dynamic flow model in both normal and panic situations. The conditions of the physical environment in the normal situation is restricted by a unidirectional walkway, which is a representative environment in many areas such as the Al-hajj area as shown in Fig. 1-2.

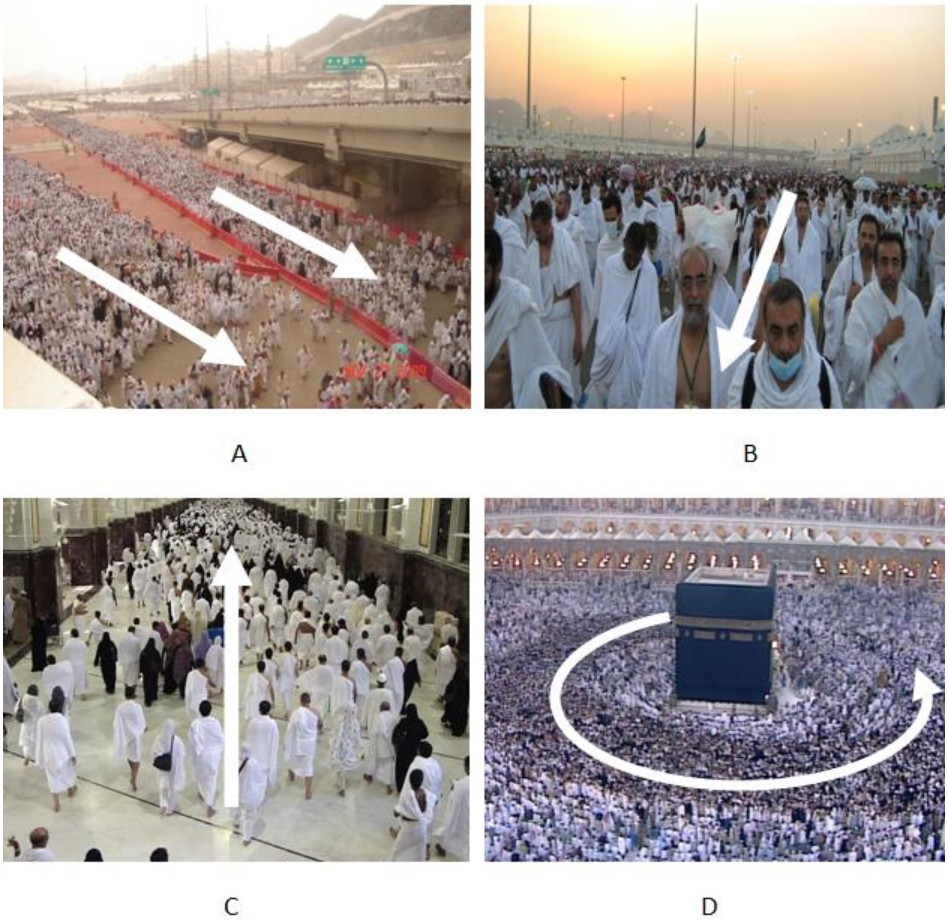

Figure 1-2: Examples of wide walkways in Makkah where pilgrims travel there to perform their Stoning ritual (A and B), Sa’e (C), and Tawaf (D). The situation is normal and a retreating process is rare.

Furthermore, the available experimental data used to calibrate the crowd-related parameters in the Social Force Model has been produced in a similar environment. In a panic situation, the evacuation process from a closed physical environment is the main environment built into the simulations, for validating the contributions of this study. No extreme global density of pedestrians is considered in both normal and panic (emergency) situations. Some psychological parameters introduced in this thesis are estimated by performing simulations several times because of the lack of relevant psychological studies.

