# Crowd Management for Large-scale Outdoor Events

## - Multi-agent Based Modeling and Simulation of Crowd Behaviors

SHI Jingjing

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy
in
Geography and Resource Management



August 2006

UMI Number: 3254612

## INFORMATION TO USERS

Thesis/Assessment Committee

Professor LEUNG Yee (Chair)
Professor LIN Hui (Thesis Supervisor)
Professor ZHANG Li (Committee Member)
Dr. P.C. LAI (External Examiner)

# ABSTRACT

of thesis entitled:

**Crowd Management for Large-scale Outdoor Events**
**- Multi-Agent Based Modeling and Simulation Crowd Behaviors**

Submitted by SHI Jingjing
for the degree of Doctor of Philosophy
at The Chinese University of Hong Kong
in August 2006

Crowd modeling and simulation have become an attractive scientific research area, especially when public safety has never been so vulnerable than before. Due to the complexity of crowd behavior, the pedestrian dynamics in large-scale outdoor events have not caught much attention and we have not had enough knowledge to answer the question "How to efficiently manage large number of people moving in a short period?". Applicable tools that can facilitate crowd management in such events are also absent in the integration of pedestrian's spatio-temporal behavior and their interactions with their behavioral environment. Considering the characteristics of collaborative works in management, the main objective of this dissertation is to set up a framework of geo-collaborative crowd management for large-scale outdoor events. Its focus is on modeling and simulating crowd behavior by the multi-agent approach.

Firstly, a conceptual framework for a geo-collaborative management of crowds in large-scale outdoor events has been proposed. This framework is developed on the data environment which stores the information and knowledge of crowd behavioral dynamics as well as their behavioral space. It also provides a visualization environment with multi-modal and multi-mode interfaces for different end-users to visualize and simulate processes of crowd behavior and events evolvement, and to facilitate communications and decisions-making. This proposed framework has shed light on the vision of moving crowd management towards geo- collaboration.

Secondly, through the study on the case of "TST Firework Display", crowd behaviors in outdoor events have been explored and analyzed from an aggregate perspective. Driving forces for crowd dynamics are comprehended by emphasizing the effects of urban spatial morphology on crowd behaviors. This urban effect is represented through pedestrian visibility differences produced by urban terrain and road networks. In this study, the on-site observation results and the analysis on historical events were used for summarizing the behavioral dynamics of outdoor crowds, enriching the knowledge on crowd behavior, and providing the basis for modeling crowd behavior in large-scale outdoor events.

Thirdly, multi-agent based pedestrian models for large-scale outdoor events (MAPMODE) are developed from a disaggregate perspective. In MAPMODE, each pedestrian is viewed as an intelligent agent. Due to their different roles, attractors, policemen, buildings, roads, facilities, and emergencies are also represented by different types of agent in the models. Three specific models are developed based on the phases formed, including the model for crowd arrival, the model for crowd dispersal and the model for crowd evacuation. Not only the long-term observations and experiences on crowd behavior, but also processes of pedestrian decision-making and spatial cognition of human behavior are combined in MAPMODE.

Finally, the platform of integration and simulation of crowd behavior (ISCB) is developed. Ten scenarios of the event are generated to represent crowd behavior under different conditions. It is found that multi-agent based modeling brings additional information on crowd behavior that can not easily be observed or estimated only through collective observations and analysis. Therefore, ISCB with the basic requirements of geo-collaborative crowd management framework provides the foundation to accomplish real geo-collaboration at same/different time and same/different places.

# 摘　要

人群建模與模擬已經成爲一個逐漸引人注目的研究議題，尤其是在公共安全被極爲關注的當今。因爲群體行爲的複雜性，大範圍戶外事件中人群移動的動力機制沒有得到很多關注，還不足于解決"如何有效管理短時間內大規模行人的移動"問題。并且，可適用的輔助管理事件中人群移動的工具還比較缺乏。考慮到人群管理中的協同工作特徵，本文的目的在于建立一個大範圍戶外事件中協同式人群管理的框架，著重在采用多智能體方法建立人群行爲模型與模擬人群行爲。

首先，本文提出了大範圍戶外事件中協同式人群管理的框架。這個框架以存儲人群移動行爲機制的信息和知識，以及人群活動的空間環境信息爲基礎，給不同的終端用戶提供一個模擬人群行爲以及事件發展的可視化環境，以不同模式和不同方式的用戶界面來輔助用戶之間的信息交流和決策制定。提出的這個框架明確提出了將大範圍戶外事件中的人群管理方法推向地理協同模式。

第二，通過對"尖沙嘴烟花匯演"案例的研究，從整體視角來探究和分析大範圍戶外事件中人群的行爲。全面理解人群行爲的動力因素，將重點放于探討城市空間形態對于行人行爲的影響。本研究分析結果顯示地形高度以及道路網絡所産生的視覺效果的不同與人群的擁擠程度呈正比。這樣，對于歷史事件中戶外人群的行爲動力機制的總結和分析，不僅豐富了關于人群行爲的知識，也爲建立人群行爲模型提供了基礎。

第三，建立了基于多智能體技術的戶外事件行人模型（MAPMODE）。該模型中，每一個行人被視作一個智能體。根據在事件中所擔任的不同角色，吸引物、警察、建築物、道路、路障工具、突發性事物等分別代表模型中不同類型的智能體。根據戶外事件中形成的不同階段，建立了三個具體的行人行爲模型，分別是：人群到達模型，人群分散模型以及人群緊急疏散模型。MAPMODE 不僅綜合了對人群行爲長期觀察和分析的信息，而且融入了行人行爲決策以及空間認知的過程。

第四，本研究開發了人群行爲綜合與模擬平臺 ISCB。所產生的十個不同場景模擬了在不同條件下的人群行爲。結果顯示，多智能體建模方法提供了整體分析中不易被發現或被預測的人群行爲信息。ISCB 基本符合了協同式人群管理的框架，爲實現真正的同步/异步和同地/异地之間的協同打下基礎。

## TABLE OF CONTENT

**CHAPTER 4 EXPLORING AND UNDERSTANDING CROWD DYNAMICS IN THE FIREWORK DISPLAY**



**CHAPTER 5 MULTI-AGENT PEDESTRIAN MODELING FOR OUTDOOR EVENTS (MAPMODE)**



**CHAPTER 6 INTEGRATION AND SIMULATION OF CROWD BEHAVIOR (ISCB)**



**CHAPTER 7 CONCLUSIONS**

# LIST OF TABLES

# LIST OF FIGURES

## ABBREVIATION

| | |
|---|---|
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| 4D | Four-dimensional |
| AI | Artificial Intelligence |
| AMS | Auxiliary Medical Services |
| CA | Cellular Automata |
| CAS | Civil Aid Services |
| CASA | the Center for Advanced Spatial Analysis |
| CATI | Computer-Assisted Telephone Interview |
| DBM | Digital Building Model |
| EAC | Emergency Access Corridors |
| FEHD | Food and Environmental Hygiene Department |
| FSD | Fire Services Department |
| GIS | Geographic Information System |
| GISc | Geographic Information Science |
| GPS | Global Positioning System |
| GVIS | Geographic Visualization |
| HCI | Human-Computer Interface |
| HKPFYT | Hong Kong Police Force Yau Tsim District |
| ISCB | Integration and Simulation of Crowd Behavior |
| JLGIS | Joint Laboratory for Geo-Information Science |
| LCSD | Leisure and Cultural Services Department |
| LoS | Level-of-Service |
| MA | Multi-Agent |
| MAB | Multi-Agent Based |
| MAPMODE | Multi-Agent Pedestrian Modeling for Outdoor Events |
| MAS | Multi-Agent System |
| NHTS | National Household Travel Survey |
| PDA | Personal Digital Assistant |
| PFES | Passenger Flow Evaluation System |
| RS | Remote Sensing |
| SHS | Scottish Household Survey |
| TRANSIMS | Transportation ANalysis and SIMulation System |
| TST | Tsim Sha Tsui |
| VENUE | the Virtual Environment for Urban Environments |
| VGE | Virtual Geographic Environment |
| YTM | Yau Tsim Mong |

# ACKNOWLEDGEMENT

I would like to take this opportunity to express my gratitude by heart to my supervisor, Professor Hui Lin, for his eliciting guidance, invaluable advice and tireless support. Especially, I appreciate his encouraging me to initiate my own ideas in this thesis, arranging interviews during my consultancy work and supporting to keep going to finish this work. Without his devoted supervision, the completion of my Ph.D study could not be achieved.

I would also like to express my gratitude to Hong Kong Police Force Yau Tsim District, for their data provided and expert information offered. Special thanks must go to Mr. Eddie Chi, Mr. R. M. Forbes, Mr. Chi-man Lai, Mr. Wing-cheong Cho for their arrangements for our conducting on-site observations and their comments and suggestions on this research. Without their support on my work, this thesis would be impossible and incomplete.

My sincere thanks also go to Prof. Yee Leung, Prof. Li Zhang, members of my thesis examination committee in CUHK, for their consist concern about my work. Their precious comments and suggestions on my thesis improved both the structure and the content of this thesis. I also express my acknowledgement to my external examiner, Prof. P. C. Lai at the University of Hong Kong for her insightful suggestions and careful grammatical revisions on the draft of this dissertation.

I am also indebted to Ms. Ming-wai Lau, Ms. Sin-ling Ng, Ms. Hei-man Sit, undergraduate students in GRM, CUHK for their assistance on data collection and preparations, Mr. Marcel Koller, training student in JLGIS for his assistant work on 3D modeling, Dr. Eric Guilbert, post-doctoral fellow in JLGIS for his suggestions on models built in this thesis especially the corrections on expressions and formulas involved within models, and Mr. Isaac Chan, colleague in JLGIS for his technical help on this work. I also express my sincere appreciations to Prof. Liming Yang at JLGIS, Prof. Liqiu Meng at the Technical University of Munich, Prof. Yunfeng Kong at Henan University, Prof. Tung Fung, Prof. Jianfa Shen, Prof. Bo Huang, Prof. Yongqin Chen, Dr. Lucy Huang at GRM of CUHK, Prof. Jianhua Gong and Prof. Yun Shao at IRSA of CAS, Prof. Mingsheng Liao and Prof. Qing Zhu at Wuhan University for their consistent cares on my progress of the thesis.

Besides, I am also grateful to my colleagues and friends in the GRM & JLGIS of CUHK, whose steady supports and warm cares on my work and living makes the writing of this thesis a pleasant experience. They are Huiyong, Yucai, Yihong, Ping, Dan, Huiye, Xiaolong, Yibin, Bingli, Chaoyang, Lu, Jinsong, Chloris, Wendy, Matthew, Sophie, Jane, Victor, …

Finally, I would like to thank my family especially my parents and my husband for their support and understanding during my study in Hong Kong.

# CHPATER 1: INTRODUCTION

## 1.1 Motivations

### 1.1.1 Crowd Safety in Large-Scale Outdoor Events

Literally defined by *Collins Dictionary*, a crowd is a large number of things or people gathered or considered together, a particular group of people. Normally, a crowd often refers to a gathering of individuals with no concern to their nationality, profession or sex and the reason that has brought them together (LeBon, 1985). However, there is a high risk of injury and even loss of life, whenever crowds are formed purposely for specific objectives like celebrations, carnivals, sports games, protests and marches, or unintentionally with no particular goals like traffic jams or shopping malls. There are enormous forces that can be exerted on a single individual by the surrounding crowds (Low, 2000). Crowd Dynamic Ltd has summarized about the death or injuries related with crowding events in Table 1.1. Fires in which the mass evacuation results in death or injury are also included (CrowdDynamcs.com). They also made statistics on crowd-related disasters happened around the world since 1902. It has showed that there is a serious and increasing problem with human safety arising from crowds and crowding, especially in recent decades. Thus a proper understanding of how the group behavior of people induces risks is vital to minimize risks in the crowding situations.

| **Types** | **Dead** | **Injured** |
|---|---|---|
| Stadia | 593 | 3245 |
| Religious | 2586 | 1356 |
| Hotel Fires | 439 | 661 |
| Concerts/Mass Gatherings | 1359 | 583 |

**Table 1.1 Crowd Related Death or Injuries**

Source: adapted from www.crowddynamics.com (Access on 2005/09/28)

Within the large number of crowded events, one type of them, the event taking place in urban areas and especially in outdoor street environments, should be paid more attention. For example, special sport games held mainly for public participation, recreational firework displays for improving citizen's quality-of-life, and large-scale celebrations or parades usually attract a huge number of people gathering together. But deficient crowd management may probably result in tragedies, like the following:

- Jan 1st, 1993, Lam Kwai Fong, Hong Kong, 22 people were crushed to death on New Year's Eve. The location (narrow streets and a sloped gradient), poor police planning and bad weather, all of these played their parts in this disaster (Bakhary, 1993)
- July, 2001, Akashi, Japan, at least 10 people died and more than 112 were injured in crowd crush after a firework display.
- Feb 5th, 2004, Beijing, China, at least 37 people were killed and 15 injured at a lantern festival. There were many people crowding to watch the fireworks and lanterns on one bridge which spans a 100-metre canal, and tragedy resulted.

It is hard to conceive that crowd safety can be guaranteed without the systematic management and cooperation of all involved in events that encourage or allow crowds to form. But, as event managers who are directly in charge of crowd safety in these outdoor events, the police departments often need to prepare and arrange carefully both manpower and material resources to maintain a safe event environment with cooperation from different management sectors. It therefore seems that they, who would normally have the first and possibly the last word on what happens on streets, should take steps to make themselves aware of any event-related knowledge that is helpful for their operations. Normally, operations adopted in such events are based on the managers' experiences, while they themselves often lack the knowledge of crowd dynamics due to complex and ruleless human behavior. Therefore, any insufficient management measure or ill-considered detail may increase possibilities of dangers. Just like the Japan event in 2001, the major crowd safety flaws that led to the crowd crush and crowd collapse disaster are, according to Crowd Management Strategies (Crowddynamics.com), deficient dispersal routes without the forecasting design for the capacity of large crowds, underestimation of the size of anticipated event audiences, lack of emergency exits on the walkway, flawed or poorly-executed or non-existent emergency plan and failure of a timely response to the initial signs of the impending disaster. Even through people find the deficiency in such events, they still do not know how to improve their managements. Just as Bokhary (1993) suggested in his final report on the Lam Kwai Fong Disaster, efforts should be made to pool and expand event managers' knowledge of the problem on dealing with crowd management. While still, there are few, if any, established tools and techniques in regular uses today capable of providing more than a limited level of assistance to the crowd management during events. '*Nip in the bud*' – to provide an effective crowd management for such large-scale outdoor events is important and urgent to prevent tragedies before or when something happens.

### 1.1.2 Collaboratively Managing Crowds in Large-Scale Outdoor Events

Large-scale outdoor events normally are of three features. Firstly, they are scheduled with the time-period and location. Before each event happens, both the event managers and event participants—mostly the pedestrians—know the time-period and venue. The crowded phenomenon is also known by both. However, neither of them will clearly know how many participants will come together, which makes the management work difficult to be estimated. Secondly, there are a large number of participants involved in the events and the venue occurred takes on a larger area than on just one point, which also makes the "Scale" mean in this thesis. Normally, this kind of outdoor events will attract thousands of pedestrians and at least several blocks will be affected by them. Just taken the example of firework display, its buffering zone can reach several miles in urban areas. Thirdly, these events are carried on a street or an outdoor environment. Most of the pedestrians' behavior will be limited on the ground for the purpose of safety. There are no obvious signs or guides that can lead the pedestrians' movements as in the built environment. Interactions between them are the largest connections between participants which are dominant with their behaviors.

The characteristics of such events make them complicated systems which researches or applicable crowd management measures are relatively difficult to explore. One of the feasible ways to manage crowds in these events is to build crowd behavioral model. In fact, crowd phenomena have attracted attentions from various disciplines. Since pedestrians are the components of crowds, pedestrian dynamics has become an growing research area that covers the range of topics including pedestrian motion, multimodal and intermodal traffic, evacuation simulation, video detection methods, operations research and optimization, offshore vessel evacuation, requirements and regulations, and etc. (Schreckenberg and Sharma, 2002). Quite a number of pedestrian models have been developed to investigate on different pedestrian behavioral dynamics. From Fruin's (1991) level-of-service concept to large number of pedestrians models like queuing models (Yuhaski & Smith, 1989; Roy, 1992), transition matrix models (Garbrecht, 1973), social force models (Helbing et al. , 2002), to AI (Artificial Intelligence)-based models (Blue & Adler, 1999; Gopal & Simth, 1990; Schelhorn et al., 1999), researchers want to find the changing characteristics of pedestrians and/or crowds to design or improve the urban facilities or overall urban systems. However, most of the studies have taken care of human behavior only under emergent situations. It is far from enough to apply them on managing crowds in large-scale outdoor events which need cares on full processes of how crowd form and disappear in normal situation, and how to evacuate crowds if there are emergencies. As Fruin (1993) pointed out, crowd management is to systematically plan and supervise the orderly movement and assembly of people. The term "management" means all measures taken in the normal process of facilitating the movement and enjoyment of people, as well as all measures prepared to be taken in the emergent process of people evacuations. Moreover, crowd management can be successful only when viewed as a combination of management of all the crowds, environment and their relationships. This is especially necessary for the large-scale outdoor events. Geographic Information System (GIS) combined with spatial database provides an effective solution for crowd management. It can integrate multiple spatio-temporal data and models in large-scale geographic environment of outdoor events to achieve management of facilities, crowds and personnel.

Furthermore, managing crowds in large-scale outdoor events is a team work involving cooperations and collaborations, as it is not only chief managers sitting in the control center and giving orders to subordinates, but also communicative decision-making processes transmitted between event managers during the whole event at same-/different- time and same-/different- location. A platform capable of supporting communicative information transfer and group decision-making is necessary for efficient crowd management in large-scale outdoor events. Geographers have begun to explore the value of merging collaborative techniques with geographic information science and technologies. As "visually-enabled collaboration with geospatial information through geospatial technologies" (MacEachren and Brewer, 2004), crowd management should be moved forward to support geocollaboration. However, most of the current crowd-related research mainly from two perspectives: crowd psychology and crowd engineering, although there have been some of studies combing GIS to explore crowd behavior in such events (Batty, 2002) in recent years, a framework for geo-collaboratively managing crowds for large-scale outdoor events is still absent.

### 1.1.3 Spatio-Temporal Pedestrian Behavior and Interactions

When crowd safety becomes our main concern for managing pedestrians, their behavioral dynamics should be paid critical attention to take reasonable measures in outdoor events. First appeared in the 1960s and early 1970s, behaviorally oriented research in geography is considered a shift in emphasis from the aggregation of the individuals. An increase in the relative volume of research is also conducted at the micro-scale. Behavioral geography treats people as responders to stimuli. It seeks how different individuals respond to particular stimuli (and also how the same individual responds to the same stimulus in different situations), how to isolate the correlations of those variable responses and how to build models that can predict the probable impact of certain stimuli. By treating with individual behavior, it is believed that human behavior is composed of external behavior and internal behavior. External behavior are that a person really acts like walking, shopping and turning left or right. Internal behavior are governed by human's spatial cognition and decision making (Gold, 1980) (Figure 1.1). It is also realized that human behavior and interactions are limited by the spatially built environment.

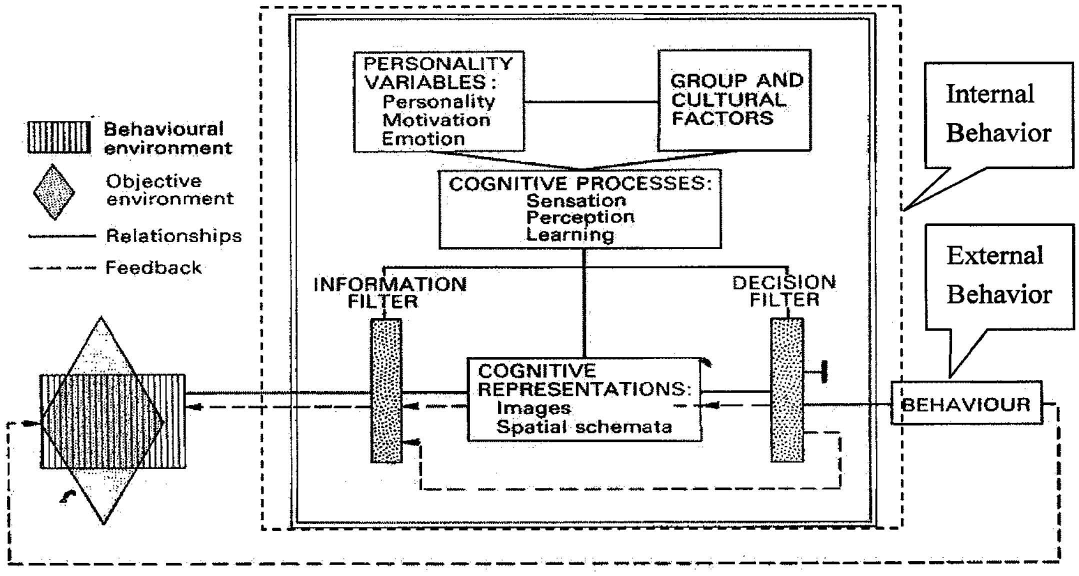


**Figure 1.1: A Paradigm of Individual Spatial Cognition and Behavior**

Source: adapted from Gold (1980).

However, time and space are absolutely inseparable from the intricacies of human behavior (Golledge and Stimson, 1997). One of the earliest spatially integrated perspectives for the analysis of human activity patterns and movement in space and time is called time-geography. Developed by a group of Swedish geographers associated with Torsten Hagerstrand (1970), the time-geographic perspective has inspired generations of social scientists, especially geographers and transportation researchers in the spatio-temporal description and analysis of human activities. Time-geography not only highlights the importance of space to understand the geography of everyday life, but also allows the researchers to examine the complex interactions between space and time and their joint effects on the structure of human activity patterns in particular localities (Cullen et al. 1972). The scale of "time" in time-geography could be daily, weekly, and even life-time. This kind of approach is also called activity-based approach, which represents the spatio-temporal human behavior based on activities they take in a period of time, but it does not consider the interactions between different individuals, for example pedestrians. Interactions become more important when we look down to a single event where individuals behave within the same space and the same time-period (Figure 1.2). "Time" in this smaller scale can be divided into "steps" that individual takes. Pedestrians in large-scale outdoor events have respective behavioral route, while their spatial and temporal behavior are restricted by their interactions. Exploring and modeling the pedestrian behavior and interactions will shed light on the new way of crowd management from a geographic perspective.

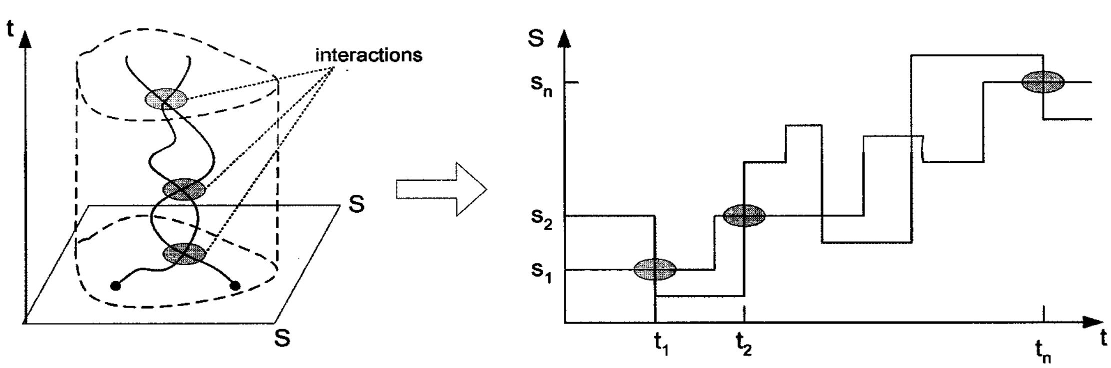


**Figure 1.2: Spatio-Temporal Human Behavior and Interactions**

Source: author.

When we focus the human behavior on one single event, motivations and intentions are simultaneously important to the conduction of behavior. Those crowds which gather to complete a social function or a duty, are encouraged or even praised, as performing positive human activities. However crowds have been regarded as somehow sinister when they gather for a political purpose (Ibrahim, 1998). Different reasons that crowds assemble bring different crowd behavior. It is vital to understand the nature of a particular crowd for two reasons: in order to effectively and efficiently mobilize personnel strength and material resources, and in order to prevent unnecessary risks of harm or violence by provoking an otherwise peaceful crowd. Further, by increasing availability of geo-referrenced high-resolution data and improvement in the representation and geocomputation capabilities of GIS, it is now more feasible than ever before to operationalize and implement spatio-temporal human activities and their interactions. Moreover, the use of GIS also allows to incorporate a large number of geographic data that are essential for any meaningful analysis of human activity patterns. GIS or GISci (Geographic Information Science), as a discipline at the same time, have developed to satisfy the requirement and support the development of pedestrian behavioral modeling.

### 1.1.4 Geosimulation: Agent-Based Modeling of Crowd Behavior

Pedestrian crowds are self-organized systems with the characteristics of complexity. Complexity is a technical term in an emerging scientific and nonlinear view of the world (Waldrop, 1992). The key insight of complexity is that, when we work with nonlinear systems, there is a limit to our powers of prediction, even if we completely understand the involved mechanisms. Due to this feature of human behavior, just as the social sciences Herbert Simon (Simon, 1987) argued as the “hard” science, pedestrian behavior is also a kind of “hard” behavior with certain kinds of hard controlled experiment. In particular, it is difficult to test hypotheses concerned with the relationship of individual behaviors to macroscopic regularities. The agent-based approach originating from computer modeling techniques can help to overcome these problems and has been largely applied in the social science research (Epstein and Axtell 1996), like pedestrian dynamics. In this approach, fundamental social structures and group behaviors emerge from the interaction of individuals operated in artificial environments under rules that place only bounded demands on each agent’s information and computational capacity. Most of the existing pedestrian models are built on assumptions, including utility maximization, complete knowledge and optimality. These assumptions are also called structural models that usually represent the movement of collective activities of population. While the human behavior is so complex that we cannot simply represent their movement by using equations, agent-based approach that represents the human behavior from disaggregate view is a better way to explore the emergent behavior through expressing the interactions and communications between pedestrians.