1.6 Research Methodology

As the main block of the pedestrian dynamic flow is the individual, understanding his psycho-social behaviors is an essential role which helps improve a microscopic model that treats further aspects of the dynamic motion behavior in real situations. The pedestrians' behaviors in the tactical level are indispensable for well-representative dynamic models. In accordance with this, the work in the present thesis mainly focuses on introducing a model to treat several aspects of decision-making capability in normal and emergency situation. The behavior of the dependent pedestrian is taken into consideration as well. In principle, the introduced model is an extension to the contribution of Lakoba et al. (2005), regarding the decision making aspects described and discussed in section 3.3. This extension is constructed on the basis of Social Force Model. That is, an essential term (principle), which is the preferred force in the Social Force Model, involves the introduced (extended) model in the present thesis. The effect of such incorporation on relevant self-organization phenomena is examined. It is worth noting that the introduced model can be easily built on the basis of another microscopic model as long as the latter includes a principle which resembles the preferred force in the Social Force Model.

The original model (the Social Force Model) described in chapter three is considered as principles that should not be changed due to the successful reproduction of the self-organization phenomena. Regarding the decision-making aspects described in chapter three, the intelligence aspects and other behavioral factors incorporated into the Social Force Model (such as the excitement factor, and the memory factor introduced in LKF contribution) are adopted. The value of a crowd-related parameter is estimated in the contribution of the present thesis by a different approach (curve fitting approach) than the recent studies which helps reproduce the fundamental diagram and the flow rate in a normal evacuation process.

1.7 Organization of Thesis

The contributions made in this thesis are divided into three parts as shown in Fig.1-3:

1) The first part is composed of the description of the state of the art of microscopic dynamic studies, which is presented in chapter two, while the adopted model is presented in chapter three.

2) The modeling of the decision making aspects of the pedestrians forms the second part of this thesis, where the contributions are divided into two chapters four and five. In chapter four, the argument for the first shortcoming that the pedestrians are short-sighted is described in details. To eliminate this behavior, the simulated independent pedestrians are provided with some kind of intelligence and more options by granting them the ability to investigate areas within their sights while they are in a normal situation. Finally, the

simulation to demonstrate the results of work by qualitatively tracing the behavior of the independent pedestrians is performed.

In chapter five, using the ability of the pedestrian to investigate his closed physical environment in an evacuation situation, the independent pedestrians are provided with more intelligence by granting them several aspects such as the familiarity aspect (assessment process to choose an exit based on many factors such as the design of the exits, the distance between the pedestrian and these exits, and the clogging crowd at these exits) and the aspect of following the directions of the others. Following leaders as an aspect of dependent pedestrians is incorporated in the end of this chapter. Simulations to trace the qualitative behavior of the simulated pedestrians corresponding to the contribution are performed.

3) The final part of the thesis in the sixth chapter is the analysis and applications for validating and calibrating the other contributions. Calibrating crowd-related parameters to produce experimental data is also presented in this part. The seventh chapter presents the conclusion together with a summary of all the contributions in this thesis.