Agent-based modeling is a process of simulation as well, since it depicts the agent's growth in time. Geosimulation, geographical simulation, is a catch-all title that can be used to represent a very recent wave of research in geography (Benenson and Torrens, 2004). In a broad sense, the field of geosimulation is concerned with the design and construction of object-based high-resolution spatial models, to use these models to explore ideas and hypotheses about how spatial systems operate, to develop simulation software and tools to support object-based simulation, and to apply simulation to solve real problems in geographic context. Simulation of human behavior in space is a powerful research method to advance our understanding of the interaction between people and their environment. It allows both to examine and to test models and their underlying theory as well as the observation of the system's behavior (Gimblett et al. 1997). Computational tools are now commercially available for the simulation and design of emergency evacuation and egress. However, most current computational tools focus on the modeling of spaces and occupancies, but rarely take into considerations of crowd behavior and crowd interactions. Understanding nonadaptive crowd behavior is essential to develop effective strategies and models for safety. Agent-based pedestrian behavioral modeling and simulation provide the alternatives for effective crowd management in large-scale outdoor events.

Agent-based modeling and simulating pedestrian behavior to manage the crowd in large-scale outdoor events also brings three requirements for technology support, which are: detailed individual-level data, high-speed calculating capability and analytical tools that can realistically represent the complexities of an urban environment. With the development of geographic information technologies and science, above requirements have been rationally fulfilled. First, since Goodchild (1999) proposed that GIS and Transportation development should move from map view to navigation view to behavioral view, more researchers have begun to work from the third view which explicitly deals with the behavior of discrete objects. There are opportunities to model complex behavior by developing measures to capture individual information and to represent thousands of individual information provided. It also means that we have the ability to look into events from top to down, from aggregated to disaggregated views, especially when exploring detailed complexities of social phenomena. Second, large-scale outdoor events normally will attract thousands and even millions of participants which challenge the speed of computation and visualization. Luckily enough that modern technologies can overcome these problems. The same is true within the GIS discipline, especially the geo-computation and geo-visualization. Geo-visualization, visualization of geographic information, is the use of concrete visual representations and human visual abilities to make spatial contexts and problems visible (MacEachren et al. 1999). There is a large number of attributes that can be used to characterize human activity patterns. By handling these attributes, geo-visualization is a promising direction for exploring and analyzing large and complex data sets. Through involving the geographical dimension in the visualization process, geo-visualization greatly facilitates the identification and interpretation of spatial patterns and relationships of complex data of a particular study area in the geographical context.

## 1.2 Research Questions

Since motivations for this thesis research come from both two sides: applicable crowd management in our daily life and academic research towards modeling and simulating nonlinear social phenomena. Research questions of this thesis work also come from views of two perspectives: event managers and researchers. First, from the perspective of event managers, this research needs to know "how to effectively manage large number of people moving in a short duration". Second, from the perspective of researchers, they try to provide new methods and platforms to efficiently facilitate the management, and find new knowledge on crowd behavior in outdoor events as well. Both questions come down to build crowd behavioral models for large-scale outdoor events.

Building crowd behavioral models firstly requires knowledge of real processes of crowd movement in outdoor events. Specific cases are necessary to be selected as a starting point for explorations. By examining carefully on existing cases, factors that affect crowd movement are analyzed or calculated, especially the effects of urban built environment on pedestrian behavior. This knowledge works as both the input for crowd behavioral models and the references for managing crowds for event managers.

Secondly, building crowd behavioral models need to choose appropriate and feasible approaches that are applicable to outdoor events. Due to the complexity of human spatio-temporal behavior, agent-based modeling methods make it easier to grasp collective behavior emerging from individual interactions. Formalizations of multi-agent based models should be explained in detail, including the definitions and classifications of agents, interactions, and behavioral rules.

Thirdly, the ultimate aim of building crowd behavioral models is to provide suggestions for event managers to make reasonable management. Platforms for event managers to exchange ideas and communicate information will be established with the characteristics of realizing geo-collaboration. As a platform for storing, manipulating and representing spatio-temporal information, GIS is an effective system to provide simulation, visualization and spatial analysis, even though it cannot represent dynamics processes. Integrating and simulating models should be implemented to make experiments on crowd behavior under different scenarios when different conditions or parameters are set.

As crowd management includes all measures taken not only in the normal phases of facilitating the movement and enjoyment of people, also in the emergent processes of safely evacuating people in a reasonable period of time, research questions can be reified into following detailed questions:

- What are the dynamics of crowd behavior during different phases in large-scale outdoor events?
- What are the driving forces for the participants' behavior in such events? Especially what are the effects of urban built environment on the activity participants?
- What are the crowd behavioral models in large-scale outdoor events? Especially what are the interactions between pedestrians and what are their behavioral rules in outdoor events?
- How to integrate agent-based pedestrian models into GIS?
- What preparations should be made for effectively managing crowds?

## 1.3 Research Scope and Thesis Objectives

Above research questions are going to be addressed in this dissertation by deeply studying the case of the outdoor event "*Firework Display in Hong Kong*". The overall objective is to establish the framework for geo-collaborative crowd management for large-scale outdoor events, with a focus on the multi-agent based crowd behavioral modeling and simulation. Dynamics of crowd behavior in the case event are explored and analyzed to provide the generalization of pedestrian models in the outdoor event, which will complement the knowledge on crowd behavioral dynamics and vice versa. Both of the dynamics and models are integrated within the crowd management which aims to provide a geo-collaborative platform to acquire a safe environment for pedestrian behavior, thereby managing the crowds, physical environment and emergencies involved in the outdoor event. This platform will also facilitate decision making by visualizations, simulations and analysis on crowd behavior (Figure 1.3).

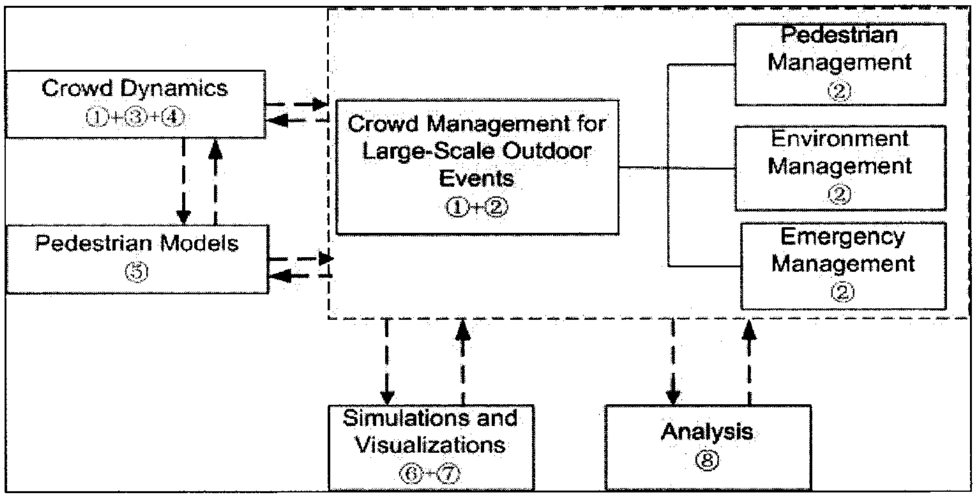


**Figure 1.3 Research Objectives**

Source: author.

The general two objectives of this thesis can be represented as:

①To find the dynamics of crowd behavior in large-scale outdoor events;

②To provide a framework for geo-collaborative crowd management in large-scale outdoor events.

For the objective of finding the dynamics of crowd behavior, practical explorations on the case event and experimental modeling on pedestrians interactions are adopted to achieve the following detailed objectives, including:

③To find the real behavioral processes of crowds in the case event;

④To analyze the driving forces for crowd dynamics in outdoor events, with the issues on the relationship between urban built environment and human behavior;

⑤To model the pedestrian dynamics in different phases;

For the objective of providing a framework for geo-collaborative crowd management, specific tasks should be accomplished, including:

⑥To integrate crowd behavioral models within crowd management;

⑦To simulate and evaluate crowd behavior in outdoor event with different scenarios;

⑧To provide analysis and suggestions for event managers on effectively managing crowds in large-scale outdoor events.

## 1.4 Thesis Structure

The remainder of the thesis is structured as follows:

This chapter introduces the research motivations of crowd management for large-scale outdoor events and outlines the objectives of this thesis work.

Chapter 2 reviews existing researches on dynamics of pedestrians and crowds from different views. Firstly, two types of models that have been proposed and developed in different fields are classified and reviewed which are aggregate models from macroscopic perspective like LOS concept, queuing models, gravity models, FIST model and fluid or continuum models, as well as disaggregate models from microscopic perspective like social force models, cellular automata (CA) models, and multi-agent models. Secondly, since multi-agent based modeling approach is used in this thesis work, latest development on modeling tools and simulation system based on multi-agent approach are emphasized and reviewed. Thirdly, evaluations on using multi-agent based modeling methods are carried on to analyze the advantages and disadvantages of this approach, thereby introducing rationales when adopting such an approach into this work. Fourthly, based on the reviews, summary is made that it is necessary to link geographic information technologies in crowd management system when modeling spatially-explicit crowd behavior.

Chapter 3 proposes the conceptual framework for geo-collaborative crowd management in large-scale outdoor events. After a discussion on the basic concepts of geo-collaboration and requirements for realizing geo-collaboration in crowd management, a conceptual framework is proposed and components within it are detailed explained including data environment, visualization environment, interface environment, user environment and technologies support. Methodologies used and data collected for the case event are also elaborated.

Chapter 4 explores the crowd dynamics in case event and analyzes the driving forces for the formation of such dynamics. Firstly, behavioral dynamics of crowds in three phases of pedestrian arrival, crowd dispersal and crowd evacuation are explored. Secondly, crowd behavior in the case are analyzed which is affected by the combination of event motivation, pedestrian's goals, pedestrians visibilities, urban morphology and spatial controls in the events. Understanding these crowd behavioral dynamics makes theoretical grounds for building crowd behavioral models reasonable and reliable, and provides quantified prerequisites for that in terms of viewshed value that is calculated on pedestrian's visibilities. Thirdly, through the explorations on crowd behavior in actual events, some of suggestions are put forward for managing crowds in large outdoor events, and dynamics of crowd behavior are gained both as knowledge for management and as hints on modeling and simulating crowd behavior.

Chapter 5 builds the *Multi-Agent Pedestrian Models for the OutDoor Events* (MAPMODE). In MAPMODE, each pedestrian is viewed as an intelligent agent that is the focus of the model. Multiple agents are represented with different roles of objectives in such event mainly according to their functions, such as attractors (fireworks in arrival phase, road exits in dispersal and evacuation phase), policemen, buildings, roads, road blocks, and emergencies in evacuation phase. Interactions between agents control the agents' growth which leads to different behavioral sequences. So first, elements within MAPMODE are defined, including agent, space, interaction, and time. Second, a generic pedestrian behavioral model in crowded event is built corresponding to behaviors including destination choice, route choice, random walk, collision avoidance, and flocking behavior. Generic behavioral framework is formed and data structure in the model is formalized. Third, three detailed models are developed based on the phases formed in outdoor event, including model for crowd arrival, model for crowd dispersal and model for crowd evacuation. Each model is carefully expounded by interactions existing and behavioral rules formed during crowd movement. MAPMODE are formalized with executable algebraic specifications for simulation development.

Chapter 6 tries to integrate and simulate MAPMODE, therefore builds a platform of *Integration and Simulation of Crowd Behavior* (ISCB) for geo-collaboratively managing crowds. Design and implementations of ISCB are explained in detail for scenario simulations. There are total 10 scenarios are experimented to represent the MAPMODE developed in Chapter 5. Simulations further provide comparisons of different measures taken and provide decision support for effectively managing crowds in large outdoor events.

Chapter 7 summarizes the work done in this thesis, draws the significance and limitations of this work, and identifies further perspectives to be done for the finalization of the framework proposed in this research.

# CHAPTER 2 RESEARCH ON DYNAMICS OF PEDESTRIAN CROWDS: A LITERATURE RIEW

## 2.1 Introduction

Pedestrian crowds have been a research interest within different disciplines for a long period. For example, psychologists try to find the relationship between pedestrians' psychology and behavior within a crowded environment; urban planners and decision-makers would like to improve the urban infrastructures through studies on different levels on pedestrian density and speed; engineers and mathematicians use models to find the dynamics of pedestrian behavior; and geographers endeavor to work on the spatial effects on pedestrian movement. Most of these research are partly involved in each other, and the common objective is to reduce the crowd disaster in terms of developing theories and technologies. As an integral part of an overall urban system, the flow of large pedestrian crowds is likely to become more important for safety with the population growth of our large cities. Although empirical studies on dynamics of pedestrian crowds have been worked on for more than four decades (Helbing, 2001) and different modeling methods and applicable systems have been developed to try to improve the built environment and reduce tragedies that crowds may cause, our knowledge on crowds is still inadequate and remain far behind the development of other transport modes (Wigan, 1993). It is an important reason accounting for few researches on the pedestrian crowds that crowd behavior is a complex reaction induced by a series of intricate psychological decision processes. Each person has his own choice of random direction, has no conversation of momentum and can stop and start at will. This walking dynamics do not completely follow the law of physics or any others. Anything including psychology seems difficult to find its nature. But still, understanding pedestrian behavior is essential for crowd modeling to plan and design urban establishment, and to manage public events (Hoogendoorn and Bovy, 2002).

Nevertheless, interest in crowd modeling has many sources. Examples include crowds associated with transport systems (Daly et al., 1991; Toshiyuki, 1993; Smith, 1993), sports and general spectator occasions (Bradley, 1993), holy sites (Al Gadhi and Mahmassani, 1991; Selim and Al-Rabeh, 1991), political demonstrations (Surti and Burke, 1971) and fire escapes (Tanaka, 1991). However, even in the same situation behavior of pedestrians varies not only with their physical characteristics but also with their purpose as shown by Polus et al. (1983) and Pushkarev and Zupan (1975). And in the modeling of pedestrian crowds, compared with the physical characteristics of crowd behavior, more psychological or "social" factors related to pedestrians are added in the models of pedestrian crowds, especially after 1990s in order to make the models more realistic. But how to quantify these social factors are still the main arguing themes. There is also a diversity of modeling approaches applied to crowd modeling and improving with the development of technologies. However, there are two fundamentally distinct philosophies for modeling pedestrian crowds, viz. aggregate models and disaggregate models. Aggregate modeling method treats the crowd as a group and tries to view the crowd as physical objects, for example gravity models, fluid-flow models, continuum models (Huges, 2003). Disaggregate models consider pedestrians in a crowd as discrete individuals and represent pedestrian behaviors generally through computer simulation. This kind of modeling approach tries to find the collective dynamics from a single individual behavior, and have become an intelligent method that models the society from bottom up. Pedestrians are modeled by using a granular material analogue (particles, cells, agents), modeling the path to optimize their immediate local behaviors, or restricting them along predefined globally determined paths. Both Lagrangian simulation, whereby individuals are followed through the domain, and Eulerian simulation, whereby an account is kept of the number of individuals in each grid box in the domain, are used.

In this chapter, current researches on crowd modeling are firstly examined and divided into two parts according to the modeling philosophy, aggregate models and disaggregate models. Secondly, the Multi-Agent (MA) based modeling method and its advantages and disadvantages are reviewed in detail, including the present pedestrian planning tools, the existing bodies of literature, and the applicability of present techniques and systems. Through the review, MA method is found feasible and suitable for the crowd management in large-scale events which deals with the pedestrian as a thinking and intelligent object. An integration of GIS and Multi-Agent system (MAS) will give better support for spatially explicit management.

## 2.2 Aggregate Models

At the beginning stage of crowd researches, models were concluded by using regressions and other statistics, and many experiments were studied in an empirical way. The evaluation methods were based on direct observation, photographs, and time-lapse films. Apart from behavioral investigations (Batty, 1997; Hill, 1984), the main goal of these studies was to develop a level-of-service (LoS) concept, design elements of pedestrian facilities, or planning guidelines. Then increasingly, there existed some aggregate simulation models. As pointed out in the former part, compared to intelligent pedestrian modeling methods developed in recent years by new information and computer technologies, aggregate pedestrian models normally views the whole pedestrian crowds as an integral part of an urban transportation system. They try to model pedestrian behaviors through analogies with natural physical phenomena, like queuing models, gravity models and gas-kinetic models. Most researches come out from transportation engineering and model the pedestrians together with vehicles.

### 2.2.1 LoS for Planning and Design

The concept of LoS was first proposed by Dr. Fruin in his book "*Pedestrian Planning and Design*", in which he defined the criteria for safety standards in places of public assembly. He defined this LoS concept where the relationship between density and speed is stated as guidelines for comfort and safety. He proposed in his book six levels for walkway, stairway and queuing differently, which mainly serve for the design of roads, stairs and buildings. He argued that body depth and shoulder breadth were the primary human measurements for pedestrian spaces and facilities. He acquired the statistic data of a fully clothed male laborer, 22.8 inches by 13 inches (57.9cm by 33cm), which indicated the necessary square meters per person related to his LoS category (Figure 2.1). This LoS concept is still used nowadays in architecture or project design as the standard for many subsequent building design and planning operations. References to Fruin have been universally accepted, although there are surely some revisions based on LoS when applied in different fields and countries in terms of different normal sizes of each pedestrian in different region, for example, the Tanaboriboon data measured in busy bazaar environments in Thailand, and the Green Guide (1997), which is used as guideline in U.K.. It is important to note that crowd behavior on a city street with many distractions is quite different from the stadium behavior, and quite different from emergency egress behavior. Therefore, the LoS in different areas has different results for every level.

**Fruin - Level of Service Category**

| Level of Service | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Walkways | >3.25 | 3.25 to 2.32 | 2.32 to 1.39 | 1.39 to 0.93 | 0.93 to 0.46 | < 0.46 |
| Stairways | >1.85 | 1.85 to 1.39 | 1.39 to 0.93 | 0.93 to 0.65 | 0.65 to 0.37 | < 0.37 |
| Queuing Areas | >1.21 | 1.21 to 0.93 | 0.93 to 0.65 | 0.65 to 0.28 | 0.28 to 0.19 | < 0.19 |

A = Free Flowing
B = Minor Conflicts
C = Some Restrictions to Speed
D = Restricted movement for most
E = Restricted movement for all
F = Shuffling movements for all

**Figure 2.1: Fruin's LoS Category**

Source: adapted from Fruin (1973).

Based on LoS concept, Aoki and Oto developed a system, Passenger Flow Evaluation System (PFES), in conjunction with the Japanese Research Institute (Aoki,1994), which is an application of the Fruin's models with suitable adjustments for the Japanese profiles and speeds measured in their transit systems (1.4 meters per second for free flows and an associated graph to determine the speed in various cross flows). Pedroute is another computer simulation system which is an extension of LoS and relies on data being an accurate representation of the crowd dynamics in local geometry. Pedroute has been extensively used to model crowd parameters in underground networks around the world. But, the deficiencies of the Fruin data were highlighted on a stadia safety conference (Stadia & Arenas 2000), in particular the problems associated with application of the Fruin data for multidirectional concourse areas.

In the end, the LoS concept was found better used as guidelines for design and planning of urban roads, stairs or buildings, which usually have the form of regression relations. However, it is not very well suitable for the prediction of pedestrian flows in pedestrian precincts or buildings with an exceptional architecture. Therefore a number of simulation models have been proposed, most of which are from the views of physics and focus on the aggregate form of crowd behavior.

### 2.2.2Queuing Models

Queuing phenomenon is a common feature in urban congested societies. People wait in line for traffic jams, banking or other services. Fruin also recorded the LoS for queuing (Figure 2.1), and there are many books written about the mathematics of queuing theory. The basic principles of queuing models are that queues have an arrival rate, a service rate, and a discipline. The arrival rate is the frequency and distribution of the things arriving for a service. It may mean the number of arrivals per hour (average) to be served and the time (average) it takes to serve each person.

The mathematics of queues is complex and application of queuing theory requires very careful considerations. It's an appropriate approach for modeling congestion in vehicular and pedestrian traffic network (Smith, 1991; Roy, 1992; Okazaki & Matsushita, 1993). There are also Garbrecht's (1973) transition matrix models, Mayne's (1954) and Ashford's (1976) stochastic models, models for the route choice behavior of pedestrians, all of which are partly related to the queueing models. They are suitable for lines of pedestrians waiting for services, while this kind of modeling method did not consider the interactions between pedestrians and obviously are not applicable for modeling crowds in a square or in more complex surface environments.

### 2.2.3 Gravity Models and Spatial Interaction

When modeling large-scale population movement or migration, researchers began to find the spatial effect on the behavior to model the pedestrian's mobility. Gravity model is such a mathematical model based on an analogy with Newton's gravitational law, which has been used to account for aggregate human behaviors related to spatial interaction, mainly including migration, traffic flows and shopping activities. Social scientists have been using a modified version of Isaac Newton's Law of Gravitation for decades to predict movement of people, information, and commodities between cities and even continents. The gravity model takes into account the population size of two places and their distance. Its main idea is that larger places attract more people, ideas, and commodities than smaller places, and places closer together have a greater attraction. George Zipf's $P_i P_j / D_{ij}$ hypothesis is probably the most widely accepted form of the gravity model which implies that migration between two cities *i* and *j* is proportional to the product of the two cities' populations and inversely proportional to the intervening distance, which can be represented as the following formula:

$$I_{i,j} = k\frac{P_i P_j}{D_{i,j}^b}$$

Gravity model and spatial interaction techniques are major methodologies in the early investigations (Batty 1976). A handful of pedestrian demand models were developed in the 1960s and 1970s for forecasting pedestrian flows and prioritizing pedestrian improvements in CBD areas, for example, Ness, Morrall, and Hutchinson (1969) applied the gravity model to forecast pedestrian volume in the Toronto area. More refined expressions of the model are used in order to predict needs in transport infrastructure. Although under various forms, the gravity formulation of spatial interaction is integral in numerous complex models, it generally summarizes the regional movements occurring in an environment where mobility and accessibility are relatively homogeneous and normally models the movement of two or more groups of pedestrians. Although quite useful from a practical standpoint, the gravity model is a poor model from a theoretical standpoint. Besides, it is a static model, which does not take into account evolution of configuration, in particular the one generated by the flows. Thus these early efforts of modeling were at a rather coarse scale to show the intensity of interaction between the origins and destinations of journeys. They might lead to unexpected obstructions due to mutual disturbances of pedestrian flows.

### 2.2.4 FIST Model

The model that we should never neglect in so many mathematical models is the FIST model. Pedestrians have abilities to think, and their behaviors are a complex cognition process. Often, different pedestrian objectives result in different behaviors. Fruin proposed in his FIST model that social-psychological factors should be considered when exploring the crowd dynamics, although it was only a conceptual model. This model was originally presented at the First International Conference on Engineering for Crowd Safety held in London, England, March 1993. A simple model with the acronym "FIST" was proposed to provide a basic understanding of crowd disasters. The acronym elements are defined as the crowd Force (F); the Information (I) upon which the crowd acts; the physical Space (S) involved, both in terms of individual density and larger scale architectural features; and Time (T), the duration of the incident. He argues that crowd will behave in different characteristics under the stimuli of different socio-psychological factors originating from activity natures. The model was used to illustrate crowd characteristics, to develop guidelines for the prevention of crowd disasters, and step forward to adding social facet into pure mathematical or physical models. FIST concept forecasts the importance of adding social-psychological factors within pedestrians or crowd behavioral models.

### 2.2.5 Fluid or Continuum Model of Pedestrian Flow

Henderson was the first one who conjectured that pedestrian crowds behave similar to gases or fluids (Henderson, 1971; Henderson, 1974). The similarity of the motion of pedestrian crowds with the motion of ordinary fluids can be best found out by a comparison between quick-motion pictures of pedestrians and streamlines of fluids. However, his work started from the conventional theory for ordinary fluids, and assumed a conservation of momentum and energy to be fulfilled. In contrast to Henderson's approach, Helbing (1992) developed a special theory for pedestrians, without the unrealistic conservation assumptions, on the mechanism of relaxation to equilibrium, the role of "pressure", the special influence of internal friction and the origin of "temperature". Additionally, Helbing (1998) found that at medium and high pedestrian densities the motion of pedestrian crowds shows some striking analogies with the motion of gases and fluids. Those include viscous fingering, propagation of shock waves in dense pedestrian crowds and pedestrian-free bubbles. Some interesting results are also derived that can be compared to real situations, for example the development of walking lanes and pedestrian jams, the propagation of waves, and the behavior on a dance floor (Helbing, 1992).

The fluid model became more realistic when sociological issues appeared in the models (Huges, 2002). Unlike a classical fluid, a crowd has the ability to think. The present sociological view of crowds is that unorchestrated crowds are rational and can therefore be expected to abide by scientific rules of behavior (McPhail 1991). The continuum model was proposed by Hughes (2002&2003) which is based on the following three hypotheses: first, the speed at which pedestrians walk is solely determined by the density of surrounding pedestrians, the behavioral characteristics of the pedestrians, and the ground on which they walk; second, pedestrians have a common potential that they face to reach their common destination, thus any two individuals at different locations having the same potential would see no advantage to exchange places; and third, pedestrians like to minimize their estimated travel time but restrict this behavior to avoid extreme densities, and this restriction is assumed that pedestrians like to be separable, thereby minimizing the product of their travel time as a function of density. A full explanation may be found in publications of Hughes (2002). In his research, the model has been used to provide possible assistance in the annual Muslim Hajj, to understand the Battle of Agincourt, and to locate barriers that actually increase the flow of pedestrians above that when there are no barriers present.

Ed Galea (1997), University of Greenwich, also adopted fluid dynamical models and coupled these with discrete virtual reality simulations of human movements. His product, Exodus, has been used in a number of major projects, worldwide. Exodus was designed to simulate the evacuation of large numbers of individuals from large multi-floor buildings. The model tracks the trajectory of each individual as they make their way out of the building or are overcome by fire hazards such as heat and toxic gases. The model is a collection of 20 attributes that fall into four categories: Physical (age, weight, gender, agility), Psychological (patience, drive) positional (distance travelled) and hazard effects (FIN, FICO2, FIH). However, a realistic gas-kinetic or fluid-dynamic theory for pedestrians must contain corrections due to their particular interactions (i.e., avoidance and deceleration maneuvers) which, of course, do not obey momentum and energy conservation. Helbing's fluid model has also begun to add in the individual behavior although based on the aggregate pedestrian flow, but still does not consider the social factors between individuals until his Social Force Model.

### 2.3 Disaggregate Models

Aggregate models are quite applicable for regional population movement or pedestrian flow in transportation system but do not consider the interaction between individuals. When in a more crowded environment and local-scale events, forces that are produced among individuals will make great functions to models, i.e., the object avoidance. At the same time, with detailed or high-resolution data easier to be acquired and the simulation technologies have increasingly developed to deal with large amounts of information, researchers have realized the advantages and importance to build micro-scale models of pedestrian dynamics. In these disaggregate models, every pedestrian is treated as a particle, cellular or an agent, and detailed interactions between individuals have been considered.

### 2.3.1 Self-Organized Social Force Models

Self-organization means the phenomena by which a system self-organizes its internal structure independent of external causes. It is a fundamental property of open and complex systems. Such systems exhibit also phenomena of nonlinearity, instability, fractal structures and chaos. After several years of studying on pedestrian motion and evaluations on a number of quick-motion video films, Dirk Helbing (1998 & 2002) found the self-organized phenomenon on the pedestrian crowds. He and his colleagues Farkas, Molnar, Vicsek concentrates on developing a micro-simulation of pedestrian crowds, which considers each pedestrian as a Newtonian particle subject, and is the first to add both physical and social forces on dynamics of pedestrian movement. The model was also called Helbing-Molnár-Farkas-Vicsek (HMFV) model in name of the four researchers. The social force concept of pedestrian motion can shortly be described as following: Pedestrians are used to the situations they are normally confronted with, their behavioral strategies are determined by their experience which makes reactions to a certain stimulus (situation) be the best, and therefore, their reactions are usually rather 'automatic' and well predictable.

The main strength of the social force models is based on the notions of social repulsive forces that keep pedestrians at a distance from each other. In the HMFV model, each pedestrian feels and exerts two kinds of forces, social and physical, on others. The social forces do not have a physical source; rather, they reflect the intentions of a pedestrian not to collide with other people in the room or with walls and also to move in a specific direction (like, toward and exit) at a given speed. When the crowd's density becomes so high that pedestrians are forced to collide, the physical forces of pushing and friction enter the picture. Thus, the force exerted on pedestrian $i$ by pedestrian $j$ has the following form:

$$\vec{f}_{ij} = \vec{f}_{social\ repulsion} + \vec{f}_{pushing} + \vec{f}_{friction}$$

Using this social force model, they simulated different situations, got comparison with the simulation results, and summarized that the HMFV model was able to explain the formation of the observed self-organization phenomena (Helbing, 2000): lane formation in both uni- and bi-directional traffic, oscillations of pedestrian flux a door through which pedestrians are trying to pass in opposite directions and inefficient use of alternative exits when the panic parameter is either too small or too large (Figure 2.2).

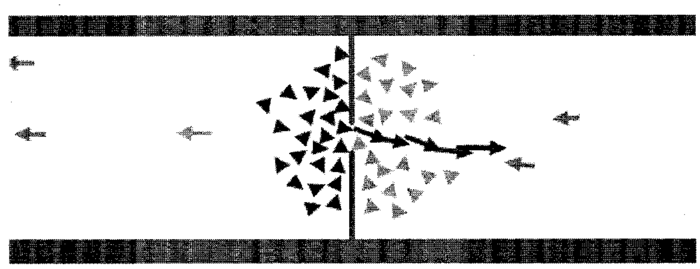

Figure 2.2a Lane Formation by the Interactions Between Pedestrians with Opposite Directions

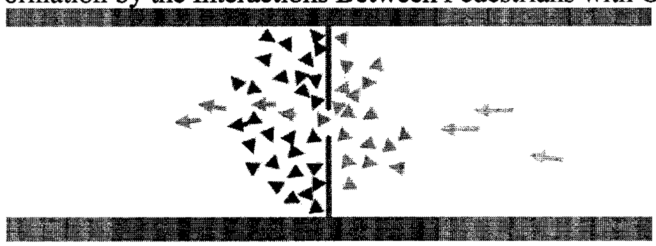

Figure 2.2b Oscillation at a Door

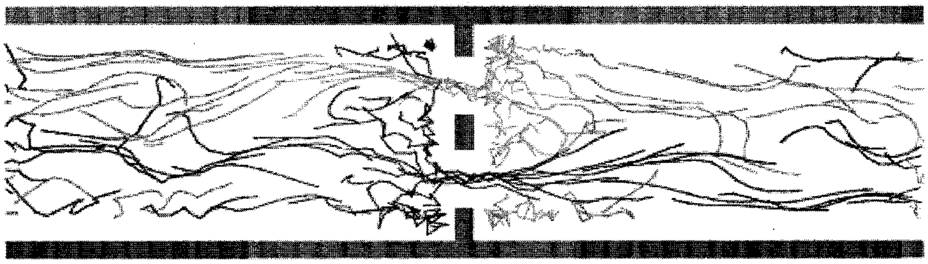

Figure 2.2c The pedestrian trajectories show that, in the case of two alternative passages, each door is occupied by one walking direction for a long time period.

**Figure 2.2: Self-Organization of Crowd Dynamics**

Source: adapted from Helbing (2000).

Social force model made a great step forward within crowd modeling, not only in a micro-scale way, but with the socio-psychological factor added in. This model allows pedestrians to move continuously in a part of the 2-D surface representing a street, a room, and so forth. However, this kind of models do not provide pedestrian with any "intelligence" or decision-making capabilities. The output of pedestrian model could become even more realistic if some amount of "decision-making" capacity were assigned to the pedestrians. Based on it, Lakoba, Kaup & Finkelstein (2005) made some modifications by preventing overlapping among pedestrians and the Forces in the HMFV model to produce a more realistic behavior of an isolated pedestrian or a small number of pedestrians while maintaining the realism of the original HMFV model to simulate large crowds.

### 2.3.2Cellular Automata Models

Social force models and other aggregate pedestrians models are complex since from a view of physics, and often simulate a limited number of pedestrians, while in reality, large crowds consist of hundreds or thousands of individuals that require simple models to provide an accurate description of reality. One such class of models, so-called cellular automata (CA), has been used in the researches on crowd dynamics. CA are simple spatial processing models with their origins in the early architecture of digital computers designed in the 1940 and 1950s. Cells arranged evenly on a tessellated grid-space, cell states, neighborhoods, transition rules and time consist of CA models. The individual cells in CA are occupied at any given time by a discrete state, e.g., full or empty, alive or dead, one or zero. Each cell has a neighborhood of adjacent cells that surround it. Neighborhoods are commonly characterized as either being 'Moore' (the cell in question and the eight surrounding cells that border it) or 'von Neumann' (the cell in question and its four cardinal neighbors) (Schadschneider 2001). Cells evolve according to their transition rules with time steps.

Cellular automata for pedestrian dynamics can be seen in models proposed by Klupfel (2000), Blue (1998), Fukui (1999) and etc. Most works have focused on the occurrence of a jamming transition as the density of pedestrians is increased. They have only nearest-neighbor interactions, except for the generalization proposed in Klupfel's (2000) which is used for analyzing evacuation processes for on-board passenger ships. The other models use a kind of "sublattice-dynamics" which distinguishes between different types of pedestrians according to their preferred walking directions. Such an update is not easy to generalize to more complex situations where the walking direction can change. Schadschneider (2001) proposed a 2-dimensional cellular automata model that is able to reproduce collective effects and self-organization encountered in pedestrian dynamics. This is achieved by introducing a so-called floor field which mediates the long-range interactions between the pedestrians. This field modifies the transition rates to neighboring cells. It has its own dynamics (diffusion and decay) and can be changed by the motion of the pedestrians. Therefore the model uses an idea similar to chemotaxis, but pedestrians follow a virtual rather than a chemical trace. Besides, Egress (SRD AEA Technology) system (Ketchell, 1993) is a pedestrian behavioral simulation system based on cellular automata approach in which the transition of people from cell to cell is based on the occupancy of the grids. They use artificial intelligence techniques to determine how a pedestrian will react in a variety of circumstances including fire. They mainly rely on the relationship:

$$F(p) = p * v(p) \text{ (Flow rate = Density * Speed)}$$

In CA models, space, time and state variables are discrete, which makes them ideally suited for high-performance computer simulations. One important point is that CA are discrete from the beginning. This discreteness is already taken into account in the definition of the model and its dynamics. This allows obtaining the desired behavior in a much simpler way. Challenges also exist for CA modeling. The key difficulties are already apparent, including issues of cellular model calibration, their capacity to represent top-down processes, the meaning of transition rules and their match with theoretical knowledge of how we understand urban systems, as well as the ramifications of tinkering with the formalism that works so well for many closed physical systems.

### 2.3.3 Multi-Agent Based Pedestrian Models

Since late 90s agent-based simulation (or system) has been used to model pedestrian flows at very fine scales of each individual agent. Agent-based models have emerged for many reasons. First, programming has become more object-oriented with individual events and artifacts treated as classes, whose behavior can be explicitly simulated. Second, fine-scale data on locational geometry, on the disposition of activities in cities, and on flows of walkers, are becoming available from various sources: remote-sensing, automatic counting, geo-demographic surveys for marketing purposes, and the integration of hitherto separate data sets in the public and private sectors across a range of spatial scales. Third, our ability to compute is doubling according to Moore's law (Batty, 2000). Fourth but most important, new ways of articulating social systems by using ideas from complexity theory have developed over the last 15 years. These are beginning to merge with similar developments in far-from-equilibrium physics, thus giving this field a sharper edge than anything in the social sciences hitherto.

Originating from computer science, agent was formalized the definition "a system situated within and a part of an environment that senses environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future" (Franklin and Graesser, 1997). Agent based models have some properties. Firstly, agents operate within environments, where they are uniquely adapted just as there may be more than one type of agent or one kind of environment in a simulation. In this context, the kinds of environment are distributed by their nature. To an agent, its environment not only means the environment where it is situated, but also an environment from other agents. Secondly, the ways in which agents 'sense' and 'act' in their environment are central determinants of the behavior which is to be modeled. Agents can be classified in many ways: a key distinction is between 'reactive' agents and 'cognitive' (or deliberative) agents. The difference is with respect to the conditions which drive the 'senses' and 'actions' of the agent. In the urban pedestrian modeling, agents range from the most 'passive' agents that are essentially reactive, to agents that display the kind of intelligence and foresight that they associate with themselves by their own cognition. However a central feature of whatever class of agent we are dealing with in multi-agent pedestrian modeling is their ability to *communicate* which enables them to interact, directly or indirectly with one another, as well as sense and respond to their environment. Interaction between agents can thus take place through the environment which acts as the intermediary.

For the General Framework of Multi-Agent Pedestrian Behavior Modeling, most researchers often get hints from software which provide platform for agent-based modeling. We can first take a look at the structure of *StarLogo*. It consists of three elements: turtles which are agents, patches which constitute the cells of the environment, and the world view which is called the observer. Interactions can occur between turtles, between turtles and patches, and between the observer and each of these elements. These interactions are largely visual, economic, or chemical in terms of the functions that enable them. Agents move according to their heading angle but various distance operators are available. There is no central coordination in the software for the observer to simply act to pass global information down to patches and agents and to organize the software displays. A picture of how the framework operates is given in Figure 2.3.

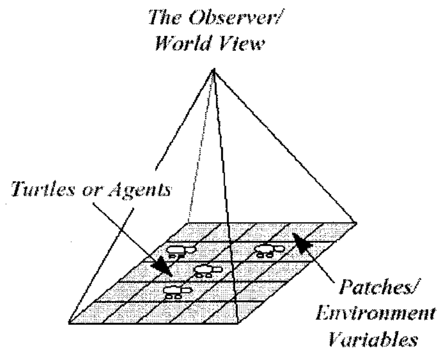


**Figure 2.3: The Turtle-Patch-Observer Structure of StarLogo**

Source: adapted from http://education.mit.edu/starlogo/ (Access on 2006/06/20).

In agent-based models, there are several thousand agents who interact and communicate each other in an environment. This kind of modeling and simulating method has rapidly applied in the field of social science. Researchers find that the paradigm of agent-based modeling and simulation fits quite well the complex social activities. A very early example was developed by Reynolds (1987) to simulate flocking amongst birds for computer animation. The same kinds of behavior can be used to simulate the way ants find and are attracted to a food source, the way investors gravitate to and from rising and falling of stock markets, and the way humans respond to emergencies in closed spaces. This latter example illustrates why such agent-based models are so important in simulating evacuation strategies, which represent another form of pedestrian movement (Helbing et al, 2000). People from geography filed began to use this method to model pedestrian movement, because of the nature of spatial-temporal human behavior. Using state of the art techniques of agent-based simulation and GIS, researchers have developed various models for pedestrian movement in town centers (see a special issue in EPB; Batty 2001). Many others are involved to use agent-based approach to model pedestrian dynamics. The Center for Advanced Spatial Analysis (CASA) has a workgroup researching on the agent-based pedestrian modeling and simulation. Many research results have been published or reported (Haklay, 2001; Jiang, 1999; Batty, 1998; Batty, 2002). The next section will mainly review the latest development of multi-agent based behavioral modeling and simulation of pedestrian crowds.

## 2.4 Latest Development on Modeling Tools and Simulation System Based on Multi-Agent Approach

Intelligent individual modeling methods make crowd modeling break through pure physical models into more socialized and rational models. This bottom-up approach mainly focuses on and integrates multiple factors on pedestrian behavior, especially multi-agent based modeling tries to let each pedestrian as intelligent as in the real world. This has attracted many researchers from different fields and made it an interdisciplinary issue. After more than ten years of researches, the models of pedestrian crowd have been improved.

### 2.4.1 Sugarscape

Sugarscape (Epstein and Axtell, 1996) is a good example that demonstrates how social structures and group behaviors arise from the interactions of individuals. It is part of the 2050 project, a joint venture of the Brooking institution, the Santa Fe institute, and the World Resources Institute. It is the beginning of using AI on study of social science. Although the work does not directly relate with the study on crowd dynamics, it can help in understanding and developing intelligent behavior of pedestrian crowds. Quite a few pedestrian and crowd modeling researches find and adopt the research results. By using MA technology, fundamental collective phenomena such as group formation, foraging, cultural influence, combat and trade have been seen to emerge from interactions within a single population of agents that follow simple local rules. Figure 2.4 describes the agents, agent attributes, and simulation scene in Sugarscape. Agents in this model are born with a vision, a metabolism, and other genetic attribute. So, they can look north, south, east, and west of their current positions and can also see things at a distance. They move in search of sugar according to simple rules. Since this research, it is found that a wide range of social or collective phenomena can be made to emerge from the spatio-temporal interaction of autonomous agents operating on landscapes under simple local rules.

Although the behavior in this system goes beyond how pedestrians actually behave in urban environment, it (and other studies on artificial society: Resnick, 1994; Gershenson, 2000) has influenced the study to learn more about behavioral issues.

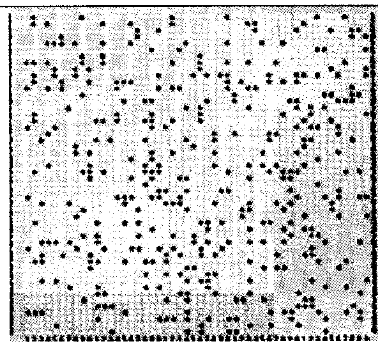

**Figure 2.4a: Sugarscape with Agents**

Souce: adapted from Epstein & Axtell (1996)

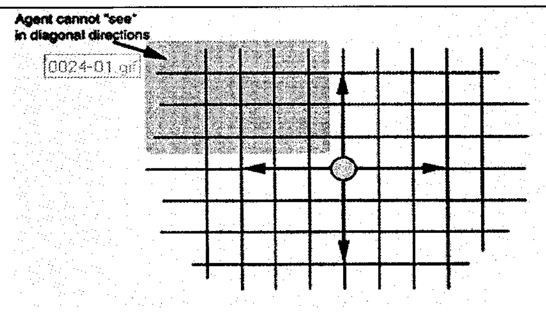


**Figure 2.4b: Agent Vision**

Source: adapted from Epstein & Axtell (1996)

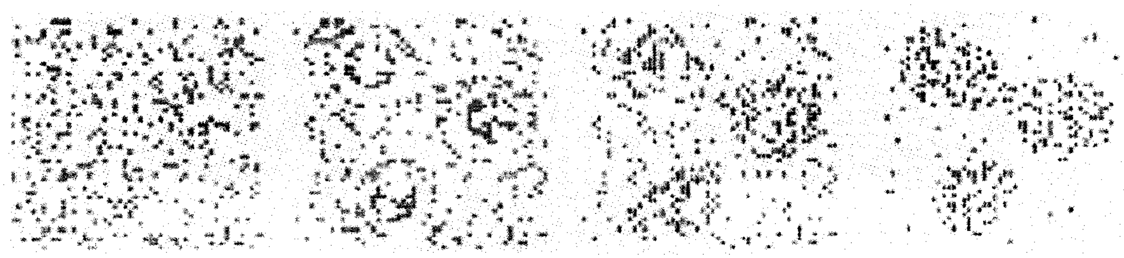

**Figure 2.4c: Simulation Scene- Foraging: Agents Swarming Sugar**

Source: http://www.discovery.com/area/science/life/day01.html, (Access on 2002/09/25).

**Figure 2.4: Sugarscape: Yellow Areas Represent Sugar, Red and Blue Dots are Agents**

### 2.4.2 TRANSIMS (Transportation ANalysis and SIMulation System)

Although not particularly modeled for pedestrian simulation, TRANSIMS is an agent-based simulation system that is capable of simulating the second-by-second movements of every pedestrian and every vehicle through the transportation network of a large urban area (http://transims.tsasa.lanl.gov/). The system can also simulate and analyze traffic impact, congestion and vehicle emissions that can be thought of a virtual world that mimics the traveling and driving behavior of real people in an urban system. With advanced computer technologies, TRANSIMS can model the activities of up to 200,000 individual travelers with detailed transportation networks and households. More recently pedestrian behaviors have been well studied with some experiments in TRANSIMS (Therakomen 2001). The system provides a series of integrated transportation and air quality analysis models and attempts to simulate the aspects of human behavior that are relevant to transportation planning. Models within that system use a multi-actor approach.

However, this system is mostly used for transportation planning or travels of home-work activities, and the pedestrian model does not contain models of cognitive aspects of human spatial behavior (Frank, 2001; Torrens, 2001). Introducing agent's autonomy and cognitive spatial capabilities in simulation models would offer new possibilities for the analysis of phenomena resulting from the decisions and actions of a large number of actors who interact with their spatial environment and other actors.

### 2.4.3 STREETS

STREETS model is an agent-based pedestrian model simulating pedestrian movement in town centers. In this model, Schelhorn et al. (1999) argue that pedestrian movement is affected by configurations and location of attractions, which begins the viewing of human behavior from the perspective of geography. And a two stage model for investigating pedestrian behavior in urban centers is presented, focusing on the division between the two stages: the first stage using GIS-based socio-economic data to populate, and the second stage which is an agent-based dynamic model of pedestrian activity. Features of the environment (e.g. buildings or pavements) and pedestrians are modeled as agents and their attributes are automatically derived from several GIS data sets (e.g. socio-economic data, street networks). Pedestrian agents emanate from gateways and move between pre-assigned way points. On their way they are 'distracted' by other agents and their route is modified by attributes like 'walkability' or 'fixation'. However, the STREETS model is essentially a meso-scopic agent-based model of large urban areas, some of the agent navigation behavior is unreliable, and some group behavior has not been incorporated into this model. At the same time, the matching of buildings with agents and the problem of setting values of building attractiveness needs further development.

### 2.4.4 PEDFLOW

PEDFLOW is developed by a team at the Transport Research Institute, Napier

University. It is a multi-agent micro-simulation tool that is used to study the conflicting pedestrian flows on a section of sidewalk or in an open or enclosed space with obstacles. The main objective of this model is to aid the design of pedestrian networks and facilities in urban areas (Kukla et al., 2001 & 2003). In this model, pedestrians are modeled as autonomous agents moving to a predetermined goal and reacting to obstructions (e.g. bus stops, other agents) according to a set of behavioral rules and each pedestrian is represented as capable of making its own decisions based upon a part of the observable scene local to that pedestrian. Objects in an object-oriented environment are used to represent entities in the real world (e.g. buildings, lamp posts). The location of these entities is described as their index in a two-dimensional array that can be interpreted as a grid or co-ordinate system with the smallest unit of 0.5 meter. Movement is a change of position to an adjacent grid coordinate and an associated delay time, which is considered a step or activation. Agents will re-evaluate their environment with their each activation, and only minimal state information is kept. A shared data structure is used to record the current position of every pedestrian as well as location information about obstacles and the pavement. Displacement behavior is specified in the form of rules which take into account a number of parameters such as preferred gap size, desired walking speed and personal space measure. In order to ensure the rule set represents veridical behavior, the rules originate from computer aided analysis of video footage and are transformed into a form that can be efficiently processed by the agent. By adding tools to extract measures of pedestrian flow, the PEDFLOW model will be made useful to urban planners to evaluate infrastructural changes intended to promote walking in the urban environment. In this model, "walking with a partner" effect has been considered.

Although the context-mediated behavior approach is very flexible, it makes high demands on computational power, because only one of all possible actions generated per step is executed. The number of possible contexts, their complexity and the non-determinism of the random choice makes it hard to calibrate and validate the model. And this model is better for simulating pedestrian flow especially at crossings than complex interactions in a crowded environment.

### 2.4.5 Alpsim

Alpsim is a multi-agent based simulation that models what tourists do. It is a model of planning with virtual Alpine landscapes and autonomous agents (Gloor, Mauron and Nagel, 2003). Eventually it is hoped that the agents although living in a virtual world will be able to plan different activities and scenarios for tourism. These agents will "see" the proposed changes in the landscape and react accordingly. It considers the physical and the mental world completely separately. The most important modules of the mental layers are Route Generator, Activity Generator, synthetic population generation, View Module, Agent Databases, and Viewers.

But in this system, Route Generator is not enough to make agents walk around randomly; for realistic applications it is necessary to generate plausible routes. The module of Activity Generator can compute routes, as the route generator does, but only makes sense if one knows the destinations for the agents. In the synthetic population generation module, the agents are generated. This includes demographic attributes to each agent, such as age, gender, income, etc. but some demographic information about the tourist population in the area of interest is entirely random. Agent Databases connect all of the modules in the system, the modules so far are capable of generating plans, and the mobility simulation is able to store exactly one plan per agent and execute it. There should, however, also be a place where plans and in particular their performance is memorized, so that memory can be retrieved later. Viewers are built so that they directly plug into the live system. This type of model owns the advantages of involving part of mental factors of tourist behavior, but are not suitable for large scale crowd simulations like pilgrimages where the agents would react mentally (using the mental layers below or additional ones) to any proposed changes of their physical environment.

### 2.4.6 Mouse.class

Mouse.class is a Java-based class used for experiments on exploring dynamic behavior in urban places (Therakomen, 2001). This study is based on the principle that the complexity of an urban system can be understood through the local movement of individuals, resulting from an interaction of an individual's visual perception and motivation, as well as the social interaction among individuals. There are, of course, many systems that cannot be characterized in this way but local movement patterns and spatial behaviors in small scale built environment appear to fit the approach rather well. Local movements, in this context, are heavily influenced by idiosyncratic factors such as physical obstructions around which pedestrians must navigate and immediate response to attractions. MouseHaus Table is a computationally enhanced physical environment that supports collaborative urban design discussion. The system consists of a custom-made table with a rear projection screen, a video camera, projector and a simple pedestrian simulation program. MouseHaus Table provides a physical interface that enables participants who have no previous computer experience to interact with a pedestrian simulation program. Input consists of inputting information by using pieces of cut coloured paper to represent buildings etc. These are then incorporated into the computer and a pedestrian model then reacts to the design. It is more effective than using a mouse to input data.

### 2.4.7 SIMPED

SIMPED tries to use agent-based approach to simulate pedestrian flows in virtual urban environment (Jiang, 1999). The aim of this model is to provide a suite of computer tools for urban design and planning using the GIS platform. It is part of CASA VENUE (the Virtual Environment for Urban Environments) project. Integrated with the researches on local movement using agent-based simulation (Batty, Jiang and Goodwin, 1998), the SIMPED simulates the impacts of morphological structure on pedestrian movement in urban cities. A virtual environment with virtual humans is constructed using software Starlogo. Agents in SIMPED have attributes of speed (up/down), heading directions (0-360) and movement (forward/backward). Buildings in real environment, for example churches, hotels, monuments, and etc, are represented as objects in simulated environment. Figure 2.5 is the virtual environment built in SIMPED and one of the snapshots of simulations of pedestrian movement. Two modes of pedestrian behavior, random walking and purpose walking, are simulated in SIMPED. The result shows that MA simulation is capable of providing a valuable tool for study on pedestrian movement in urban area. However, the results at this stage still seem inconclusive. Since SIMPED is based on a kind of local interaction, pedestrian agents can only see one step ahead and they have no ability to improve their behaviors intelligently. In addition, only one type of agents is defined in this model and interacts with other static objects, which makes the model lack of flexibility. This work, so far, may not be sufficient to model pedestrian behavior in real urban environment (Jiang, 1999).

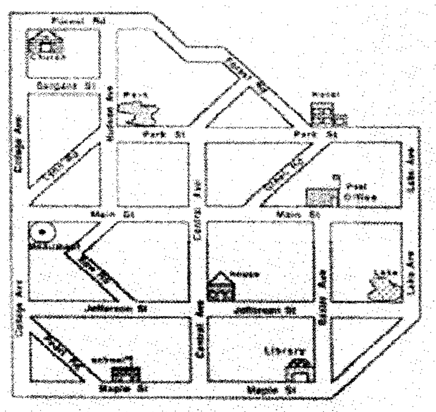

Figure 2.5a: the Virtual Environment in SIMPED

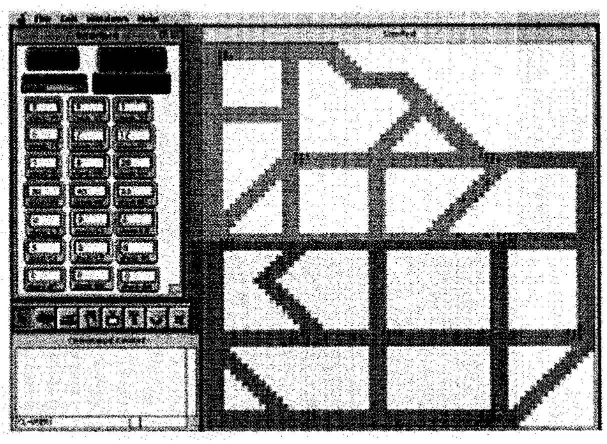

Figure 2.5b: A Snapshot of Pedestrian's Movement in SIMPED

**Figure 2.5: Illustration of SIMPED**

Source: adapted from Jiang (1999).