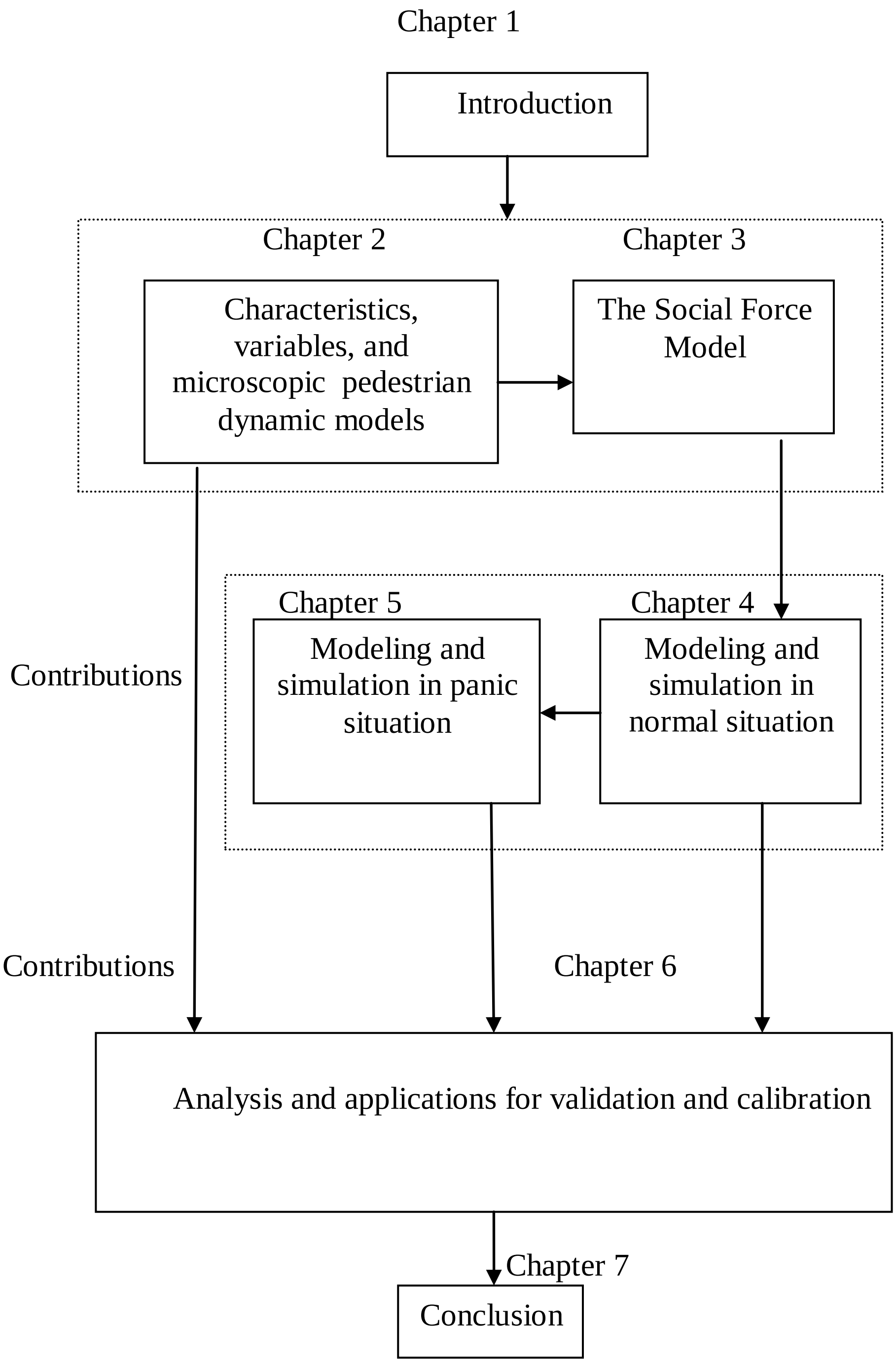

Figure 1-3. Overview of the thesis outline

CHAPTER 2

PEDESTRIAN DYNAMIC FLOW STUDIES

2.1 Introduction

In this chapter, the literature review for the pedestrian flow characteristics, behavior and models is provided. The first section is dedicated to the description of the most important microscopic and macroscopic variables which are frequently used to describe the pedestrian walking flow used in this thesis. The composed relationships of these variables are useful for the practical applications of the pedestrian dynamics, such as the assessment of escape routes and the optimization of pedestrian facilities. The microscopic variables are concerned with the individual behavior and his interaction with the environment, whereas macroscopic variables are concerned with the collective behavior of the crowd. Therefore the latter variables are useful to describe behaviors in large-scale and large crowd simulations, where the users are more interested in the collective behaviors. They are also useful for describing the collective behavior of local groups or crowds such as their flow while exiting or walking in a corridor. In the second section of this chapter, several microscopic models for simulating the pedestrian dynamic flow are briefly described. Among these are; the Cellular Automata Model (CA model), the Magnetic Force model (MF model), the Social Force Model (SFM model) and the Queuing model (Q model). The common characteristic of these models is the treatment of the individual separately. These models account for the interaction of each individual with the other individuals who directly surround him and the effects on his motion.