### 2.4.8 The Notting Hill Carnival Public Safety Project

This project is a cooperation work between CASA and Intelligent Space Company, and aims to examine public safety for the Notting Hill Carnival (Batty, 2002). The Notting Hill Carnival is the single largest operation which the Metropolitan Police undertakes. Carnival events, due to their nature, comprise large numbers of people which constitute crowds. It's an outdoor event in which crowds are the main focal points and their safety and the risks of disorder are the primary concerns. This project tries to study on the carnival event, understand the nature of the crowds in such events, and plan effectively for them. Crowding is a critical problem with conflicts between the parade, moving vehicles, and pedestrians, with dense crowds around the fixed sounds systems (bands). In this project, MA based models have been built to examine how crowds move to the Carnival and within the streets of the Carnival area, and a two stage simulation model is developed to test the interactions between MA. So, thorough this research, alternative routes for the parade that seek to minimize the problems of congestion are found and proposed. This research deals with crowd behavior in large-scale outdoor events by building simple individual behavioral rules for pedestrian agents. But the simulation in this project is not complete since spatial controls are not integrated and simulated, and has not considered the geo-collaboration in practical crowd management. But still, it is a good starting example for focusing on crowd safety in large outdoor events.

### 2.4.9 MAGS Project

The MAGS project is supported by the Network of Centers of Excellence in Geomatics, Defense Research and Development-Valcartier, the Natural Science and Engineering Council of Canada and le Fonds Québécois de Recherche sur la nature et les technologies. It is project providing the platform for multi-agent geo-simulation (Moulin, 2003). Since current available systems for crowd and pedestrian flow simulation rely on very simple agent movements on grids, they often do not take into account terrain characteristics and environmental factors that may influence the agents' perception and navigation. In addition, agent's decision making capabilities are quite basic and group behaviors are non existent or at best very simple. So in the MAGS project, a generic software platform for the creation of multi-agent geo-simulations is developed involving several thousand agents interacting in virtual geographic environments and endowed with spatial cognitive capabilities (perception, navigation, reasoning). Perception and navigation are the two fundamental spatial cognitive capabilities available to MAGS agents. The current MAGS system and its application to the simulation of crowd behavior as well as the potential of this kind of approach for various kinds of simulations in which agents should exhibit plausible cognitive spatial behavior. The MAGS system is not fully completed and optimized. The MAGS teams are still currently working on the development of the scenario specification module and on the agent's spatial memory capability. They are also exploring various alternatives to distribute the computing load on networked computers.

## 2.5 An Evaluation of Multi-Agent Based Modeling Methods

As an individual-based modeling method, multi-agent modeling needs to know the basic attributions of individuals. This is particularly different from traditional crowd research, since behavior of pedestrian crowds is a complex system involving too much individual differences and psychological and cognitive information. It is a hard task for researchers to solve the problem of obtaining real-world individual data, while they have started observing and collecting this kind of data. As an individual-based modeling method, it has the limitation of Analytical Intractability that needs careful treatments during the computation. And validation is still an issue that crowd models are facing with. Although arguing has never been stopping, this individual and intelligent behavioral modeling has become an intriguing way of representing spatio-temporal human behavior when we focus on a local activity and simulating large number of crowds for better management.

### 2.5.1 A New Perspective from Microscopic Individual-based Modeling

The biggest problem with modeling in social science as it emerged in the 1950s was the aggregation problem. Most models were aggregative, built from the top-down. Although there were also some micro-scale models, they were generic, like the theory of the firm. These models cannot explore the exact interactions between pedestrians as the requirement of knowing the pedestrian dynamics increases. The notion of microscopic individual-based modeling method emerges as an approach of modeling from the bottom-up. It is a basic tenet of complexity theory and become possible computationally when enough individual actors can be simulated to provide predictions of more global structure from local action. Crowd behavioral modeling fits this notion of agent-based modeling almost literally.

Individual-based models are a subset of MAS which includes any computational system whose design is fundamentally composed of a collection of interacting parts. Individual-based models are distinguished by the fact that each "agent" corresponds to autonomous individual in the simulated domain. Microscopic techniques provide insight on the behavior of a system under a wide range of conditions. It is an excellent discovery tool and can provide valuable information over a wide range of behavioral inputs and allows operators to test sections of their environment for behavioral dynamics. New approaches based on modeling individual objects, agents, and particles take a very different view of probability than that used in more traditional models. It is already to be known the limits to predictions on human systems that the search for total predictability is a myth. Even in the physical sciences, predictability is a subject fraught with controversies in that only with complete control can such predictability be assured. In real systems, this can never be the case. New developments in complexity, uncertainty, and in the analysis of rare events are beginning to show that we need to develop new ways of thinking about what we are able to predict. Individual-based models are simulations based on the global consequences of local interactions of members of a population. These models typically consist of an environment or framework in which the interactions occur and some number of individuals defined in terms of their behaviors and attributes. In an individual-based model, the characteristics of each individual are tracked through time. This stands in contrast to modeling techniques in which characteristics of the population are averaged together and the model attempts to simulate changes in these averaged characteristics for the whole population.

### 2.5.2 Intelligent Behavioral Modeling

Unlike other individual based modeling objects (particles, cells), agents are not limitedly located in a set range (like grids), have actions and reactions, and change behavior according to surrounding environment, so it is an intelligent modeling method (Table 2.1).

| particles | Cells | agents |
|---|---|---|
| no format | their spatial behavior is constrained by a lattice | allowing for a much richer range of spatial processes |
| no information change | information exchange is mediated through the neighborhood | Agents can "communicate" with other agents as well as with their environments. |

**Table 2.1: Comparison of Different Kinds of Individuals**

Source: author.

However, there is an overlap between agent-based models and CA models. Many pedestrians agents in the multi-agent pedestrian models are situated in cellular environment, each agent owns one cell at one time. But actually, agent-based environment are not constrained within cells, they can be any formats. The core in the agent-based models is the interactions between agents. Perhaps the significant difference is whether the simulation's inner loop proceeds cell by cell, or individual by individual, although that distinction is muddied by parallel-processing hardware. The philosophical issue is whether the simulation is based on a dense and uniform dissection of the space (as in a CA), or based on specific individuals distributed within the space.

### 2.5.3 A Way of Modeling Social Process

One of the important reasons for agent-based modeling as a powerful alternative to more aggregate and more geometric approaches to spatial modeling might be that this is a new way of articulating social systems by using ideas from complexity theory, which have been developed over the last 15 years and begin to merge with similar developments in far-from-equilibrium physics Thus it give this field a sharper edge than anything in the social sciences hitherto. Another reason for MA modeling as a powerful approach might be that it is at the same time a way of modeling social process, thereby involving simulation in modeling. In geo-simulation, MA method is suitable to implement the spatio-temporal processes. Mandl (2000) pointed out that geo-Simulation is a useful tool to integrate the spatial dimension in models of interactions of different types. Figure 2.6 sketches the necessity of geo-simulation methodologically and by content (Mandl, 2000). It can be found that either models of spaces that are mainly static or models of processes do not implement the space-specific facts. And most models represent the entire objects or at least groups of objects, while in a lot of cases it is necessary to take individual properties of the objects into account as they will not be grasped by using global parameter (Mandl, 2000).

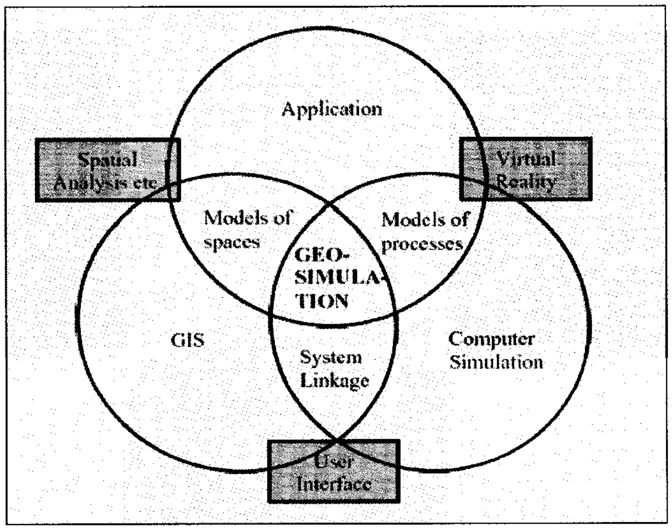


**Figure 2.6: The Field of Geo-Simulation Within an Interdisciplinary Context**

Souce: adapted from Mandl (2000).

Like Mandl's argumentation, MA based approach is preferred for representing interactions of different types. While every agent is doing its tasks as an element within a system, the interactions could generate one or more 'new' unpredicted properties valid for the entire system and not for the elementary agents as individuals (Castelfranchi, 1998). Sichman et al. (1998) also specified the MAS as a strong emphasis on the whole agent rather than solely on its actions and careful attention paid to the process of construction of planning rather than just decision-making and choice. However, although simulation is employed, MA modeling does not necessarily aim to provide an accurate representation of a particular empirical application. Instead, the goal of agent-based modeling is to enhance the understanding of processes that may appear in different applications (Axelrods, 1997).

### 2.5.4 Difficulty in Obtaining Individualized Data

But, one of the disadvantages of MA modeling is that it is difficult to obtain or synthesize demographic data especially at the level of individual and the number of hundreds of thousands pedestrians in a large city. Pedestrian movement is a special complex system. Each pedestrian in this system has his own personality, cognition and behavioral formats. Age, ability, gender, position in the society, all of thee will make effect on his behavior. Also, psychological and cognitive attributions also affect individual pedestrian behavior. For the explicit pedestrian behavior, like, speed, orientation, traditional ways of getting such data are from observation, photographs and statistics, while this data is far not enough for the agent-based modeling. Aerophotography, Remote Sensing (RS), and Global Positioning System (GPS) technologies are now modern means for measuring behavior attributes. Aero-photography seems a realistic way through taking a series of photos that record the pedestrian movement and analyze it, while it cost a lot and will have many social problems in practical usage. Remote sensing technology has developed into a step of high-resolution, all-weather and hyper-spectral. However, for a localized zone and crowded environment, technologies image processing and mode recognition still need improvement, although some researchers are studying the use of RS images to extract information on pedestrian movement. GPS is a very good tool for collecting individual pedestrian behavior through sensing delicate change of location made according to pedestrian preferences. Experiments are still going on, since it is not easy to do it on a large number of people.

Although detailed geo-referenced digital data are now relative easily available, socio-economic data at the micro-scale of individual households, buildings and tracts are still very similar to those that have been available for many years. Realizing the importance of detailed demographic data on the movement of people, there have been simulation systems that statistically sampled. TRANSIMS is such a system simulating the daily movement of individuals in a virtual region or city with a complete representation of the population at the level of households and individual travelers, daily activities of the individuals, and the transportation infrastructure. Individual travelers are assigned a list of activities for the day, including home, work, school, social/recreational, and shop activities, obtained from the household travel activities survey for the metropolitan area (Chowell, 2003). Data on activities also include origins, destinations, routes, timing, and forms of transportation used. Travel Diary is another new survey for collecting individual pedestrian behavior based on activities. A travel diary is a record of trips made by an individual over a 7-day period, recording where they went to and from, how they traveled, how far and at what time they traveled, whom with and the purpose of the trip. CATI (Computer-Assisted Telephone Interview) household survey is conducted about every five years over a 5% sample. Typically, it represents about 160,000 people belonging to 65,000 households declaring some 400,000 individual trip records for an average weekday. Individual trips are geo-referenced for the residence, trip origin and destination, modal junction points, and are described for their household and personal characteristics (age, gender, car license, car ownership, income) in addition to the trip attributes (purpose, mode, departure time, train-subway-bus routes taken if traveling by transit, bridges and highway taken if traveling by car). The survey method has been described in several papers (Chapleau 2001, 2003). A lot of cities and countries are taking this survey to analyze the household or individual behavior, for example, SHS (Scottish Household Survey), NHTS (National Household Travel Survey, U.S.), and etc. And the data has been applied to analyze the socio-psychological factors effects on human movement behavior. With more detailed individual data being collected, it will be rather improved for individual based modeling and will better for decision-making and management.

### 2.5.5 Care in Addressing Analytical Intractability

One of the main criticism for microscopic techniques is the problem of analytical intractability which is described by the "little old lady" effect. When in a busy underground station, the location, speed and direction of slower moving individuals (the little old lady) can have considerable effect on the following crowd behind them. So it is very important to consider very carefully when building the model from the beginning and need to test a much wider range when simulation. Although multi-agent method permits the setting of different types of agents, each of which will have its own characteristics, we still need to think of how many “little old ladies” need to be built in and how many different positions may the “little old lady” occupy amongst a group of individuals. However, this can be decided by observations of real events. Different nature of activities will attract different crowds that result in different behavioral modes. This phenomenon can be avoided as if detail considerations and observations. Uncertainty is unavoidable given that each individual in the real life is different in behavior. Simulation is at best representation and abstraction of a real event that is happening, happened or will happen, but not real world. Simulation provides a good platform to explore possible.

### 2.5.6 Validation

Although multi-agent modeling methods and techniques operate with individualized parameters (eg: aggression, speed of movement, size, affinity, family, social position, disability etc, etc), they also involve a much higher degree of validation. Agent models provide an excellent organizational framework for modeling pedestrian behavior that ignites evolutionary development in the complex pedestrian system. The results of computational models provide insights into the underlying structure of systems, and models are often validated by comparing outcomes of simulated systems to actual outcomes. However, there are no standard parameters for validating the models, since each run of a simulated result will be different and every result is reasonable and likely. So the more important thing is how to analyze and utilize each simulated result only if we can make sure of the validity of individual data and their behavioral rules (interactions). This should also be traced to the problem of acquisition of individual data.

### 2.6 Summary

In the long modeling history of pedestrian crowds, researchers from a multitude of disciplines (physics, mathematics, transportation, psychology, computer science, Geographic Information Science (GISc), etc.) have all contributed in the study on complex human behavior, through using macro-scale and micro-scale approaches. These researches have helped a lot in the site analysis, traffic design and public safety. Compared with different kinds of models and approaches, MA based behavioral method is selected in this dissertation to model the crowd behavior in an outdoor event for crowd management. This choice is because MA owns the ability to model a behavioral process of intelligent pedestrian and their interactions, thereby offering crowd management a new perspective through the integration of GIS and MAS.

#### 2.6.1 Using MA Approach to Model Spatially Explicit Crowd Behavior

Pedestrian behavior is spatial-temporal activity. Multi-agent based models are a consequence of much better micro data, more powerful and user-friendly computer environments often based on parallel processing, and the generally recognized need in spatial science for modeling temporal process. Such method is now providing an alternative approach to model space-time dynamics in a variety of disciplines where computing is essential to applications and is able to simulate complexity through the interaction of agents comprising large populations, where each agent would act and interact locally. These MA simulations are thus quite suggestive for space-time dynamics in that they allow exploration of relationships between micro-level individual actions and emergent macro-level phenomena. In outdoor events, crowded phenomena are the main features, interactions between pedestrian and between pedestrian and environment are the main factors that will affect the crowd behavior (See chapter 4 for details). MA based modeling is a useful tool to represent them and simulate what can hardly react at any time in reality. It will be a good platform for exploring and preventing crowd disasters that might happen in an event.

#### 2.6.2 Crowd Management Instead of Crowd Control

For a successful outdoor event, the main task of event mangers is to manage crowds rather than control them only when emergencies happen. Crowd management will include every facet concerning how to design rational pedestrianization area, how to arrange manpower and facilities, how to make preparations for emergencies, and et cetera. Each of the details will link to whether the event will progress smoothly and safely. Applicable tools that can facilitate crowd management for outdoor events are still absent in the integration of pedestrian's spatio-temporal behavior and their interactions with their behavioral environment. It is very necessary for event managers to have a platform to discuss measures and communicate information. Because crowd management is a work full with collaboration, this platform should be developed to not only support management of crowds, crowd behavior and crowd behavioral environment, but also support the collaborative work during the management.

### 2.6.3 Linking GIS and MAS

As a powerful spatial information management system, GIS obviously acts as a media for event managers to manage data on the crowds and spaces in outdoor events. This media will transfer information to guide crowds to make. While linking MA behavioral modeling within GIS brings existing GIS new challenges in capturing finer and more localized events and in emphasizing on interactions between agents. The information systems should move from representing maps towards representing the processes that make the changes (Christman, 1998). In this context, it is very useful to conceptualize appropriate models that are able to represent interactions. Therefore linking GIS and MAS can overcome their respective disadvantages which in GIS involves static considerations of spaces and in MAS concerns the aspatial representations. Although there have already been a few researches realizing the importance of the integration of GIS and MAS and experiments on such a linkage, a lot of issues still need to be explored. MA pedestrian modeling is a good example for such cross disciplinary research. It has been common sense that the trend of geographic information science is to link MA method within the GIS.

# CHAPTER 3 BUILDING A CONCEPTUAL FRAMEWORK FOR GEO-COLLABORATIVE CROWD MANAGEMENT IN LARGE-SCALE OUTDOOR EVENTS

## 3.1 Introduction

Most of the science and decision making involved in geo-information is the product of collaborative teamworks. Current geographic information technologies are limiting because they do not provide any direct support for group efforts. Geo-collaboration is demanding when exploring space-time issues (both same/different time and same/ different places), which have multi-user interactions with dynamic visualization environments designed to facilitate group understanding of the information displayed (MacEachren and Brewer, 2004). Figure 3.1 explains the four types of geo-collaboration in applications. Crowd management for outdoor events is a collaborative work for event managers to make decisions. So the management needs a virtual geographic environment that can be manipulated by different groups, whether they are different levels of event managers or the people who completely have no professional knowledge. Whether they have expert GIS manipulation skills or not, they can discuss the same question and participate in decision-making activities.

| | Same Time | Different Time |
|---|---|---|
| Same Place | emergency response coordination | air traffic flow control center |
| Different Place | multiuniversity team data exploration | threaded asynchronous discussion |

**Figure 3.1: Sample Geo-collaboration Applications for Each of the Four Space-Time Situations**

Source: adapted from MacEachren and Brewer (2004).

Through discussions on spatio-temporal behavior of crowds in outdoor events, event managers can know the dynamics underlying this pedestrian behavior, and more importantly, find out how the results would be if they set up different methods to manage them. By simulating variations by adding or removing management facilities, they can estimate the possible results of such arrangements on the event, which will be very important and contribute to making preparations for route choices or risk assessments in emergency situations. Not only the managers, but also the public need to know the potential environmental changes and can express their opinions on responses to incidents in events. Interactive simulations can offer powerful tools to facilitate these discussions. All of them need researchers and scientists to develop a geo-collaborative framework for crowd management as both a platform and a media for communications among users. So, it is very necessary to build up the framework for managing crowds in large-scale outdoor events. In the following sections of this chapter, after understanding the existing problems on establishing such a platform, a conceptual framework has been proposed and components in the framework are elaborated, followed by methodologies and data used in the case study on the event of "TST Firework Display".

## 3.2 Understanding Geo-collaboration for Crowd Management

Currently, the only practical way for teams to collaborate on geospatial applications is to gather in a single place and interact with analytical tools by having a single person "driving" the software on behalf of the group, which is deficient for discussing the same problem when team-workers are distributed in different places or times. So in a broader context, geo-collaboration is viewed as a committed effort on the part of two or more people to devise a new understanding or solution for a geographical decision task. Group participants agree to work on the same task to reach common goals. Geographers have begun to explore the value of merging collaborative techniques within geographic information science and technologies. When exploring discrete themes of research, there must be different issues existing, especially in crowd management.

### 3.2.1 Concepts and Characteristics of Geo-collaboration

Geo-collaboration as an activity is defined as a group work on geographic scale problems with the facilitation of geospatial information and information technologies, while also as a field of GIScience research, geo-collaboration can be a study on group activities and the development of methods and tools to facilitate them

(MacEachren, 2003). Geo-collaborative methods and technologies would bring improvements in many geospatial contexts. In general, collaborative work can be characterized by its spatial and temporal components. That is, at the dimension of space, the location of participating individuals may be the same or different, for example face-to-face or distributed. And at the dimension of time, the individuals may interact at the same time or different times, like synchronous or asynchronous. The term of "teleimmersion" (Armstrong, 2001) has been used to represent such characteristics of geo-collaboration. Teleimmersion is a unifying grand challenge for multidisciplinary research at the intersection of geospatial information science and information technology. It has been considered to use immersive, distributed virtual environments in which information is processed remotely from the users' display environments (Defanti and Stevens, 1999). The goal of teleimmersion is to provide virtual environments for participants to meet and interact in natural ways. To achieve the aim, the main challenges of geo-collaboration involve the capabilities of supporting group decisions by developing technologies and tools such as collaborative geo-visualization, collaborative human-computer interface, and team-based decision support systems.

### 3.2.2 Geo-collaboration in Crowd Management

Crowd management is a cooperative work by groups to explore interactions between pedestrians and their environment, including geographical and social-economic environment and make decisions on the same task through real situations and what-if scenarios. Crowd managers may be distributed in different sites to observe and control pedestrian movement, act and react according to different situations, and make decisions and control operations. Crowd management can also provide for commercial companies to find special pedestrian behaviors, for governmental sectors to make decisions, for publics as one kind of tourist products, or even be used as an education tool. A geo-collaborative crowd management should fulfill the needs of different groups, which means that it needs geo-collaborative visualization of crowd behaviors and their environment, geo-collaborative human-computer interactions and needs to support geo-collaborative decision making for crowd management.

First, visual representation of crowd behaviors and their behavioral environment is one of the most important objects in geo-collaborative crowd management, and an entity for discussion and manipulation. Users can explore crowd dynamics randomly through visualization generated from crowd behavioral models. Visualization of crowd behaviors also should provide support for dialogues of information, plans, methods, strategies, or decisions on crowd behaviors. Dialogue is the interaction methods between users and geo-collaborative crowd behavioral visualization. But, data for visualizing crowd behaviors and their behavioral environment in large-scale outdoor events are surely complex and of huge volumes. Traditional visualization methods emphasize spectacular visual renderings by sacrificing interactivity. Geo-visualization, integrating approaches from scientific visualization, cartography, information visualization, exploratory data analysis, and image analysis (MacEachren and Kraak, 2001) makes flexible and highly interactive exploration of multivariate geospatial data enabled.

Second, the way of interaction is another important characteristic for geo-collaborative crowd management, as crowd managers need to interact with spatio-temporal information on pedestrians in order to cooperate. So the interaction in crowd management should allow every user of the platform to have access to this information, but the ways users interact with such information can be multiform because of the different capabilities and authorities of the individuals. New technologies in crowd management screen—such as large high-resolution displays that can enable same-place collaborative work and smaller and lighter devices that generate or use georeferenced information anywhere and that are linked to wireless communications—should support users of different terminals to take up group work. Furthermore, new communication ways and tools in crowd management are necessary to be developed to facilitate natural interface (like eyes-moving, touching, gestures, etc.) in place of tradition mouse-clicks to suit different abilities of users. Such interaction problems give rise to two issues for geo-collaborative crowd management; firstly, how to present information to groups, and secondly, how to design interfaces to facilitate group work.

Third, since decision making is one of the most important applications of crowd management, crowd management in large-scale outdoor events should support collaborative group decision making. Examples of such applications include facilities management, accurate crowd dispersion routing, environmental management, emergency preparedness and responses, and the deployment of personnel. Geospatial decision making is now usually a same-place activity, but that could change dramatically as technology begins to support geocollaboration. The requirement of collaborative decision making support comes down to the problems on developing useful tools to support group work, such as different interfaces and representation, effective geospatial group work environment, and scenario generation tools to facilitate discussions and communications.

## 3.3 A Conceptual Framework of Geo-collaborative Crowd Management

A Conceptual framework for geo-collaborative crowd management is formalized here to meet the requirements of geo-collaboration in large-scale outdoor events so as to keep the sustainability of managing an activity involving large crowds.

### 3.3.1 Conceptual Framework

Figure 3.2 presents the structure of the proposed conceptual framework for crowd management in large-scale outdoor events.

Geo-collaborative crowd management is composed of five sub-environment: (1) data environment, which is a data warehouse storing all the data, models, knowledge used in an event; (2) visualization environment, which visualizes the scenarios of event processes, mainly the crowd behaviors and the urban morphology; (3) interface environment, which provides users a platform to communicate and discuss options and can be used by multiple users and provide tools to coordinate problem finding; (4) user environment, that means this management can be applicable in different devices, like mobile devices, PCs, wearable systems and others, and different user groups; and (5) technology support environment, which comprises mainly of GIS, telematics and information technologies. Central features of the geo-collaborative crowd management are its abilities to (1) understand and act on natural multimodal requests for crowd behavioral information, (2) allow each member to work with pedestrian's spatio-temporal information individually or collaboratively, (3) manage mixed-initiative dialogues for collective decision making, and (4) access existing data and services from an enterprise spatial (and non-spatial) informational infrastructure.

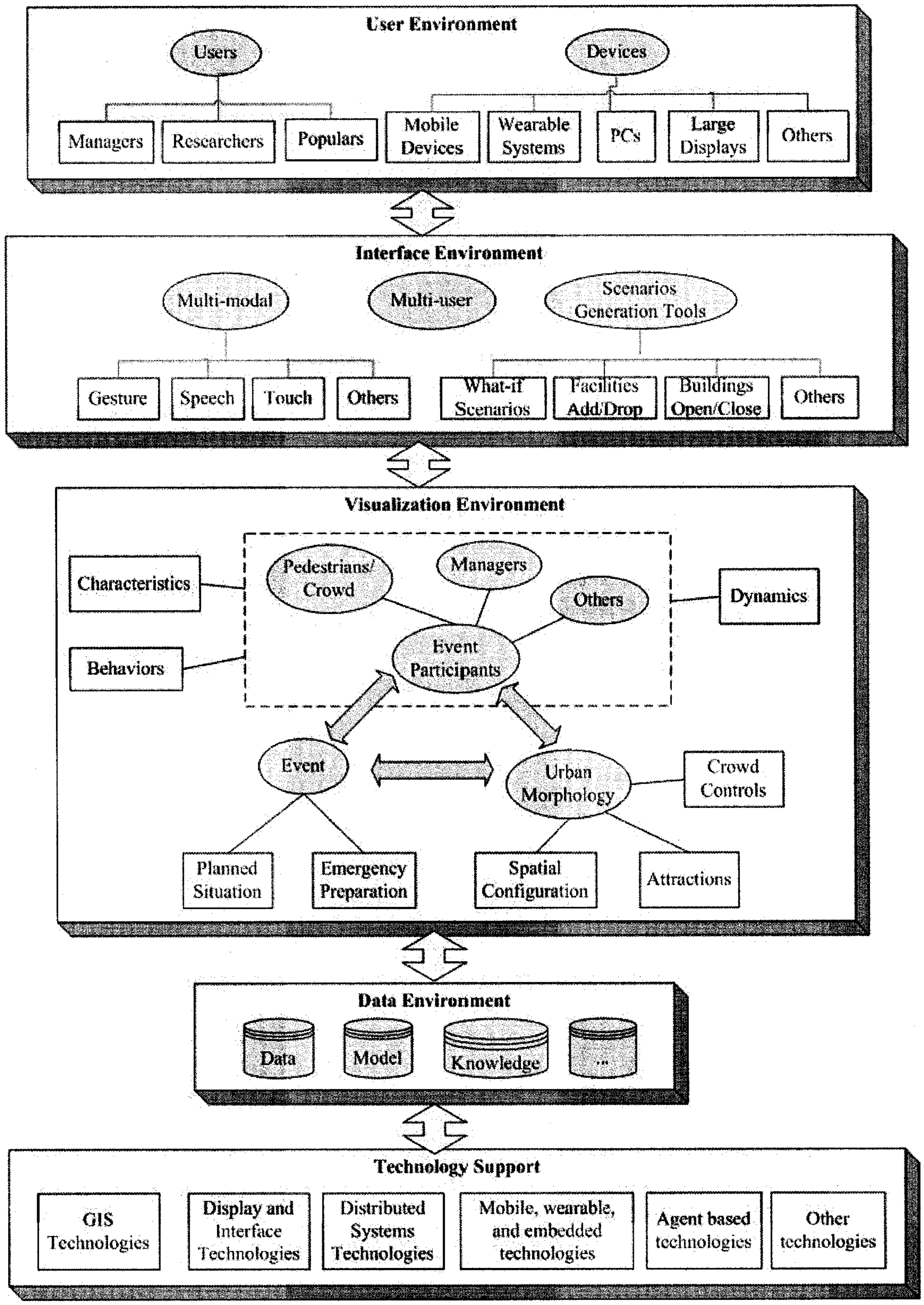


**Figure 3.2: A Conceptual Framework for Geo-collaborative Crowd Management in Large-Scale Outdoor Events**

Source: author.

### 3.3.2 Data Environment

Data environment is the heart for the whole crowd management, and it is an environment to store all the information related with the outdoor event. It includes not only the relational and spatial database, but also the digital urban models, pedestrian behavioral models and knowledge. Users can get crowd information from data environment, manipulate and analyze information and feed information back to the environment. A detailed description of data stored in this environment is covered in section 3.4.

### 3.3.3 Visualization Environment

The Visualization environment is a platform for event managers or other users to gather around and discuss plans or specific development issues on crowds. It served for group works in the form of maps, images, processes and simulations on the event, event participants and urban morphology.

The majority of map literate societies in the world (Wood 1992) and academic research (Van Driel 1989) suggest that understanding 2D abstractions of reality is less intuitive and demands more cognition than 3D or profile equivalents. 2D Maps and texts are the traditional visualization formats in GIS which require users to abstract the real world, while two dimensional maps have been inadequate for visualizing high-dimensional information and require users to have map reading skills. 2.5 dimensional or 3D virtual environments have been researched and incorporated into GIS and are recognized as useful in effective communication and collaborative decision-making. Complementary research has enabled the creation of movie-quality time-series map animations. Both research thrusts have exploited dramatic advances in computer processing power and in parallel algorithms for dealing with very large data sets. In geo-collaborative crowd management, visual display will not be constrained within one single format of whether 2D or 3D representation. Not only maps or text, but also the terrain information, 3D or 4D and even higher dimensional details, simulation and other display formats have been combined together. A hybrid visual display is a good solution to such management.

### 3.3.4 Interface Environment

Interface environment is a platform to facilitate users to discuss crowd management issues with characteristics of multi-user-suitable, have-scenario-generation-tools, and multi-modal.

Collaborative work on crowd management will require viewing and responding to crowd information in real time, sharing diverse perspectives on the information and the problem. Because of different authorizations and tasks, users often have access to different sources of information, each of which may be content sensitive, limited in scope, incomplete, or of variable quality, for example, individuals in the field and chief managers in the command center may have different access authorities. Limits on sharing information may be imposed by technological limitations of broadcasting or display capabilities, privacy and security concerns, time factors (crisis decisions often must be made immediately). So the interfaces should be personalized, and each user's view can be customized, based on their specific needs. Users can also share some of their personal information with other users.

Scenarios Generation Tools will be particularly important for decision-making in crowd management. Scenarios generation tools let users quickly explore the real-time event and represent group suggestions on such events in real-time. At most time for crowd management, users need to know the result through what-if scenarios, compare different schemes and make decisions. This would include:

- Set roads blocked or unblocked
- Set buildings open or closed
- Crowd's movement controlled or uncontrolled
- Select alternative road exits
- Emergencies

To realize geo-collaborative crowd management, multi modal interfaces is a target that needs long-term researches. For centuries, visual displays in the form of maps and images provided a critical interface to information about the world. Now, however, emerging technologies create the potential for multimodal interface—involving not just sight but also other senses, such as hearing, touch, gestures, gaze, and other body movements—that would allow humans to interact with geospatial information in more immediate and "natural" ways. Our voice, hands, and entire body, once augmented by sensors such as microphones and cameras, are becoming the ultimate transparent and mobile multimodal input devices. The research on multi-modal interface has expanded rapidly since Bolt's (1980) "Put That There" concept demonstration, which processed speech and manual pointing during object manipulation (MacEachren 2003a), for example, speech and pen input (Oviatt, in press), and speech and lip movements (Rubin, 1998).

### 3.3.5 User Environment

In geo-collaborative crowd management, users might be event managers who try to keep a safe environment for crowd activities, researchers who want to find pedestrian dynamics underlying their behaviors, populations who are interested in such events and may provide their advises on management, or others. They can be equipped with a large-screen display, wireless or mobile devices (e.g., a Tablet PC) or wearable systems.

### 3.3.6 Technology Support Environment

Technologies support is one of the basic conditions for realizing geo-collaborative crowd management. They are mainly from GIS, telematics and information technologies.

Data related with large outdoor event is huge. Users need to be able to access such huge amounts of complex, heterogeneous geospatial data, construct knowledge from these data, and apply the data/knowledge to problems that matter. As tools and tool-makings, GIS technologies support the crowd management from the data acquisition, data storage, data analysis to data modeling and data integration and simulation. In data acquisition, technology advances in GIS are making it possible to capture pedestrian positional information with ever improving accuracy and precision. Commercial remotely sensed images from space offer a resolution of one meter or better. Satellite telemetry using the GPS can now achieve accuracies well within one centimeter. GIS technologies help to make collecting individual-level geo-referenced data easier than before. Geographic data sets show two clear trends: they are becoming increasingly abundant and they are growing ever more precise, which has also challenged GIS Technology to develop new spatial databases to store and manage them. At the same time, spatial analysis of human behavior at the individual level has become more possible with the development of GIS technologies. Further, instead of basing the analysis on certain behavioral assumptions, the researchers can now use GIS-based deductive methods such as neural networks to deduce or discover the behavioral rules or principles underlying various spatial behaviors. These behavioral rules can in turn be built into behavioral models for obtaining more realistic or accurate results. For data visualization and simulation, MacEachren (1995) suggests that, "GVIS (geographic visualization) has the potential to help us cope with the flood of information that technology increasingly provides, and to stimulate insightful discovery."

To support a geo-collaborative crowd management, information technologies also provide great supports for visualization on and interactions with human behavioral information. First are technologies of the display and interface. Human interaction with geospatial information has been linked to visual display for centuries. Recent advances include developments in immersive virtual environments, large and very high-resolution panel displays, flexible displays, multimodal interfaces, and new architectures supporting usability. Second are distributed system technologies. Technologies that support remote access to information and remote collaboration also are having a dramatic impact on how people interact with information of all kinds. Among these are high-bandwidth networking, wireless networks and communication, digital library technologies, and interactive television. Third are the mobile, wearable, and embedded technologies. These new technologies include wireless personal digital assistants (PDAs) that support both data collection and information dissemination; augmented reality devices that support the matching of physical objects with virtual data objects; distributed sensor fusion techniques to support multivariate visualization in the field; and pervasive computing infrastructures that can interact with mobile humans or computational agents to inform them about local context. Fourth are agent-based technologies. Software agents now are being applied in a wide array of contexts. As these technologies mature, there will be considerable potential to extend them for facilitating human interaction with geospatial information. Among the agent-based technologies that show promise are intelligent assistants for information retrieval, agent support for cooperative work and virtual organizations, and computational pattern-finding agents.

## 3.4 Methodologies Used

### 3.4.1 A Case Study—Firework Display in Tsim Sha Tsui (TST), Hong Kong

It is increasingly the trend of outdoor activities taken place especially in urban cities to attract a large number of people gathering together. Crowd management for these outdoor events is in urgent need for a safe crowded environment. A case study is a good starting point for building an efficient crowd management framework and exploring human behavioral characteristics in such events. Firework Display at the Victory Harbor in Hong Kong is a special event planned by the Hong Kong government to promote urban image. It is held at least five times a year, and often attracts a large number of people assembling mainly on both sides of the shorelines: Yau Tsim Mong (YTM) District and Central District. YTM District is located at the southern tip of the Kowloon Peninsula, starting from the TST Seashore and northward to Boundary Street. It is one of the busiest and most attractive districts in Hong Kong. It is also the center of business, culture and tourism which makes it lively and bustling especially at the TST. In this research, crowd management in TST area is selected as the case to explain human behavioral dynamics in large outdoor events (Figure 3.3).

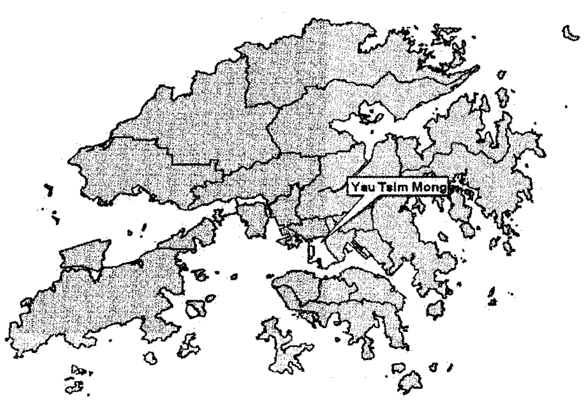


Figure 3.3a: TST in Hong Kong

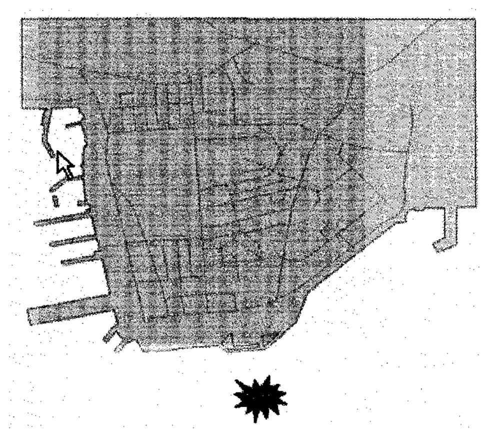

Figure 3.3b: General Location of Firework Display

**Figure 3.3: Background of the Case Event of "Firework Display"**

Source: author.

The event of Firework Display is characterized by a huge number of pedestrians over a short duration. People gather together with a strong intention to view the display which is the main cause of the crowd formation. The Hong Kong Police Force Yau Tsim District (HKPFYT) is the main department to manage the events. Other governmental departments are also involved in the events including Civil Aid Services (CAS), Anxiliary Medical Services (AMS), Food and Environmental Hygiene Department (FEHD), Leisure and Cultural Services Department (LCSD) and Fire Services Department (FSD). Firework display is an activity that needs order, safety and cooperations from participants.

Three phases are involved with respect to the prevailing conditions on the ground: crowd arrival, fireworks display, and crowd dispersal. In the process of watching the display, most of the crowd will remain stagnant and stay at their respective positions, and not much crowd interactions will happen. Researches are focused on the processes of crowd formation and crowd dispersion. Considering preparations for emergencies, this research also makes studies on crowd evacuation. Overall in this case, three kinds of crowd behavior in outdoor event have been investigated for management that are: crowd formation, crowd dispersion and crowd evacuation.

### 3.4.2 Consultatory Interviews with Event Managers

HKPFYT have rich experiences on arrangement of manpower and facilities, and have accumulated rich knowledge on operations executed during the event. Discussions on how to effectively manage the crowd in Firework Display have been held and different viewpoints have been proposed and communicated. Based on the existing situation and their requirement for crowd management, the conceptual framework is built and some of the crowd behavioral dynamics in the events are concluded. The Issues mainly discussed at interviews are listed in following table 3.1.

| Issue | Content |
|---|---|
| I1 | What is the existing situation to manage the crowds for the Firework Display? |
| I2 | What is the most important issue for managing the crowds in the event? |
| I3 | What are the criteria for keeping order and avoid possible troubles that crowded phenomenon will bring? |
| I4 | What is the basic crowd behavior in the event? |
| I5 | Is there any computerized system to support for your management? What are your expectations for intelligent management tools? |
| I6 | Avoiding terrorism has been recognized as an important task for the police department. Have you ever think about making preparations for evacuation in such emergencies? |
| I7 | For large events that crowded phenomenon will appear, which factors will you consider in preparation of the events? |
| I8 | Do you keep records of the events? |
| I9 | What preparations are in place for events with an extra large number of pedestrians? What plans for controling the number? |
| I10 | Comments and advice on the proposed framework. |

**Table 3.1: Issues Discussed at Interviews**

Souce: author.

The TST area is one of the busiest places in Hong Kong with its museums, hotels, commercial and private apartment buildings. Public transportation there is very complex to include subways (MTR), trains (KCR), buses, and ferries. Constructions and reconstructions are on-going almost every day, which requires much preparation of the police department for large events. At least 2 months before each event, the police begin to have meetings on arrangements for the event to discuss detailed deployment and scheduling. However, they still have no system to manage basic information about the area and to support their decisions. Paper maps are still the main way to support their discussions and decisions. Until now, there have not been serious incidents happening in past events, they but still try to find better ways to prepare and arrange events more effectively and efficiently, given that event management is time-consuming in times of resource shortage. They are interested in using the GIS to manage events and expect that it will be useful for cross-departmental cooperation. Secondly, they admit that they need more knowledge on crowd behavior in order for better work in management. They have many years of experience in keeping order and most decisions were made according to those experiences on past events and have not tried to consider the social or psychological behavior of crowds, while they are not very sure whether it is useful for better management.

Upon preliminary interviews with event managers at the initial phase of this thesis work, requirement and expectations of event managers were distilled and some of the crowd dynamics in such events were explored (see chapter 4 for detail). Throughout the research undertaking, interviews with event managers were held periodically to get comments and advices.

### 3.4.3 Participatory Observations of Event

With approval and assistance of the police department, on-site observations on how they coordinate work on crowd management were taken and the actual needs of event managers were further confirmed. Their main command post is set on the 5$^{th}$ floor of the New World Center, from where they can have an overview of an event as it unfolds. They mainly use paper maps to assist in decision making and to communicate with field managers by walkie-talkie and mobile phones.

Data needed for crowd management are derived from on-site observations. These include average speed of pedestrian movement, crowd density along each road, crowd distribution during an event, some behavioral features of pedestrian movement, all of which provide the original and real data of an event. Through on-site observations in the firework display, some dynamics of crowd behavior are instantaneously analyzed and concluded.

### 3.4.4 Analytical Models for Urban Morphology: Spatial Configuration and Attraction

Spatial configuration and attractions are the two factors that will influence significantly crowd behaviors. GIS provides a comprehensive description of urban structures in both topology and geometry. Using spatial analysis, GIS also analyzes the visibility value that pedestrians will have at each geographic location. The analytical results can be integrated into the mind of an individual simulated pedestrian in the crowd behavioral modeling, as they provide some global knowledge for pedestrian movements. Models to simulate urban morphology are built in this work, mainly including the digital building model (DBM) and an axial map of the road networks. Both of these two models serve for the exploration of the effects on crowd behavior brought by urban built environments.

### 3.4.4.1 Creating a Digital Building Model (DBM) of TST Area

The TST area is one of the busiest places with its tall and dense buildings. Pedestrian's visibility of fireworks is largely blocked by these buildings and consequently this consideration will affect his movement on his way to the display. Viewshed is one of the forces that drive crowd behavior. This DBM is developed by representing the urban environment as 3-dimensional entities, and serves as both inputs in crowd behavioral modeling and objects for visualization and simulation in geo-collaborative crowd management. Figure 3.4 draws the procedure for developing the DBM.

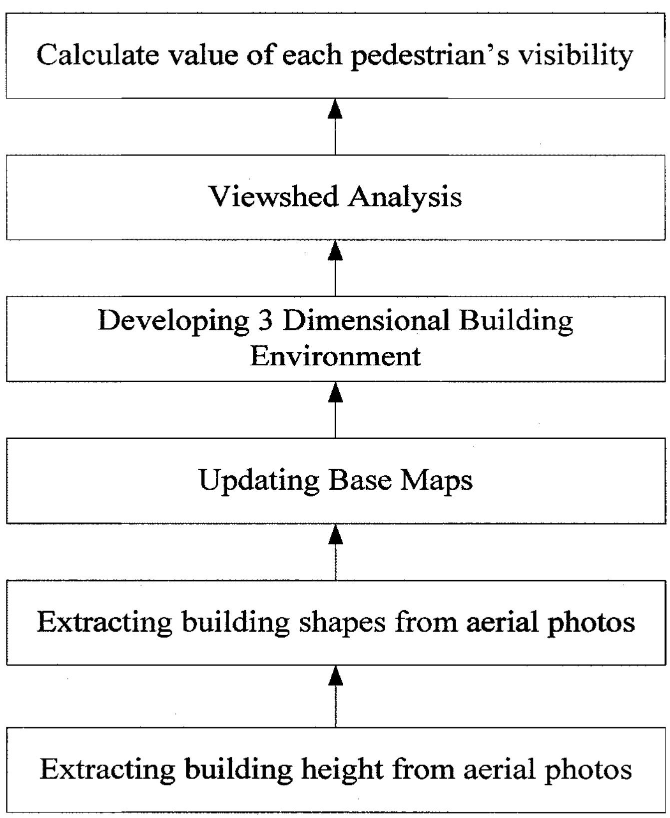


**Figure 3.4: The Procedure for Digital Building Model**

Source: author

#### 3.4.4.2 Syntax of Street Network

As streets are the main infrastructures for directing crowd movement to or from the firework display, their network and spatial configuration have great effects on crowd behavior. Space syntax provides a method for partitioning a spatial system into relatively independent but connected subspaces so that the importance of these subspaces can be measured in terms of their relative nearness or accessibility (Hillier and Hanson, 1984; Batty, 2002). In this research, each road in TST area is analyzed through the method of drawing an axial map to valuate the effects of the roads on crowd behavior.

### 3.4.5 MA Based Crowd Behavioral Modeling

Three pedestrian models which represent three processes in an event will be created: a model for crowd formation, a model for crowd dispersion and a model for crowd evacuation. In these models, each pedestrian is viewed as an intelligent agent, and multiple agents are represented with different roles in such an event according to their functions like firework-attractor, policemen, geographic objects, peoples who arrive there just for viewing the display, and et cetera. Interactions between agents control the agents' growth which leads to different crowd behavior.

Crowd behavioral models are developed through four stages: model formalization, model calculation, model simulation and model validation. Figure 3.5 is a representation of modeling stages. At the first stage of model formalization, conceptual models based on crowd behavioral rules are developed using multi-agent based method; secondly, mathematical calculation of the models are carried to make them adaptable to visualization and simulation; and finally, through simulation and analysis of model runs, the model is validated and updated.

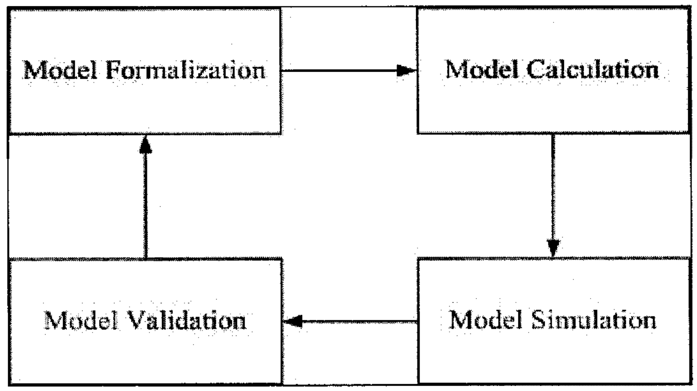


**Figure 3.5: Four Stages for Crowd Behavioral Modeling**

Source: author.

### 3.4.6 Spatially Explicitly Integration and Simulation

This method tries to integrate crowd behavioral models with urban environmental models to visualize and simulate crowd behaviors in different scenarios, and make analyses and decisions (Figure 3.6). This integration and simulation also provide interface for users to communicate in cooperative works. Effective management can be compared, prepared and summarized through simulation.

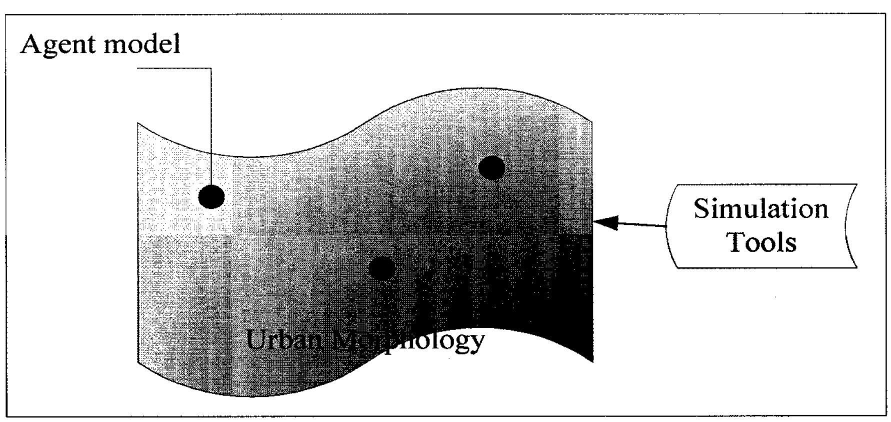


**Figure 3.6: A Framework for Integration and Simulation**

Source: author.

## 3.5 Data Collected

Data used in this thesis mainly include two parts: physical environmental data and pedestrian crowd data. These data can be collected from digital maps, aerial photos, publications, records of event managers, and on-site observations. Analyzed data of crowd dynamics will be discussed in detail in chapter 4. Figure 3.7 shows the data prepared and processed for modeling and management.

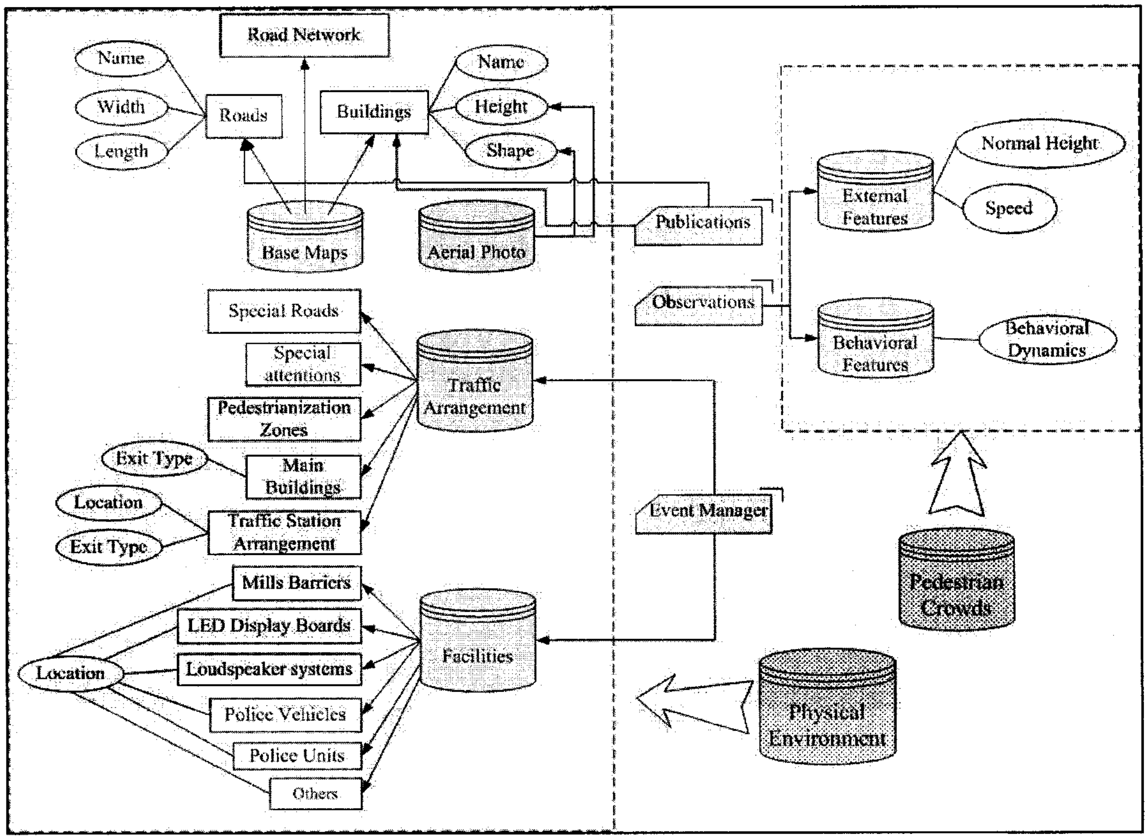


**Figure 3.7 Data Collected**

Source: author.

### 3.5.1 Aerial Photos

The Joint Laboratory of Geo-information Science (JLGIS) has a series of aerial images of the whole of Hong Kong taken on a measurement campaign during March 2001. Two images HK15-207 and HK15-208 cover the area of research interest – TST (Figure 3.8). Using VirtuoZo – the Digital Photogrammetric Station from Supresoft Corp, most of height information of buildings in that area can be extracted. The shape of buildings can also be known and stored, since normally one building will have multiple height information for each shape. However, the shapes of houses in TST area are of enormous varieties, manual feature collecting process is time-consuming, only some of the important landmark buildings (e.g. Cultural Center, Tower Building, etc.) are worked on in order to get better 3D effect. Shapes of other buildings are from the base maps (see following section) and have no detailed height information for every different shapes. This information will be stored in the DXF file, as a 2D polygon with height information as an attribute.