2.2 Macroscopic and Microscopic Characteristics of Pedestrian Walking Flow

2.2.1 Microscopic Characteristics

It is worth mentioning here that microscopic variables are mostly defined on the basis of the study itself. For this reason, it is rare to find global microscopic variables adopted by all pedestrian studies. However, in the next subsections, the microscopic variables used to describe the pedestrian walking in related microscopic models are defined.

2.2.1(a) The Trajectory

The trajectory of a pedestrian is his walking path over time, which is introduced graphically and provides complete information about the pedestrian motion such as the location and the movement in longitudinal and lateral directions. Lately, much research has been devoted to calibrate the parameters of models in use, by extracting data from videos for observations or empirical studies using the trajectory variable (Teknomo, 2002).

2.2.1(b) The “Efficiency” of Motion

This measurement was used by Helbing et al. (1997, 2000 and 2001), on the basis of the Social Force Model. It is denoted by E_{eff} and has the following formula:

$$E_{eff} = \frac{1}{T}\int_{t_0}^{t_1}\frac{1}{N}\sum_{n}\frac{\vec{v}_i.\vec{e}_i^{\,0}}{v_i^{0}} \qquad (2.1)$$

where $\vec{v}_i$ is the actual velocity of pedestrian i; v_i^0 is the preferred speed at which the pedestrian i prefers to walk; $\vec{e}_i^{\,0}$ is the preferred direction at the preferred speed; T is the total time to measure the efficiency of motion E_{eff} which is the average of the actual velocities of all pedestrians as a components into their preferred directions, in relation to their preferred speeds respectively. The magnitude lies between 0 and 1: it is equal to one in the case of each pedestrian walking with his preferred velocity (speed and direction) and it is equal to zero in the case of a blocked situation for all pedestrians considered. This measurement helps optimize the pedestrian facilities, whether the pedestrians are walking conveniently in the considered facility or not.

2.2.2 Macroscopic Characteristics

The essential macroscopic variables frequently used by most pedestrian studies are; the density, the flow and the mean speed (Haight, 1963).

2.2.2(a) Density

The density is defined as the number N of pedestrians within a specific area A at any given moment. It is calculated by:

$$\sigma = \frac{N}{A}. \tag{2.2}$$

The unit of the density is represented by P/m^2; where P denotes the number of pedestrian and m denotes a meter. The reciprocal of pedestrian density is called Space module or Area Module, denoted by M_σ, which is a unit of surface area per pedestrian (m^2/P).

2.2.2(b) Mean Speed

There are two general forms for representing the mean speed:

i. The local mean speed $\overline{V}_{loc}$ which is defined as the average over time of the speed of pedestrians $\bar{v}$ passing a cross-section of a specific area, or a line. The speed of the pedestrians is computed by the following formula:

$$\bar{v}(t_j) = \left(\frac{\sum_{i=1}^{n_j} v_i(t_j)}{n_j} \right) \tag{2.3}$$

where n_j is the number of pedestrians passing the cross-section at time t_j. The speed of a pedestrian in this notation is the component of his velocity into the perpendicular direction of the cross-section. The local mean speed is computed within a period of time with length T. This period may be determined with regards to the purposes of the relevant study. The equation for the local mean speed is given by:

$$\bar{V}_{loc}(t) = \frac{\sum_{j=0}^{end} \bar{v}_{t_j}}{T} \tag{2.4}$$

where $T = t_{end} - t_0$ is the period of time.

ii. Instantaneous mean speed is defined as the average value of the pedestrians' speeds (the components of the velocities into the considered direction) that are present in an area *A*, at a given moment *t*. It is computed by the formula:

$$\bar{V}_{inst}(t) = \sum_{i=1}^{n_t} \frac{v_i(t)}{n_t} \tag{2.5}$$

Where n_t is the number of pedestrians inside area *A* at time *t*. The mean speed is assumed to follow normal or lognormal distribution, with a mean m and standard deviation σ , as proposed by Older (1968). However, Henderson (1971) found that the mean speed is Gaussian distributed. An inverse relation between the deviation and the density was proposed by Lovas (1994).