Figure 3.8a: the Overview of Aerial Photo of TST Area

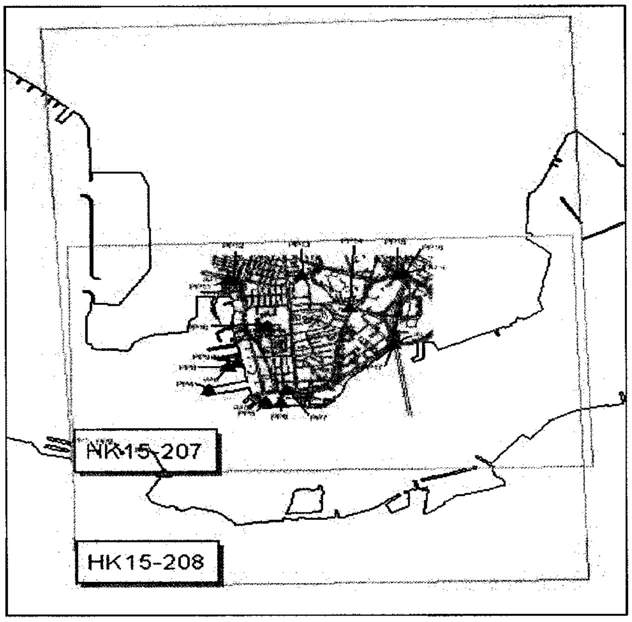


Figure 3.8b: the Original Aerial Images Used in Project

**Figure 3.8: Aerial Photo of TST Area**

Source: author.

### 3.5.2 Base Maps

The Department of Geography and Resource Management, The Chinese University of Hong Kong has updated digital base map for the whole of Hong Kong. The TST area is extracted as in Figure3.9. Base information includes graphics of road central lines, buildings, boundaries, and their attributes. Base maps are further updated and enhanced after processing of and extracting with aerial photos.


**Figure 3.9: An Overview of Base Map Layers**

Source: author.

### 3.5.3 Traffic Arrangement

Data on traffic arrangement for the firework display is provided by the Hong Kong Police Department, and is an example of the event taken on Oct 1st, 2004.

#### 3.5.3.1 Zone Demarcation

There are 3 zones divided by event managers (Figure 3.10) and each zone is managed by a separate team. Crowd behaviors will be limited within zones.

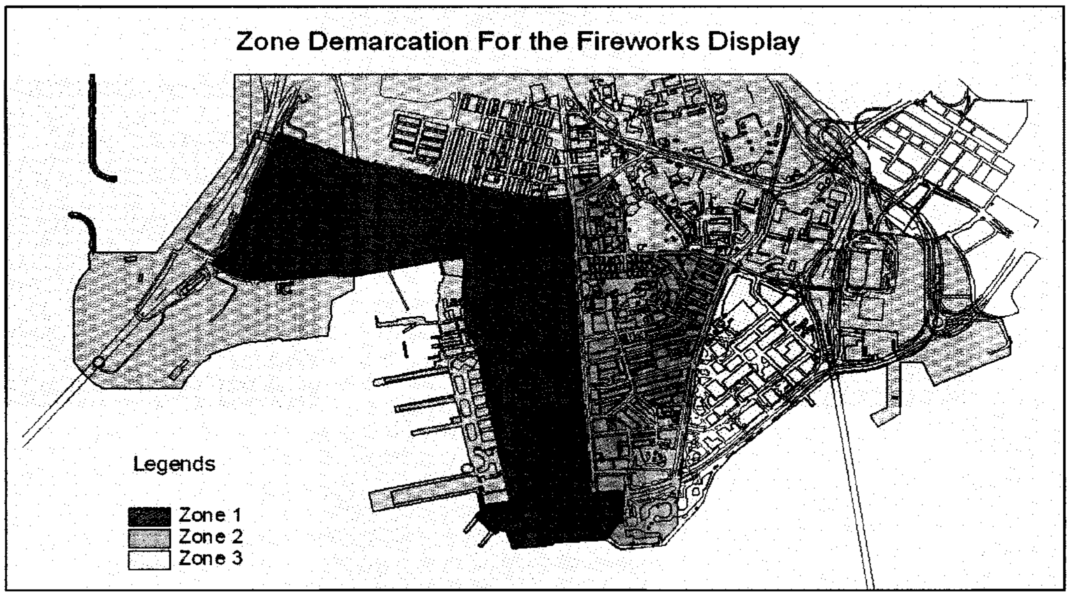


**Figure 3.10: Zone Demarcation for the Fireworks Display**

Souce: HKPFYT.

Zone 1 covers the western side of TST, from the Star Ferry Concourse northward to the YMT Division. It is bound by the seafront in the south, Canton Road in the West, Jordan Road in the North, and Nathan Road in the East.

Zone 2 is bound by Nathan Road to the West, Jordan Road to the North, Chatham Road South to the East and Salisbury Road to the South.

Zone 3 is bound by Austin Road/ Hong Chong Road to the north and east, the seafront promenade and AOS to the south, and Chatham Road South to the West.

#### 3.5.3.2 Transportation Arrangement

There are about five modes of transport for people to arrive at the TST district, including trains, subways, private vehicles, buses and ferries. The area covers a total of 11 KCR exits, 13 MTR exits, 60 bus stops, 33 car parks and one ferry pier (Figure 3.11). To effectively manage the crowds, the police department takes different measures to control various entrances and exits during the arrival and dispersal phases (Table 3.2).

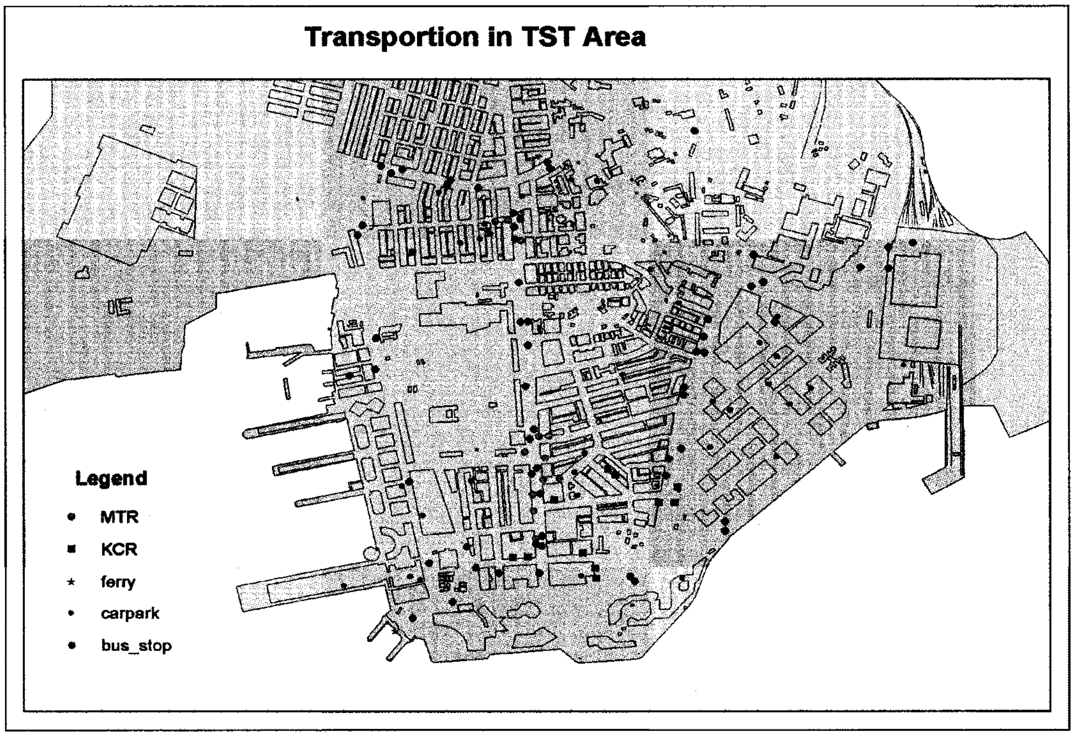


**Figure 3.11: Transportation in TST Area**

Source: author.

| Vehicles | Number | Controls |
|---|---|---|
| KCR | 11 (Exits) | under control |
| MTR | 13 (Exits) | 9 Exits under control |
| Bus Stop | 60 | Forbidden |
| Car Park | 33 | Limited entrance |
| Ferry | 1 | Under control |

**Table 3.2: Controls on Different Transportation**

Source: HKPFYT & author.

East Tsim Sha Tsui stop of the KCR is a big interchange station between KCR and MTR and is also the terminal station of KCR. There are 11 exits located within the three zones. During the pedestrian arrival phase, 7 exits are closed to forbid people passing by, and the remaining 4 exits only allow people to walk out from the station (Figure 3.12). During the crowd dispersal phase, 7 exits are closed, 3 exits allow out-walking, and only 1 exit is used to let people walking into the station (Figure 3.13). With such a control strategy, large number of people will select exits which are outside the zones, thereby dispersing the crowd in a more rapid way. Two main MTR stations are located within the zones, including the Tsim Sha Tsui station and Jordan station. Jordan station is at the edge of pedestrianization zones and maintains a normal service to move people. Meanwhile, as the Tsim Sha Tsui station is at the center of the crowded zones, 9 exits of that station allow either a one-way passing or are closed. During the arrival phase, 4 of them allow people entering, and 5 of them only allow out-walking (Figure 3.12). At the dispersal phase, 5 of them allow entering, only 2 exits let people walking out, and other 2 exits are closed (Figure 3.13).

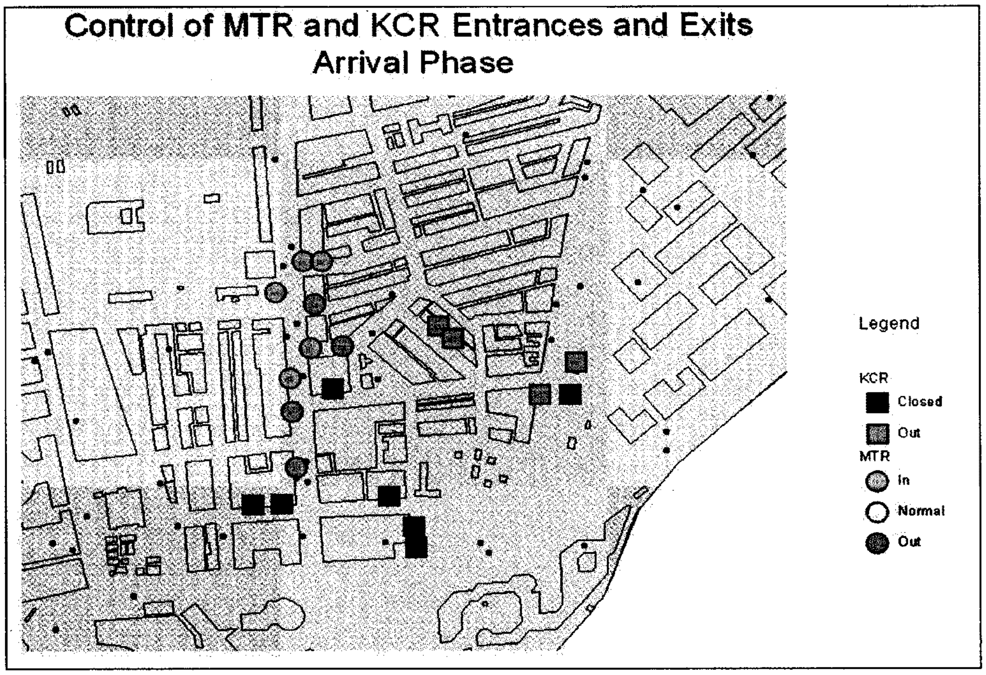


**Figure 3.12: Control of MTR and KCR Entrances and Exits- the Arrival Phase**

Source: HKPFYT & author.

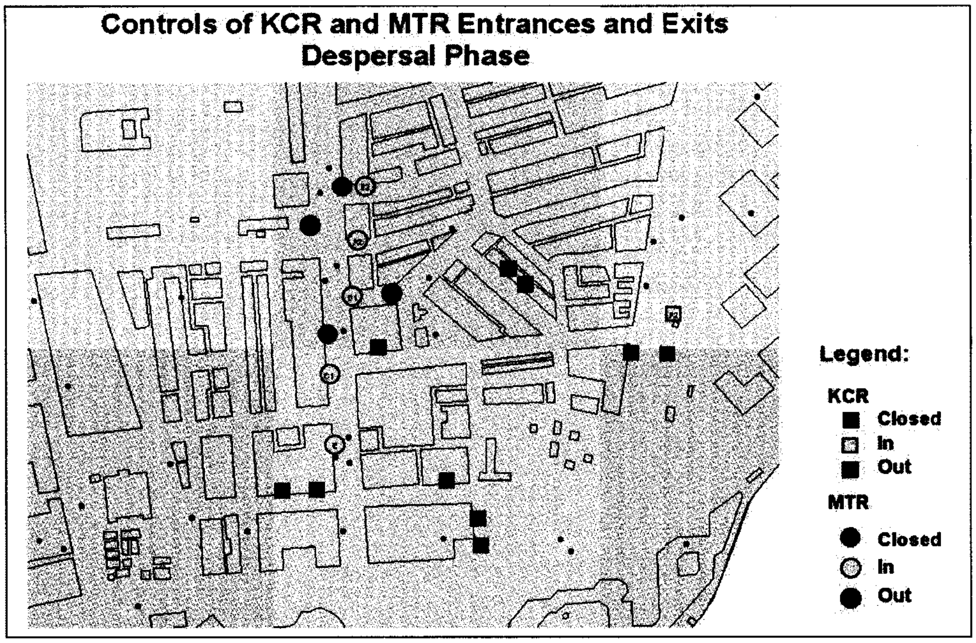


**Figure 3.13: Control of MTR and KCR Entrances and Exits- the Dispersal Phase**

Source: HKPFYT & author.

As pavements and the seafront area become more congested, pedestrianization will take place. Buses reversions will be implemented followed by traffic restrictions. No buses will enter the zones until the finish of crowd dispersal. Private automobiles are not encouraged for people coming to see the firework display. Only airport shuttle buses and vehicles bearing hotel logos will be allowed to enter the pedestrianised zones under the escort of the police department. They will set down resident guests up to 30 minutes before the fireworks display at two drop-off points: Kowloon Park Drive/ Peking Road; and Chatham Road South/ Mody Road. Car parks affected by road closures will be closed about 75 minutes before the display, and remain closed for as long as pedestrianisation is in effect. Generally, no cars enter the zones during the three phases.

Quite a number of people will select the ferry to arrive at and depart from the zones. The hall for people waiting for the ferry is one of the most crowded places. But the ferry will be closed during the display. So it is considered to be closed in this work.

### 3.5.3.3. Roads

Street networks are the main infrastructures that event managers need to take care of, especially major thoroughfares, major crossroads, and major road junctions. Major thoroughfares in Zone 1 are Canton Road, Kowloon Park Drive and Salisbury Road, in Zone 2 are Nathan Road, and Chatham Road South, and in Zone 3 are Chatham Road South and Austin Road/ Hong Chong Road. Major crossroads in Zone 1 are Peking Road, Austin Road, and Jordan Road; in Zone 2 are Middle Road, Peking Road, Mody Road, Carnarvon Road, Haiphong Road, Humphrey's Avenue, Cameron Road, Granville Road, Kimberley Road, Austin Road, and Jordan Road; and in Zone 3 are Salisbury Road, Mody Road, and Granville Road (Figure 3.14).

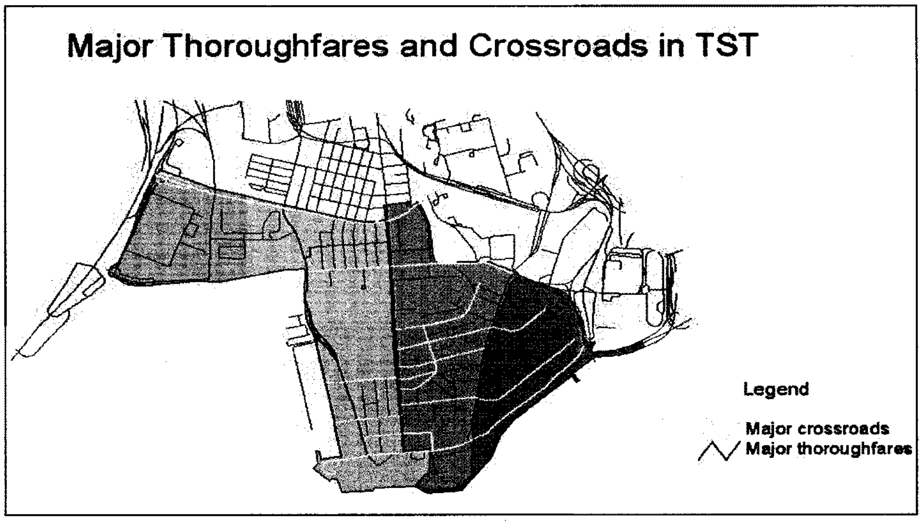


**Figure 3.14: Major Thoroughfares in 3 Event Zones**

Source: HKPFYT & author.

Major road junctions requiring control are listed in table 3.3.

| **Zone** | **Important Road Junctions** |
|---|---|
| Zone 1 | Salisbury Road/ Canton Road |
| | Salisbury Road/ Kowloon Park Drive |
| | Salisbury Road/ Nathan Road |
| | Canton Road/ Peking Road |
| | Canton Road/ Haiphong Road |
| | Canton Road/ Kowloon Park Drive |
| | Canton Road/ Austion Road |
| | Kowloon Park Drive/ Peking Road |
| Zone 2 | Salisbury Road/ Middle Road |
| | Nathan Road/ Middle Road |
| | Nathan Road/ Peking Road |
| | Nathan Road/ Mody Road |
| | Nathan Road/ Carnarvon Road |
| | Nathan Road/ Haiphong Road |
| | Nathan Road/ Humphrey's Avenue |
| | Nathan Road/ Granville Road |
| | Nathan Road/ Kimberley Road |
| | Nathan Road/ Austin Road |
| | Nathan Road/ Jordan Road |
| Zone 3 | Salisbury Road/ Mody Lane |
| | Salisbury Road/ Chaham Road South |
| | Chatham Road South/ Mody Road |
| | Chatham Road South/ Granville Road |
| | Chatham Road South/ Austin Road |
| | Science Museum Road/ Hong Chong Road (both ends) |

**Table 3.3: Major Road Junctions**

Source: HKPFYT.

#### 3.5.3.4. Emergency Preparations

There are three zones that have been preserved for emergencies by the police department. They are closed for crowd movement in normal situations. The first is the "sterile zone along the seafront", which is a one-meter sterile zone along the seafront, and will be manned using mills barriers. No public access into the sterile zone is permitted, including the placement of bags and camera tripods. The sterile zone is implemented and must be kept clear to allow police and other emergency services quick access to any area along the seafront. The other two Emergency Access Corridors (EACs) are to evacuate the crowd in any emergency situation.

### 3.5.4 Facilities Arrangement

Facilities used in the event include mills barriers, LED display boards, loudspeaker systems, and police vehicles. Their locational information is provided by the Police Department and will be managed using GIS (Table 3.4, 3.5, 3.6).

| Zone | Position |
|---|---|
| Zone 1 | Salisbury Road/ Canton Road (outside the HKCC) |
| | Salisbury Road/ Nathan Road (outside the Space Museum) |
| Zone 3 | Mody Road near Mody Lane (outside the Empire Center) |
| | Salisbury Road/ Mody Lane (near westbound carriageway) |

**Table 3.4: Location of LED Display Boards**

Source: HKPFYT.

| Zone | Position |
|---|---|
| Zone 1 | the Star Ferry NPO in the Star Ferry Concourse |
| | Outside the Star Ferry NPO near Clock Tower |
| | 3/F, Ocean Center (Canton Road/ Peking Road) |
| Zone 2 | 1/F of Manson House, No.74-78 Nathan Road (at the junction of Nathan Road/ Humphrey Road opposite to the entrance/ exits 'A1' of TST MTR station) |
| Zone 3 | Chatham Road South/ Mody Road |
| | On the footbridge near the Hung Hom Bypass on westbound Salisbury Road by the promenade |

**Table 3.5: Location of Loudspeaker Systems**

Source: HKPFYT.

| Location | | Quantity |
|---|---|---|
| Star Ferry Concourse | Outside entrance to the Clock Tower | 60 |
| | Outside Star Ferry NPO | 80 |
| | Outside telephone booth | 70 |
| TST Promenade | Along the sea front from Star Ferry to Inter-Continental Hotel | 150 |
| | The end of fly-over opposite Shangrila Hotel | 30 |
| | The end of fly-over opposite South Center | 40 |
| | To Hung Hom stair case (temporary) | 10 |
| | Opposite Wing On Plaza | 30 |
| | Avenue of Stars | 180 |
| Along Salisbury Road | Salisbury Road at junction with Chatham Road | 60 |
| | Entrance to Inter-Continental Hotel | 20 |
| | Salisbury Road at the junction with Nathan Road | 50 |
| | Salisbury Road at the junction with Hankow Road | 30 |
| | Salisbury Road at the junction with Canton Road | 20 |
| | Salisbury Road at the junction with Mody Lane | 30 |
| | Salisbury Road opposite Shangrila Hotel | 30 |
| | Salisbury Road at the junction with Kowloon Park Drive | 40 |
| | Salisbury Road outside Eastrail Station | 10 |
| | Along Salisbury Road from the Palace Mall to vehicle entrance of HK Cultural Center | 120 |
| Cultural Center | HK Cultural Center (cordon) | 150 |
| | HK Cultural Center main entrance | 30 |
| | Special path near restaurant | 40 |
| | Special path (HK Museum of Art) | 50 |
| TST East | Cheong Wan Road junction with Hong Tat Avenue | 10 |
| | Science Museum Road/ Science Museum Avenue | 10 |
| | Mody Road junction with Science Museum Road | 10 |
| | Next to New Mandarin Center | 30 |
| Along Peking Road | Peking Road at the junction with Canton Road | 40 |
| | Peking Road at the junction with Kowloon Park Drive | 30 |
| | Peking Road at the junction with Ashley Road | 10 |
| | Peking Road at the junction with Hankow Road | 10 |
| | Ashley Road at the junction with Middle Road | 20 |

**Table 3.6: Location and Quantity of Mills Barriers**

Source: HKPFYT.

| Zone | Position |
|---|---|
| Zone 1 | Salisbury Road/ Hankow Road (outside the Hong Kong Cultural Center) |
| Zone 2 | Salisbury Road/ Middle Road (outside New World Center) |
| | Carnarvon Road/ Nathan Road (outside the MTR TST Station; entrances/exits 'D') |
| | Nathan Road/ Kimberley Road (outside Miramar Hotel) |
| | Nathan Road/ Jordan Road (outside Yue Hwa Emporium) |
| Zone 3 | Salisbury Road/ Mody lane (opposite TST Centers) |
| | Designated Viewing Area on the Hung Hom Bypass |

**Table 3.7: Location of Police Vehicles**

Source: HKPFYT.

### 3.5.5 General External Feature of Pedestrians

Obviously, individuals have different characteristics, like breath, depth, height, and area, and external behavioral features, like maximum speed, initial walking speed, and etc. In individual-based modeling, especially a model with hundreds of thousands of individuals, these individual differences can be negotiated by using the average data of individuals who have been researched and published, since interactions among individuals are the most important factors within a model. However, in conditions of powerful computation capabilities, these external features of individuals can still be set and work as parameters of crowd behavioral models.

The Still(2000) report on anthropomorphic sizes of the world population, breath, depth and area indicated that an average Hong Kong male is 47cm, 23.50cm and 0.17m$^2$; and Hong Kong female is 43.50cm, 27cm and 0.18m$^2$. In different activities, pedestrian normally keep a certain different distance with others, like, their favorite distance with others are at least 35feet, while this distance will change according to different situations (Figure 3.15).

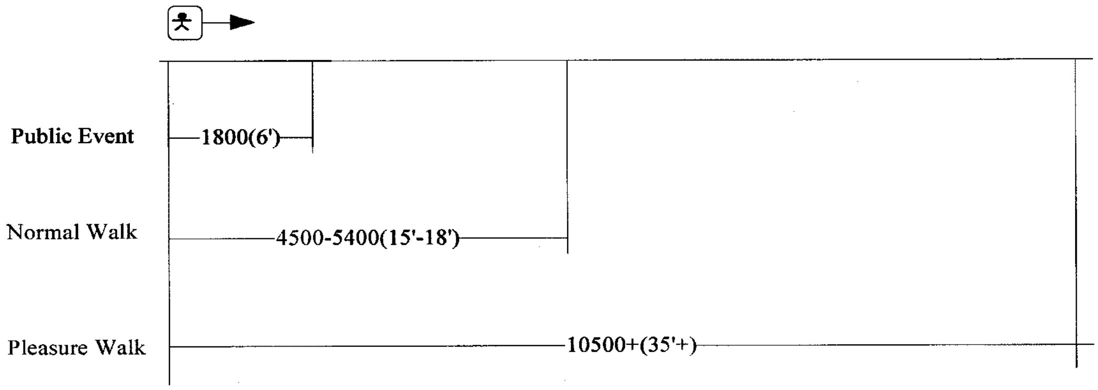


**Figure 3.15: Forward Spatial Bubbles**

Source: Landscape Architect's Portable Handbook (2001).

### 3.5.6 General Behavioral Features of Pedestrian Crowd

In multi-agent pedestrian behavioral modeling, interactions between agents and between agents and environment are the focuses of the whole framework. Pedestrians behave according to their interactions, and that also means that pedestrian behavioral rules control the reactions when an agent senses its environment. In order to model and simulate the interactions between agents, behavioral rules or dynamics should be concluded. While some of general rules have already been found and verified, and these existed rules become the theoretical foundations and are partly combined into crowd behavioral models in this work.

#### 3.5.6.1 Hierarchy of Individual behaviors

Individual behaviors can be better understood by distinguishing several layers: vegetative, reflex, reactive, motivated, reasoned, and conscious (McFarland, 1981; Gerhenson, 2001). Figure 3.16 show the type of intellectual behaviors, as higher levels involve higher and more complex cognition.