Table 2.1: The mean speeds and the standard deviations resulted from some important studies conducted in corridors in mildly crowded situations.

Study	Mean speed	Standard deviation
Older (1968)	1.31 (m/s)	0.30 (m/s)
Fruin (1971*b*)	1.4 (m/s)	0.15 (m/s)
Henderson(1971)	1.44 (m/s)	0.23 (m/s)
Weidmann (stated in Helbing & Molnar (1995))	1.34 (m/s)	0.26 (m/s)
Sarkar & Janardhan (1997)	1.46 (m/s)	0.63 (m/s)

For mildly crowded corridors where density is approximately less than 0.5 m^{-2}, the mean speed is approximately identical to the preferred speed at which the pedestrian prefers to walk at. The reason for this is that there are enough distances among pedestrians which allow them to walk conveniently.

2.2.2(c) Pedestrian Flow Rate

The flow rate (the flow) f is defined as the number of pedestrians passing a cross-section (usually measured per meter) of an area during a specified period of time (usually per second). It is directly computed by:

$$f = \frac{N}{L.T} \tag{2.6}$$

where N is the number of pedestrians passing the cross-section which has length L meters, during the time period of T seconds. It's dimension is (P/m/s). This measurement is helpful to examine the capacity of pedestrian facilities. It was studied in detail by Haight (1963). For evacuation situations, such a notation is frequently used in several studies, to measure the evacuation process for the number of pedestrians from a room with a specified length of door (Parisi et al., 2009). According to Parisi et al. (2009), in normal evacuation situations, most studies showed that increasing the width of the exit would not affect the value of the flow rate. Furthermore, the various values of flow rates in normal evacuation situations corresponding to these studies lie within the range of 1.25 to 2 p/m/s. It is also worth mentioning that the flow through a door differs from the flow in a corridor of the same width, since the pedestrians close to the door experience different forces, both from the walls and the other individuals (Fig. 2-1).

The aforementioned three macroscopic variables (flow rate, density and mean speed) are the main components composing the fundamental traffic flow formula:

$$f = \sigma . \overline{V} \tag{2.7}$$

This formula is very helpful in introducing the relationship between speed, flow and density (Haight 1963). Each relation has its graphical and mathematical representation as described in the next section.

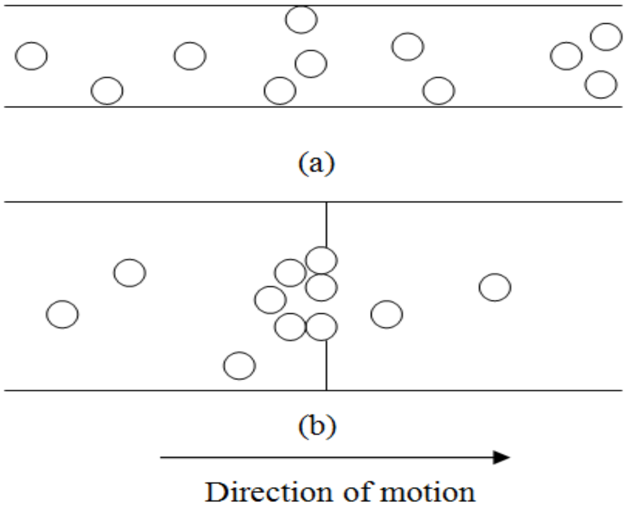

Figure 2-1: The flow through a door and a corridor. The corridor in (a) and the door in (b) have the same width, however, such different environments may cause different flow. This phenomenon is discussed in details in chapter 3.

2.2.3 Diagrams

Diagrams are graphical representations of the relationship between two macroscopic variables. These diagrams are important to describe the visual relationships between variables.

2.2.3(a) Fundamental Diagram

This diagram is a graphical representation used to describe the relationship between two macroscopic variables such as the mean speed and the density $\overline{V} = \overline{V}(\sigma)$, the flow and the density $f = f(\sigma)$ or between the flow and the mean speed $f = f(\overline{V})$. Based on the traffic flow formula (2.7), obtaining one relationship induces the others. These relations are useful for assessing the models, as it describes the pedestrian stream appropriately with respect to the empirical studies (Parisi et al. 2009) and (Seyfried et al., 2005; 2006). Furthermore, these diagrams are of immense benefit for optimizing some parameters of the model in consideration for calibration. For this reason, researchers have conducted simulations to fit models with the fundamental diagrams, resulting from empirical studies as calibration to the models. However, due to the variations in pedestrian environments where empirical studies were conducted, the conditions which the researchers adopted in their empirical studies were also varied. This has led to the resulting relationships and the corresponding fundamental diagrams to vary from one study to another as shown in Table 2.2 and Fig. 2-2. On the other hand, empirical studies cannot be conducted under emergency situations because of the difficulty in controlling the conditions under such situations. Accordingly, most researchers conducted empirical studies to obtain fundamental diagrams for their own models, with common achievable conditions: homogenous and stationary flow in unidirectional walkway and normal situation, with no repulsive or attractive sources.

Table 2.2 Examples of estimated speed-density and flow-density relations for unidirectional pedestrian traffic flow.

Reference	Speed-density and flow-density relation	The situation
Fruin (1971*a*)	$v(\sigma) = 1.43 - 0.35\sigma$ $f(\sigma) = 1.43\sigma - 0.35\sigma^2$	Peak-hour flows at large commuter bus terminal
Weidmann (stated in Lakoba et al., (2005))	$v(\sigma) = 1.34\left[1 - \exp\left(-1.91\left(\frac{1}{\sigma} - \frac{1}{\sigma_{\max}}\right)\right)\right]$ $f(\sigma) = \sigma * 1.34\left[1 - \exp\left(-1.91\left(\frac{1}{\sigma} - \frac{1}{\sigma_{\max}}\right)\right)\right]$	Pedestrian traffic
Sarkar & Janardhan (1997)	$v(\sigma) = 1.46 - 0.35\sigma$ $f(\sigma) = 1.46\sigma - 0.35\sigma^2$	Metropolitan transfer area
Older (1968)	$v(\sigma) = 1.31 - 0.34\sigma$ $f(\sigma) = 1.32\sigma - 0.34\sigma^2$	Shopping street

As shown in Table 2.2 and Fig 2-2, most studies use a linear speed-density relation, while Weidmann (see Parisi et al., (2009)) used a double S-bended curve.

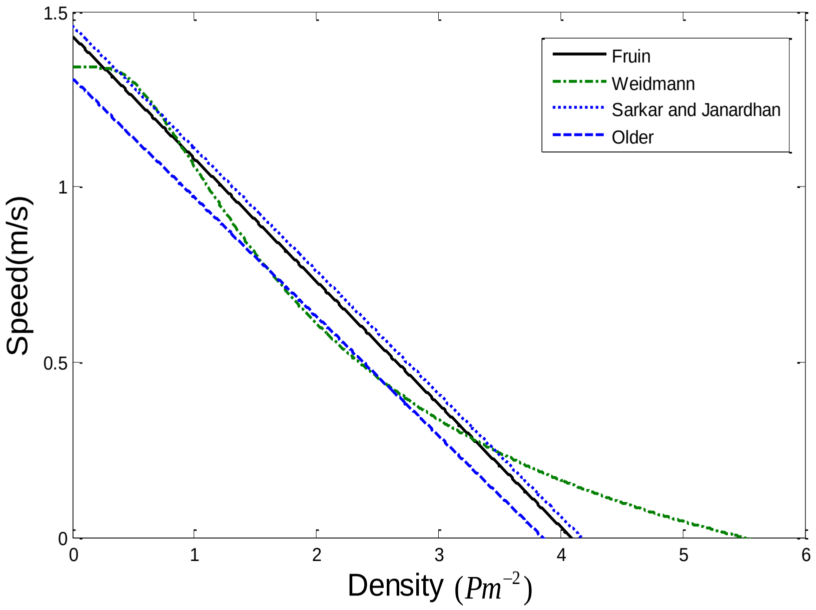

Figure 2-2: Estimated speed-density relations for unidirectional pedestrian traffic flow.