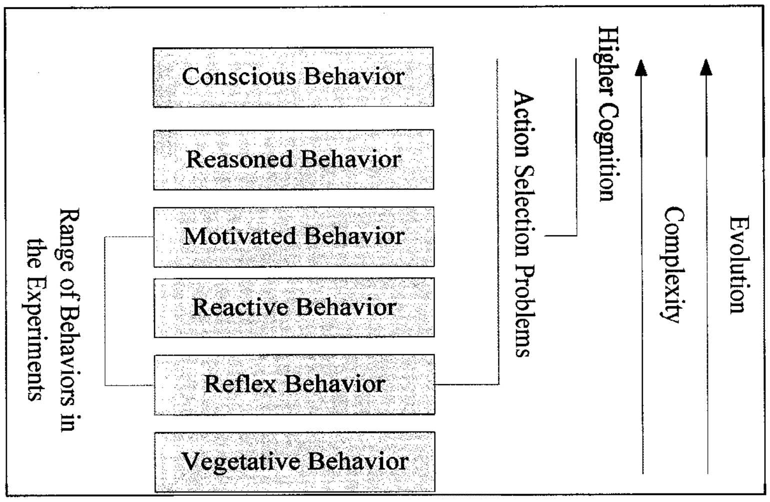


**Figure 3.16: Hierarchy of Individual Behaviors**

Source: based on McFarland (1981) & Gerhenson (2001).

**Vegetative behaviors** are those in an organism by default, such as breathing, heart beating, metabolizing, etc. They can be seen as implicit, internal behaviors and are not noticed. This lowest layer of behaviors does not affect our understanding on how individuals react to the environment, therefore it will not be considered in modeling. **Reflex behaviors** are those response actions. This is probably the most important layer of behavior since every other higher behavior level needs the reflex behavior to execute actions, making an individual moves. It is also called this layer of behavior as "motor" (Blumberg and Galyean, 1995) or "locomotion" (Reynolds, 1999) behavior. Behavior at this level does not require any external perception and internal state of motivation. **Reactive behaviors** shows complete dependence of "external perception" (McFarland, 1981) such as when we see an obstacle gets in our way, we pick another way to avoid that obstruction. Reactive behavior is also called steering behavior (Reynolds, 1980), and it works as path and speed determination, expressing concepts like: "go left", "go fast", or "stop". **Motivated behaviors** are more complex because of involving action selection. This behavior depends on internal state of motivation and the external stimuli that correspond to the needs inside. More intelligent behaviors are involved in **Reasoned and Conscious behaviors**. They represent more complex thinking process before sending signals down to the less complex levels to execute actions. Conscious and reasoned behaviors have the ability to recognize the layout of spaces, like those people who are familiar with the environment. However, when we focus on local movements, meaning that each individual will make a local decision according to their perceptions (not experience) of space, we will not consider these two levels of behavior in pedestrian behavioral modeling.

In order to study how an individual interacts with elements in his environments, at least, a range of reflex, reactive, and motivated behaviors need to be focused on (Figure 3.17) that each pedestrian will select action, determine path and speed, and execute action when he moves. For details, please see chapter 5 for the descriptions of models developed in this thesis work.

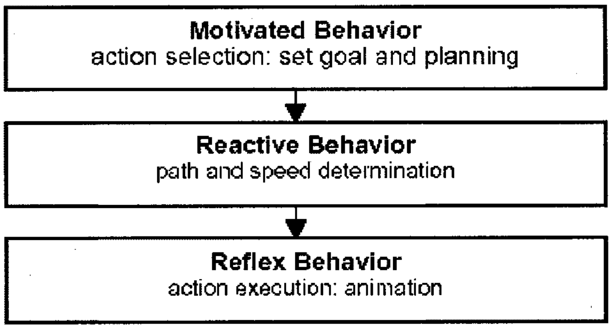


**Figure 3.17: A Hierarchy of Motion Behaviors**

Source: based on Blumberg (1995), Reynolds (1999) & Gerhenson (2001).

### 3.5.6.2 Social Behavior

Adaptive behavior is one important character of a complex system because it requires interaction among the components of a system to provide rich perceptions, action selections and movements. Social behavior is actually an adaptive behavior, as a society is a complex system. Social behavior is an interaction of individuals sharing a moment in the same space. Crowds in outdoor events interact not only with elements in space but also with other pedestrians as well. Pedestrian social behaviors can range from perceiving or being aware of each other to having a conversation or any form of communication. There can be social action among non-cognitive individuals although most social phenomena involve the interaction of cognitive individuals. Many works in the field of artificial societies, such *Turtles, Termites, and Traffic Jams* by Resnick, *Growing Artificial Societies* by Epstein and Axtell, and *Zero Intelligence* by Gode and Sunder, show clearly how complex social phenomena are resulted by very simple social rules. When thousands of individuals follow simple rules, the behaviors of the whole system turn out to be very complex, with social properties emerging.

**Flocking Behavior** is one of the social behaviors that has been found in the motion of a flock of birds, and has been recognized as a kind of behavior applied on the crowds. Reynold (1987) built the boid model to describe this flocking behavior which consists of three simple steering behaviors to describe how an individual boid maneuvers based on the positions and velocities its nearby flockmates, which are: **separation**, steering to avoid crowding local flockmates; **alignment**, steering towards the average heading of local flockmates; and **cohesion,** steering to move toward the average position of local flockmates (Figure 3.18).

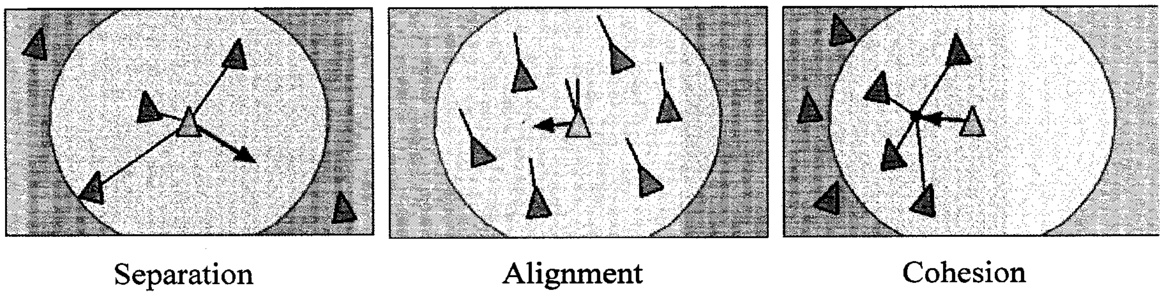


**Figure 3.18: Flocking Behavior**

Source: adapted from Reynold (1987).

### 3.6 Summary

A conceptual framework for geo-collaborative crowd management has been built to depict a beautiful blueprint for a deep understanding of the group work and applications of issues on human safety. Rapid advances in both information and geographic information technologies are creating the potential for dramatic advances in how people use and communicate with geospatial information. Geo-collaboration is at the center of that potential. A range of devices from hand-held PDAs to wall-sized displays are used by different groups of people to make group decisions. Network technologies are enabling both high-bandwidth connections and ubiquitous, mobile connectivity accessible by an increasing array of users. We can imagine the scene: in front of a platform for such a geo-collaborative crowd management, the process of crowd dispersion in an urban street environment is on simulation. Different users are using multiple display devices- PDAs or large screen display, through network. They are making group decisions about how to effectively arrange the crowd dispersion and arrange the appropriate personnel or facilities. And they can use gestures, dialogues or other ways to communicate.The users can be commanders from the police department, standbys from the fire department, medical department, or can just be public who want to have real experiences or students who are being trained in such events. The case of "Firework Display" serves as a good starting point for research on such a geo-collaborative work.

Lin and Gong (1999, 2002) proposed a concept of virtual geographic environment (VGE) defined as a human-centered environment that represents and simulates geographic environments (physical and human environments), allows distributed multi-users to implement exploratory geospatial analysis, geo-computation and geo-visualization, and conducts collaborative work for supporting designs and decisions. In some senses, geo-collaborative crowd management can be considered as one kind of applications of VGE. The potentials of geo-collaborative applications are clear. However, a perfect geo-collaborative crowd management needs to overcome problems from visualizations, ways of human-computer interactions, and co-operative group work support. These problems will involve a series of issues on data, data representation, data modeling, data transfer, interface design and etc. While in this thesis work, crowd behavioral modeling and simulation are emphasized to address questions on:

- Crowd behavioral dynamics: what are the crowd behavioral dynamics in outdoor events, and what are the driving forces that affect crowd behavior in such events?
- Crowd behavioral modeling: what are the behavioral rules that crowds exhibit in outdoor events, and models of their behaviors?
- Crowd behavioral simulations: what are the results that crowd behavior yield in under different scenarios?

These questions are going to be answered in the following three chapters, and these findings will become the components in geo-collaborative crowd management.

# CHAPTER 4 EXPLORING AND UNDERSTANDING CROWD DYNAMICS IN THE FIREWORK DISPLAY

## 4.1 Introduction

Any spatial-temporal models imply interactions that are sustained by movements of people, goods, or ideas between two or more locations which are usually classified as origins and destinations, over different time scales and at different speeds (Batty, 2002). Dynamics of interactions are different within each model. At the regional scale, these interactions are normally characterized by cost or purpose, like shortest path or traveling salesman problems, while at the local scale, detailed interactions between individuals become important since density turns into dominant phenomena. Outdoor events normally have predefined routes, or origins and destinations of movements are known, or movements taking place in a limited street environment in which crowding is the main feature. Issues resulting from interactions are keys to problem solving.

Therefore, before modeling the crowd interactions that will be used to assist management for these events, it is necessary to examine what and how the interactions through movement will affect the human system, since different streams of movements composed of different types of individuals have their own dynamics. However, there is little descriptive materials on which good models of these dynamics might be built, and there are few interpretations that do exist within mainstream geographical, urban or architectural analysis or within summaries on historical events by event managers. But still, there is a useful classification from Canetti (1962) who describes crowds as certain kinds of groups. There is also a persistent line of research in psychology from LeBon (1995) that deal with crowds as 'madness of crowds'. Actually, as a kind of spatio-temporal behavior, dynamics of crowd behavior must be affected by the built spatial morphologies. However, the detailed relationship still needs exploration. Here it will be illustrated through analyzing crowd dynamics in the case of Firework Display. This case provides a research entity through which human-environment relationship at the local scale is well digged out and become references for analyzing crowd behaviors. Knowing crowd dynamics and driving forces behind them are also necessary for modeling and simulating crowd behavior. Acknowledgement of the dynamics of crowds during an event is furthermore important for cooperative work between teams. Since simulation and decision support are the main goals for this work, phases are discussed according to the prevailing conditions on the ground: crowd arrival, crowd dispersal and crowd evacuation.

In this chapter, followed by an exploration on crowd dynamics exhibited during three phases in the firework display, the underlying factors that form such dynamics are analyzed mainly from the view of spatial structures of urban built environment and morphology, trying to find the relationship between human activities and built environment in these local outdoor events, and argue that both the nature of the events and built spatial configurations have great effects on crowd behaviors. At the end of this chapter, some suggestions on crowd management for these outdoor events are proposed, and methods for modeling and simulation are generalized.

## 4.2 Exploring Crowd Behavioral Dynamics in the Firework Display

Crowd dynamics means the study of how and where crowds form and move above the critical density of more than one person per square meter (Still, 2000). It has received growing attentions in the context of crowd evacuation management, and panic situation analysis which are related with human safety issues. Panic situation analysis is probably the one which has motivated a large majority of research activities in the field (Helbing, 2000; Helbing, 2002). However, it is a specific situation, and the behavior of individuals is dictated by the unique objective and may become irrational (Schultz, 1964; Quarantelli, 2001). In many cases, especially events taking place in urban cities, formation of crowds and their interactions cause high risk safety problems which need taken care of at any situations, like in "normal" situation instead of only emergent or panic situations. In this case that we research on the firework display, to know the causes of crowd formation and crowd's growing or vanishing process at both normal and emergent phases is the key to analyzing the crowd behavior and modeling them. For crowd management in this event, it is necessary to explore crowd dynamics within three phases: crowd formation, crowd dispersion and crowd evacuation. The first two former phases can be concluded through observations, while as preparations for management, the dynamics of crowd evacuation can only be obtained according to existing references.

The area of focus is located in the downtown of Hong Kong, with dense buildings and complex road networks. Before the start of firework display at the Victoria Harbor, as pavement and seafront areas become more congested, pedestrianization will be taken measure by event managers. This is followed by special traffic arrangements in which buses will change their routes and not enter the crowded area, MTR and KCR (subway systems) entrances are controlled with "only in" or "only out" or closed access, and the full pedestrianization of road streets are formed (Figure 4.1a). No vehicles are allowed into this region except the police vehicles used for emergencies through pre-planned emergency routes. In addition, originally as a pedestrianization area, the seafront area (Figure 4.1b) will be one of the most crowded areas in the event due to its advantageous geographic location. These two pedestrianization areas combine the crowd environment in the event of a firework display where most crowd behaviors will take place (Figure 4.1c), and will be removed pedestrianization after crowd dispersion. Examinations of crowd dynamics in this outdoor event will be carried out mainly in these pedestrianization areas.

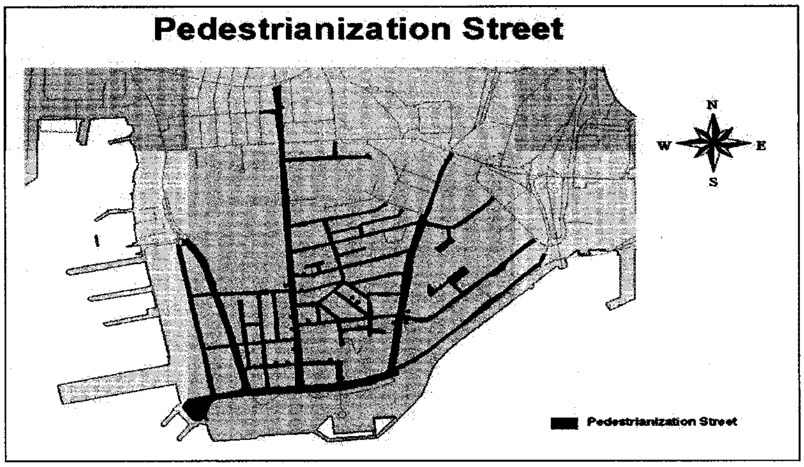


Figure 4.1a: Pedestrianization of Road Streets in the Event

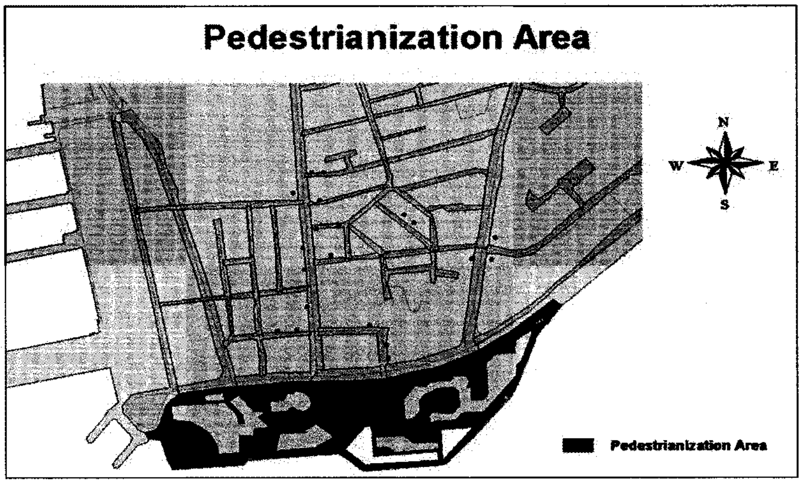


Figure 4.1b: Pedestrianization of Seafront Area

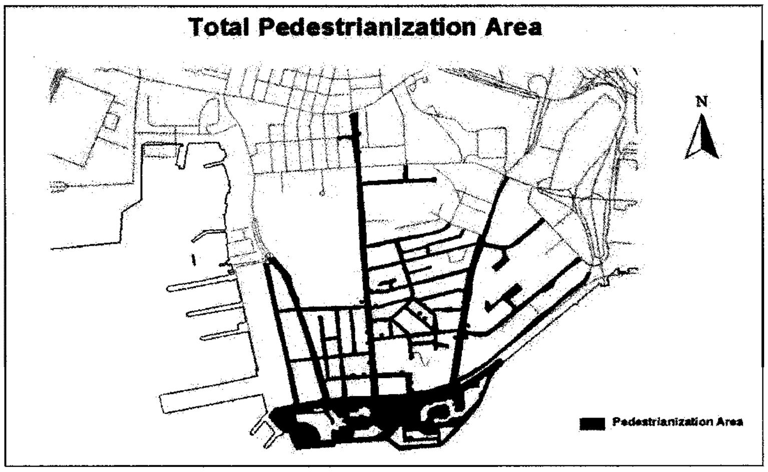


Figure 4.1c: Total Pedestrianization Area

**Figure 4.1: Pedestrianization Area Formed in the Event**

Source: author.

### 4.2.1 Dynamics of Pedestrian Arrival

In this phase of crowd arrival, general direction for pedestrian movement is from north to south to get closer to better viewing places along the darker front (Figure 4.2).

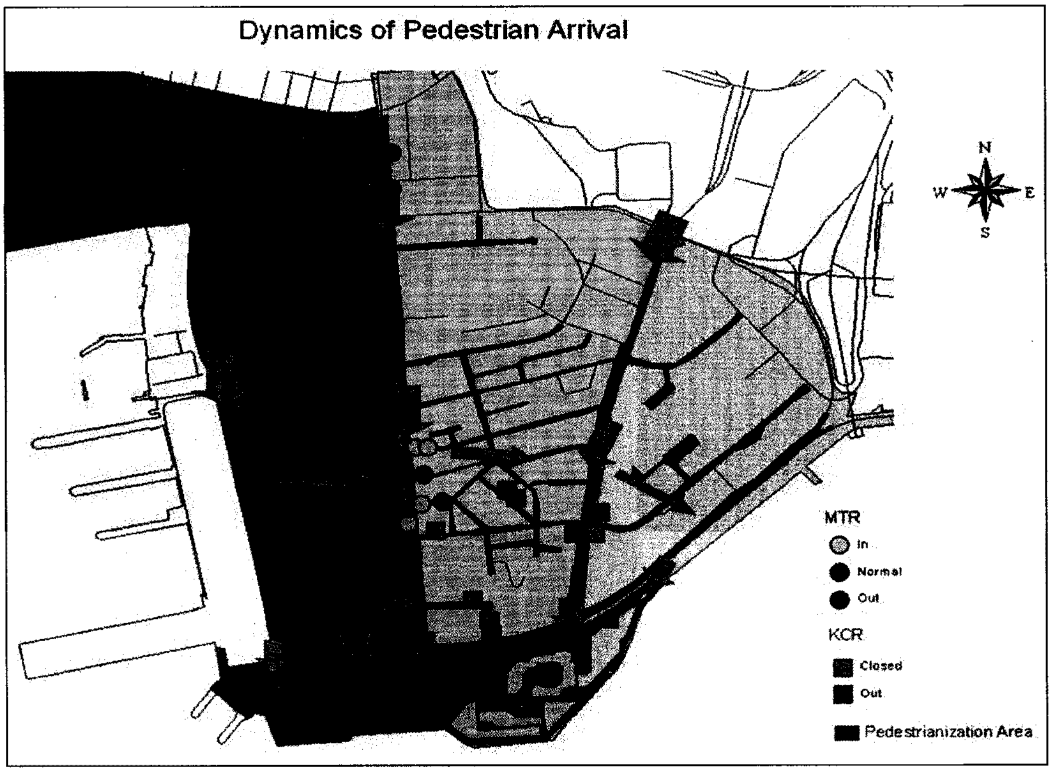


**Figure 4.2: Dynamics of Crowd Arrival**

Source: author.

Roads with KCR and MTR exits are the main sites where large quantities of pedestrians appear. In addition, main roads like westbound of Canton Road, eastbound of Chatham Road South and eastbound of Salisbury Road within the pedestrianization areas are also the places through which crowds enter this prime viewing area. There are totally about 13 points that can be viewed as starting sites where populations start to move during the crowd arrival phase (Figure 4.3). Crowd movement is constrained within each zone guided by event managers. In zone 1, crowds are encouraged to move westward to get into the seafront viewing area, and in zones 2 and 3, they are guided to move eastward to reach better viewing areas. At each road intersection, there are event managers to guide and control the movement of crowds along selected roads. Normally, crowd density is the guideline for event managers to judge whether one viewing section is approaching full capacity and this density is about 80%. When density of pedestrians on the roads are found bigger than this standard, miller barriers or other facilities will be used to temporarily stop crowd movement until the crowding phenomenon dissipates. And when a viewing section is full of crowds, event managers will close the section and direct spectators to the next available viewing area.

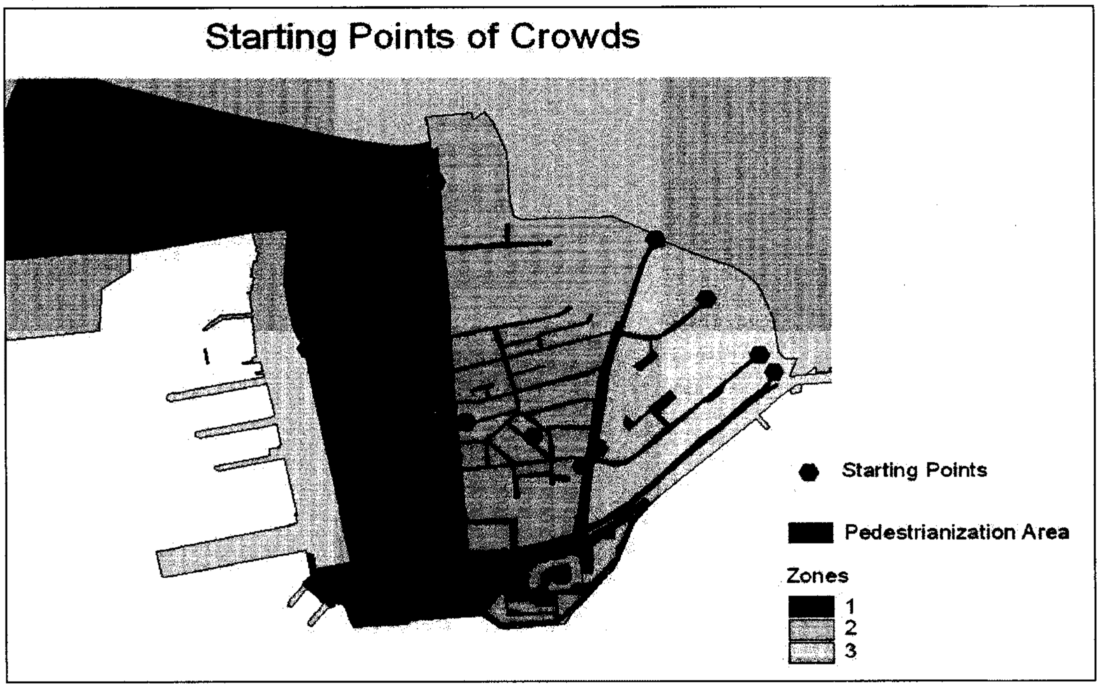


**Figure 4.3: Starting Points of Crowd Arrival**

Source: author.

For most pedestrians, their behavioral dynamics in this phase are similar and can be uniformed. First, each pedestrian has his own initial walking speed and heading. Their walking speed can be expressed by the normal speed that a person feels comfortable in public event. They will find a suitable route to get closer to a good viewing spot. Secondly, each pedestrian is heading toward to a section which has the best viewshed. Having reached this goal, they may wander within that section in search of a point to stop and wait for the firework display. Otherwise, they will try to find the next best viewshed area and so on until they stop. Thirdly, their speed and heading directions are affected by their surrounding environment including the physical environment and other pedestrians.

### 4.2.2 Dynamics of Crowd Dispersal

Prior to the completion of the firework display, event managers have cleared all facilities on the roads that are used to control pedestrian movement during the display to keep a smooth pedestrianization area for dispersal. After the firework display, crowds will disperse generally northwards, in a large, high density mass (Figure 4.4).

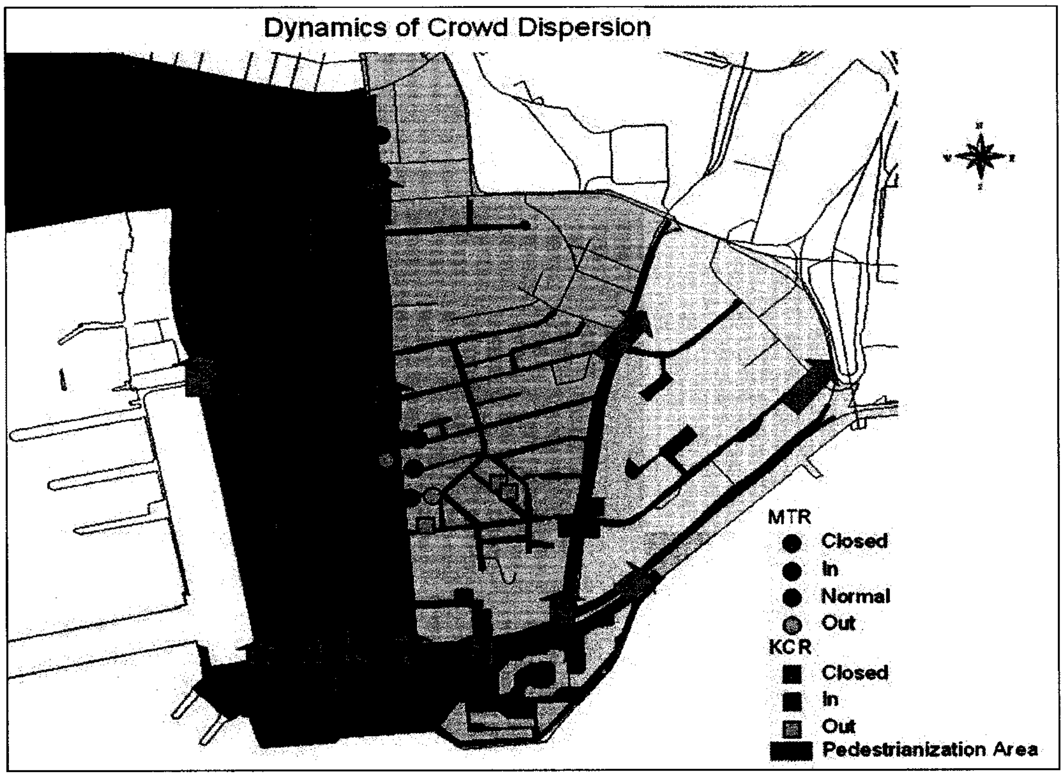


**Figure 4.4: Dynamics of Crowd Dispersion**

Source: author.