The diagrams for the estimated flow-density relations stated in Table 2.2 are graphed in Fig. 2-3 below.

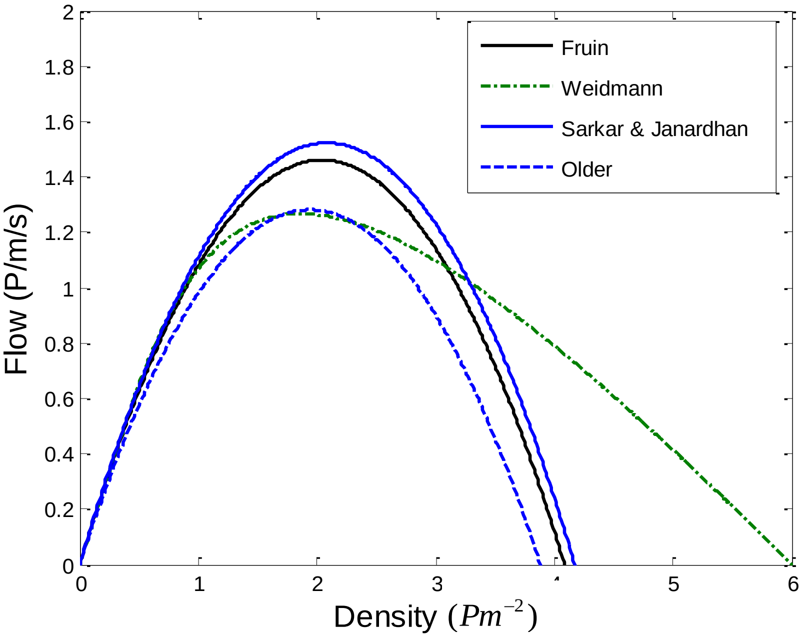

Figure 2-3: The estimated flow-density relations for unidirectional pedestrian traffic flow.

2.2.3(b) The Cumulative Plot

The cumulative plot is a graphical representation to introduce the cumulative flow during a particular period of time, starting at a specific moment. This diagram also presents the local mean speed.

2.3 Self-Organization Phenomena

Self-organization phenomena are dynamic structures (groups of pedestrians with similar walking characteristics) arising from the dynamic interactions of pedestrians with their environment and other pedestrians. `Self-organization' signifies that these structures emerge without the planning from the pedestrians to create such phenomena. Examples of self organization phenomena in normal situations are lane formation, oscillations at bottlenecks and dynamics at intersections and in emergency situations such as “transition to in-coordination” and “faster is slower”. The physical environment and the different preferences of the velocities and directions among the pedestrians are important factors which govern the quality of the structures of these phenomena and its emergence.

Researchers (Hoogendorn & Daamen, 2001; Teknome, 2002; Helbing et al. 1997, 2002, and 2005) have considered the successful introduction of these phenomena as a primary criterion to validate the pedestrian models. Therefore, it is expected that the realistic model must be able to reproduce these dynamic phenomena in simulations. According to the nature of these phenomena, some (such as lane formation) have qualitative appearance with no ability to reproduce quantitative measurements. On the other hand, some could reproduce quantitative measurements along with the qualitative appearance.

2.3.1 Self-Organization Phenomena in Normal Situation

In principle, based on maximization utility, the pedestrian is assumed to minimize his energy while interacting with others, or to change his environment to what he is suited (Zipf G. K., 1949). Among the options available to the pedestrian (acceleration, deceleration, changing direction), he, intuitively, chooses the option which reduces the physical contact with others. The pedestrian keeps following this behavior until he reaches a stable state (the optimal state), where the surrounding situation is homogenous. Therefore, the pedestrian’s state is similar to the states of others who surround him. This stability is permanent, as long as there is no more possibility that exists to minimize the energy of walking. However, the stable state