As the crowd disperses, running, crushing, or pushing will be stopped immediately. Entrances to the MTR and KCR stations are the directions to which crowds move. In addition, some main roads, like westbound of Canton Road, eastbound of Chatham Road South and eastbound of Salisbury Road, which will lead crowds away from this pedestrianization areas are also the main directions that they move to. Bottlenecks may occur during this phase given the intention of the crowds to leave the pedestrianization areas. Junctions between roads are the congested areas that need guidance from event managers. An event manager may also consider using facilities to stop crowd movement temporarily when the crowd becomes too dense. As the crowd density reaches 50%, dispersion is considered completed because pedestrians can now move freely. The interactions between crowds and their behavioral environment are reduced.

As for the crowds, most of them will select leaving this region as soon as possible, although a few may wander within this area. Each pedestrian will try to find an exit within his range of vision, and move towards it having interactions with his surroundings.

### 4.2.3 Dynamics of Crowd Evacuation

Although no calamities or terrorist activities happened during the firework display, it is still necessary to make preparations for such emergencies in this kind of events. The emphasis for crowd management is not only to keep order of safety issues, but also to make preparations for emergent situations. It is the trends for preparing for human safety issues at any time especially in this kind of high-risk crowded events. Dynamics of crowd evacuation will be decided by different kinds of emergencies that may appear and this is also one of the important goals for modeling and simulating crowd behavior at the evacuation phase, since it is hardly possible to rehearse the scene with thousands of hundreds of pedestrians in reality.

There is an emergency corridor which is located at the westbound of Hung Hom Bypass (from Hung Hom Road to Salisbury Road that has been set aside by event managers in anticipation of sudden emergencies (Figure 4.5). This corridor is divided into two parallel paths separated by fences and ropes and only one path is allowed for pedestrians to view the display while the other path is kept open for vehicles of event managers to navigate freely within this area to manage crowds, as well as for crowd evacuation in times of emergencies. There are also two other emergency corridors for free entries of managers' vehicles. These are Kowloon Park Drive Southbound and Chatham Road South southbound (between Granville Road and Salisbury Road), with the Hung Hom Bypass reserved for crowd evacuation. Functions of emergency corridors will be evaluated in the simulation part.

**Emergency Access Route**

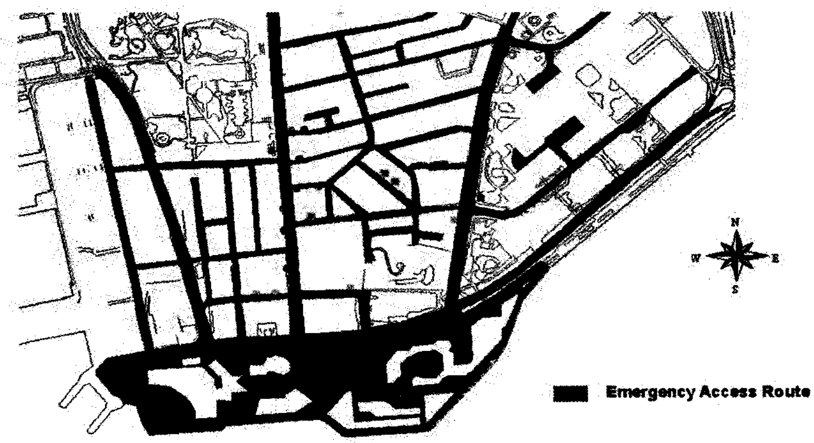


Figure 4.5a: Emergency Route set by Event Manager

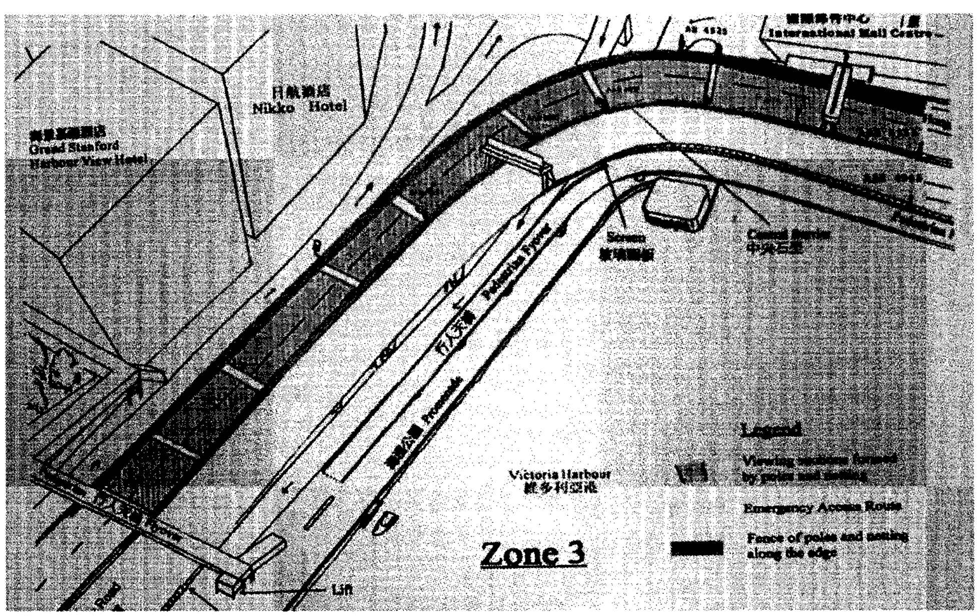


Figure 4.5b: Detailed Displacement of Emergency Route

**Figure 4.5: Emergency Route**

Source: HKPFYT

Emergencies in this kind of outdoor events mainly may result from blockages which appear suddenly, for examples, unexpected fights, road closures, jams or small fires. Just like in the 1993 Lan Kwai Fong event, except that both geographical facilities and weather finally induced a tragedy (Bakhary, 1993), the lack of preparations for evacuating crowds under this situation might also be a factor leading to this disorderly event. In the TST firework display, northwards is the only way for crowds to dissipate from this pedestrianization area. Dynamics of crowds at this phase will be somewhat similar to the dispersion phase, particularly in terms of blockage specific roads and prohibited entries of subway stations in the event of an emergency.

For pedestrians at this phase, guidance from event managers are most important. Each pedestrian may first try to leave the emergency area as fast as possible by looking for the nearest exit to leave this region. And in this phase, interactions among pedestrians especially stand out to affect their behaviors.

## 4.3 Understanding Crowd Dynamics in the Firework Display

An exploration of crowd dynamics in the firework display reveals the behavioral processes of crowd movement in an outdoor event, and provides a basic framework for modeling and simulation. Better crowd management of large outdoor events requires a clear comprehension of the underlying driving forces for these behavioral dynamics and making these dynamics applicable broadly when analyzing different events.

### 4.3.1 Motivation of an Event Decides the Crowd Type

The event of firework display has been ongoing in Hong Kong for more than ten years, and crowd behaviors in this event can be assembled to form references. A firework display is a kind of activity promoted by the Hong Kong government to improve the quality of life and for image-building. It has been one of the most attractive highlights in Hong Kong. People gather around to view the display for enjoyment and visual entertainment. This recreational nature of the event dictates the kinds of pedestrians or the participants of this event who are mostly polite, orderly and emotionally mild, although little conflicts occasionally happen. These populations who assemble at the viewing area at that time have a clear objective of viewing the display and will leave quickly at the conclusion of the display. These behavioral features also make the event to comprise a combination of three phases: crowd arrival, firework display and crowd dispersion, which makes the crowd management in this event purposive and also makes crowd behavioral features in these events regular and easy to predict. Hence, before making management decisions for an event, it is very important to understand the nature of such an event, which will decide the crowd types. Different types of crowds behave in different ways. It will be different behavioral rules represented in an outdoor parade in comparison with the firework display, largely because the crowd type is different.

Crowds have been classified as four types in the literature as follows:

- Heterogeneous/Casual Crowd, in which crowds are composed of different elements, they have no common bonds except for the event that bring them together; for examples, shoppers, on-lookers, or watchers who come and go.
- Homogeneous/Cohesive Crowd, composing of individuals more or less akin. They have a common interest but behave and think as individuals. This type of crowds usually assembles for a common purpose without leadership; for example, crowds in this event of firework display, or other activities.
- Expressive Crowds, who come together to deliver messages. They assemble purposely and have leadership and the intention of expressing an attitude for or against some person or idea; for example, the crowds in the event of "July 1st Parade in Hong Kong".
- Aggressive Crowd, a type of crowd that is likely to erupt in unlawful acts. They usually assembled for some purposes, have positive leadership, are determined to accomplish a specific end, and move actively toward their objectives. Usually high emotional tension is present; for example, the crowds in a football riot. Consequently, this type of crowd presents an acute police problem.

It is important to know, for example, the social mix of visitors to anticipate probable behaviors and make appropriate arrangements for it (HSE, 2000). It is important for the police and even for the crowd itself to be familiarized with the nature of a crowd.

However, crowd types are decided and can be anticipated by the nature of an event. Recreational events often draw polite and disciplined crowds; Celebrating events normally bring exited crowds; crowds in political parades are often expressive and radical; sports games, especially football games, will appear as aggressive crowds. Understanding the nature of an event and making judgments on possible types of crowds will facilitate the modeling and simulating of crowd behaviors and accordingly for better crowd management.

### 4.3.2 Pedestrians Goals and Attractors

Whichever type of crowds, pedestrians always gather together with their individual goals and behave to reach the goals. In an outdoor event, crowds normally have their common goals, which make their behavioral dynamics well-regulated. In a certain sense, they are attracted to behave by their goals. In the event of firework display, pedestrians come to the activity area for viewing the firework display and they move forward until the completion of this goal. The firework display becomes the attractor that pulls them to form the crowds. While in the phase of crowd dispersion, road exits and subway station exits become the attractors that pull crowds away from the area. In this phase, the goals of pedestrians are to leave the area, and crowd interactions appear in search of individual goals (Figure 4.6). Apparently, crowds will form their goals to evacuate from the area as soon as possible if an emergency were to happen. Under this circumstance, exits to this area will be the attractors, while objects of emergencies can also be viewed as a kind of negative “attractor” that will push pedestrians to evacuate quickly.

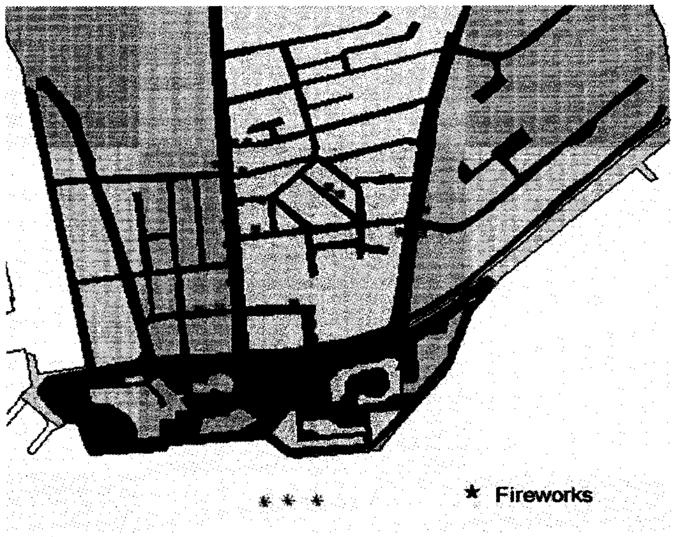


Figure 4.6a: Fireworks as Attractors in Crowd Arrival Phase

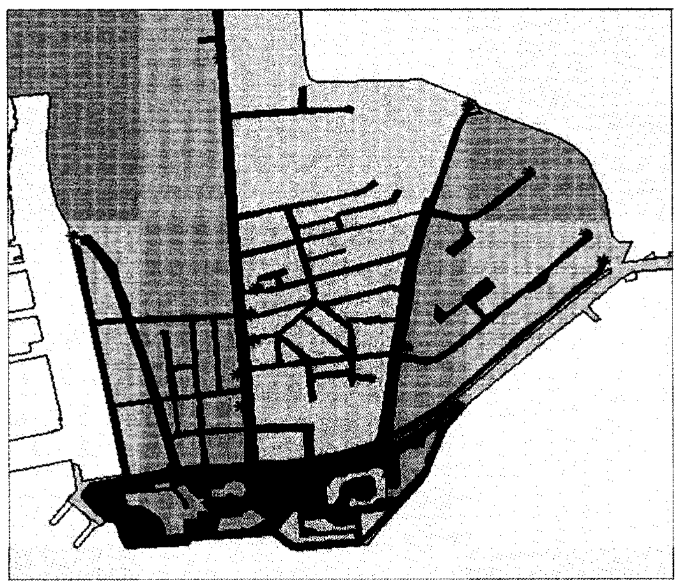

Figure 4.6b: Exits as Attractors in Crowd Dispersion

**Figure 4.6: Attractors in the Event**

Source: author.

Pedestrian goals become an important factor affecting crowd behaviors in outdoor events and they need to be considered and analyzed when managing crowds. Goals may be multiple and hierarchical. For example, in the firework display held on the New Year's Eve, pedestrians gather together both for viewing the display and celebrating the festive occasion, which will result in different behavioral dynamics between two kinds of firework display events. Besides, crowds may have a main goal for viewing the display, and a second goal for eating or shopping somewhere in the area, which makes the human interactions more complicated.

Likewise, attractors need to be considered carefully in the crowd management. Attractors may be dynamic. In the evacuation phase, emergencies are considered a kind of special attractor, and this kind of attractors has its own growing dynamics. For examples, a fire has its own spreading dynamics which will cause strong interactions with crowd behaviors. Taken another example of Carnivals, attractors may be the parades that will attract a large number of populations who will have their own moving routes.

#### 4.3.3 Pedestrian Visibility and Viewshed

In addition to the effects on crowd behaviors brought by the nature of an event, behaviors of pedestrians are largely influenced by the spatial environment in which they are involved. The results of this influence are the different pedestrian visibilities of their goals with regard to the different locations they stand. The visibility analysis is a way of modelling what pedestrians can see and where they can go within buildings and street networks. In this firework display, it represents the extent to which the crowd can see the display at the arrival phase and how the individuals cognize the road networks at the dispersion and evacuation phases.

##### 4.3.3.1 Viewshed by Buidlings

It is obvious that individuals in a crowd always want to find places which have the best viewing effects, while this effect is restricted by buildings located in this area. High buildings will block visibility of the fireworks and cast shadows on the roads. Analyzing the visibility of pedestrians at selected points is useful for understanding crowd behaviors in this event. Through the visibility analysis, a list of potential crowded zones can be found. Therefore, the viewshed value at each grid cell of the target areas is calculated in this research and will be used as one of the parameters in crowd behavioral models.

**(1) Definition of the Viewshed Value**

We define the Viewshed Value ($V_{ij}$) as the relative result that pedestrian can see the firework display at Point *P(i, j)*. P is the centroid of each cell whose area represents the area that each pedestrian occupy (Figure 4.7). $V_{ij}$ is decided mainly by two factors: visibility which represents the extent to which pedestrians can see the firework at a certain point, and distance between the point and the firework which is in proportion to the viewshed value $V_{ij}$.

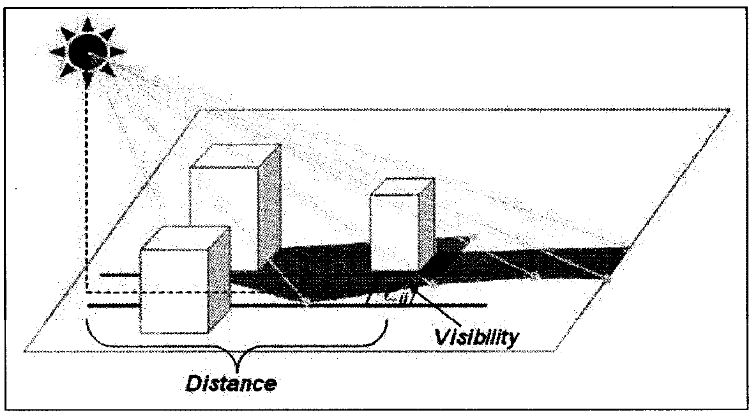


**Figure 4.7: Viewshed Value by Firework**

Source: author.

**(2) Creating a Digital Building Model (DBM)**

Height and shape of buildings are the main two factors that influence the visibility of the fireworks. Acquiring these data is evitable for analyzing the visibility. It is necessary to build a DBM which is intended to describe the surface details. First, buildings height information is extracted by using the digital photogrammetric station "VirtuoZo", Version 3.5. With this software, it is possible to extract the third dimension of objects through the stereo model and aerial triangulation of the original two aerial images. Secondly, it is also possible with this software to get the shapes of each building, but unfortunately, the quality of a big part of the data obtained with VirtuoZo is not satisfactory in several aspects. For example, the polygons of a rectangular house should enclose four rectangular angles, but none of the angles are really rectangular. This is only one reason of the needs to improve the quality of the VirtuoZo measured shape data with AutoCAD, especially when the shape of a building becomes more complicate than just a rectangle. Thirdly, some of representative buildings in this area, like the Hong Kong Cultural Center and the Hong Kong Space Museum, do have irregular shapes and different height in different parts, and their 3D models are improved with writing and using Scripts (Figure 4.8). The final DBM of the TST area is created as in Figure 4.9.

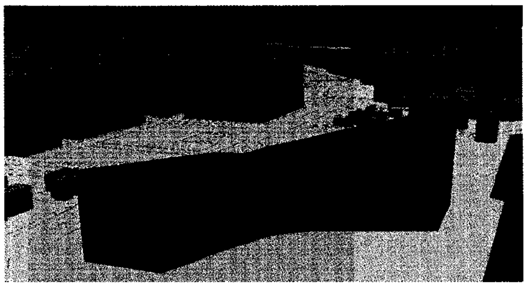

Figure 4.8a: Hong Kong Cultural Center

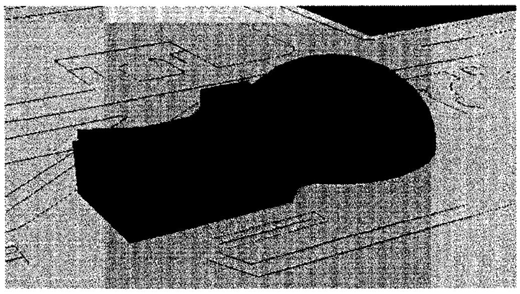

Figure 4.8b: Hong Kong Space Museum

**Figure 4.8: Examples of Typical Irregular Building Models**

Source: author.

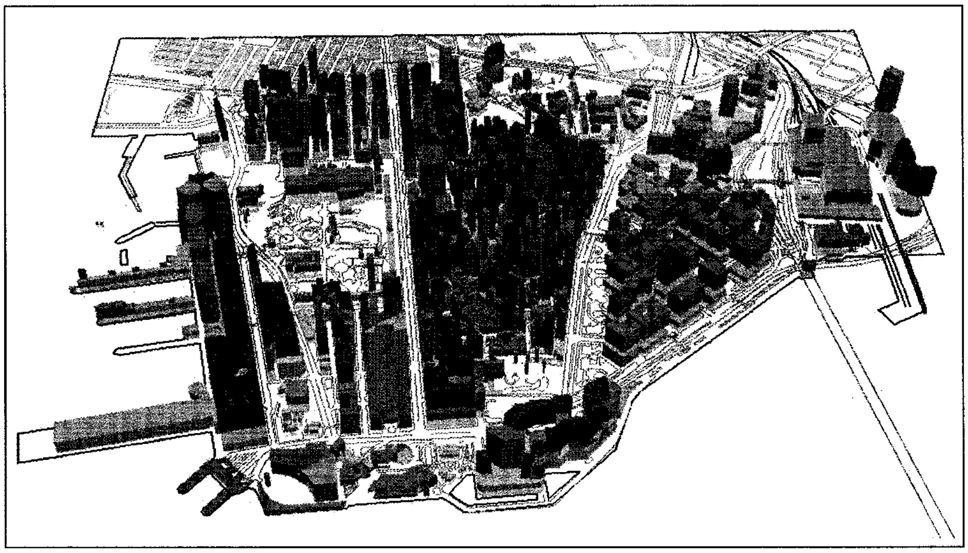

**Figure 4.9: A Digital Building Model of the TST**

Source: author.

The creation of DBM is a necessary prelude for analyzing visibilities in a fireworks display. To a certain extent, visibility is one of the driving forces that engages a crowd in making different decisions in their movements before and during the event.

As a 3D model, DBM also serves as one of the components of visualization environment in the geo-collaborative crowd management, although this model can improve with textures and details added. Visualization has until now been confined within the displays of maps and texts, but 3D representations of the real-world or dynamic models have improved the display platform for communicating geographic information. It can be said that developments in technologies have made visualization become a media for senders communicating information in various forms to receivers, and an interface for different users who are distributed at different places to make co-operative work. Therefore, for the crowd management, the development of a complex digital building model is essential for the management of extensive, collaborative and geographically distributed data and processes.

DBM is also a foundation for the crowd behavioral modeling and simulation as it provides adequate information on the buildings involved. As a type of objects in the human movement system, interaction between crowds and buildings form one of the interactions with crowd behavior affected by the physical confine of building structures. The representation of the building models will also be embodied in the simulation of crowd behavior and systems integration. Attributions of buildings will become controls that will generate different crowd behavioral modes.

**(3) Visibility Analysis**

In GIS dictionary, viewshed identifies the cells in an input raster that can be seen from one or more observation points or lines. Each cell in the output raster receives a value that indicates how many observer points can be seen from each location. Normally, visibility is decided by observer's height, observation height, topography, surface objects, and azimuth. TST area is almost a plane region, and there are no obvious topographic differences on height. Buildings are the main objects that will block lights from fireworks. Since this work focuses on the visibility on street network, vegetations on this area are not considered within visibility analysis, while actually they can be viewed as part of objects combined with buildings. In addition, pedestrian's azimuth can be random, so the visibility of each cell can be represented by:

*visibility(<crowd's general height>, <heights of sampling firework points>, <DBM>).*

In this analysis, the visibility has divided as 10 levels, points where pedestrians can view the total fireworks are represented by 10, where pedestrians are blocked by buildings and totally cannot see fireworks are represented by 0. The result is illustrated as Figure 4.10, which analyzed the visibility value in the whole TST area.

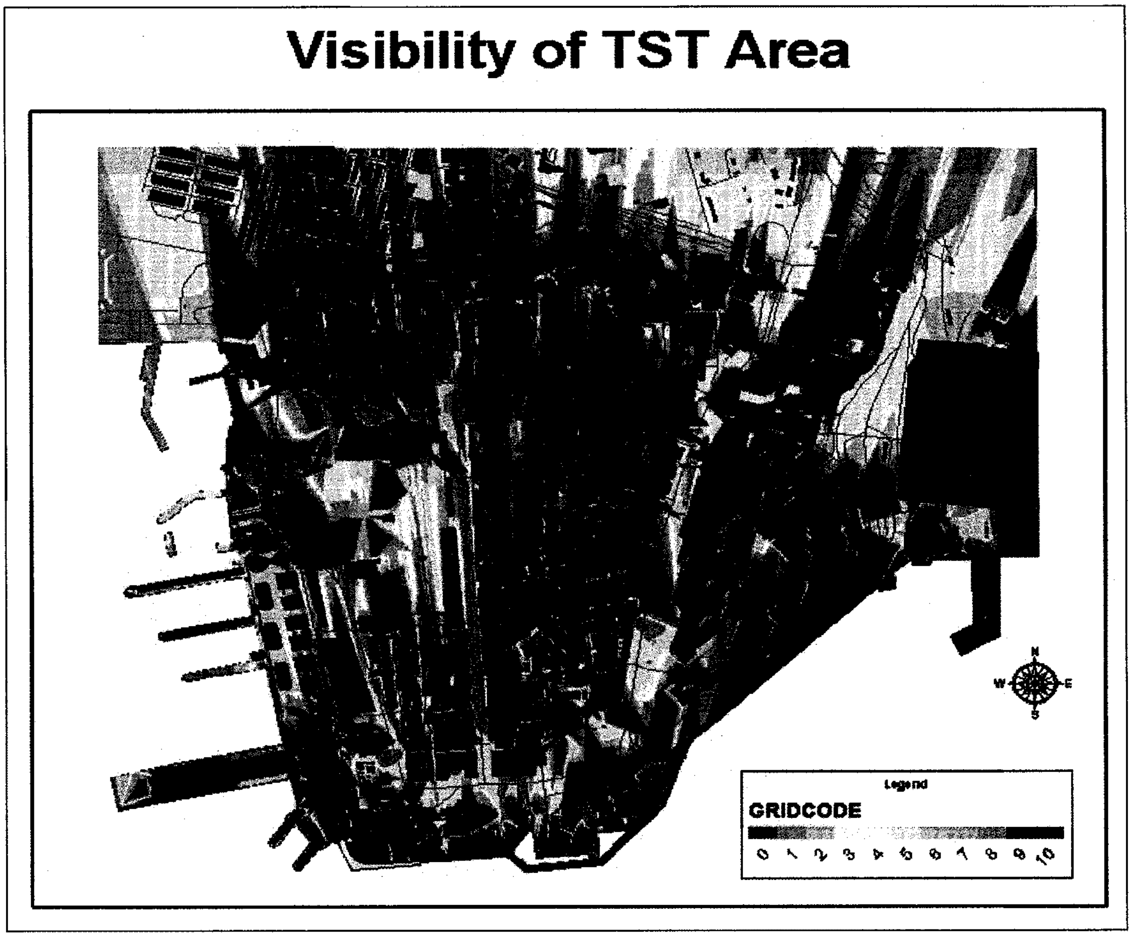


**Figure 4.10: Visibility of TST Area**

Source: author.

Analyzing the visibility in whole region is useful for preparation before the event. Sections which have high visibility by the firework will surely attract more people gathering, while they may be constrained with their configuration or geographical functions. For example (Figure 4.11), through visibility analysis, the purple circled area has a higher visibility, while it is found as Kowloon Park, which means that event managers should consider the risk of opening this area for viewing the display. In fact, in view of the complex configuration and interlaced byways, this area is controlled not entering, while still managers need to take extraordinarily attentions on crowd behavior who intent to crash into it.

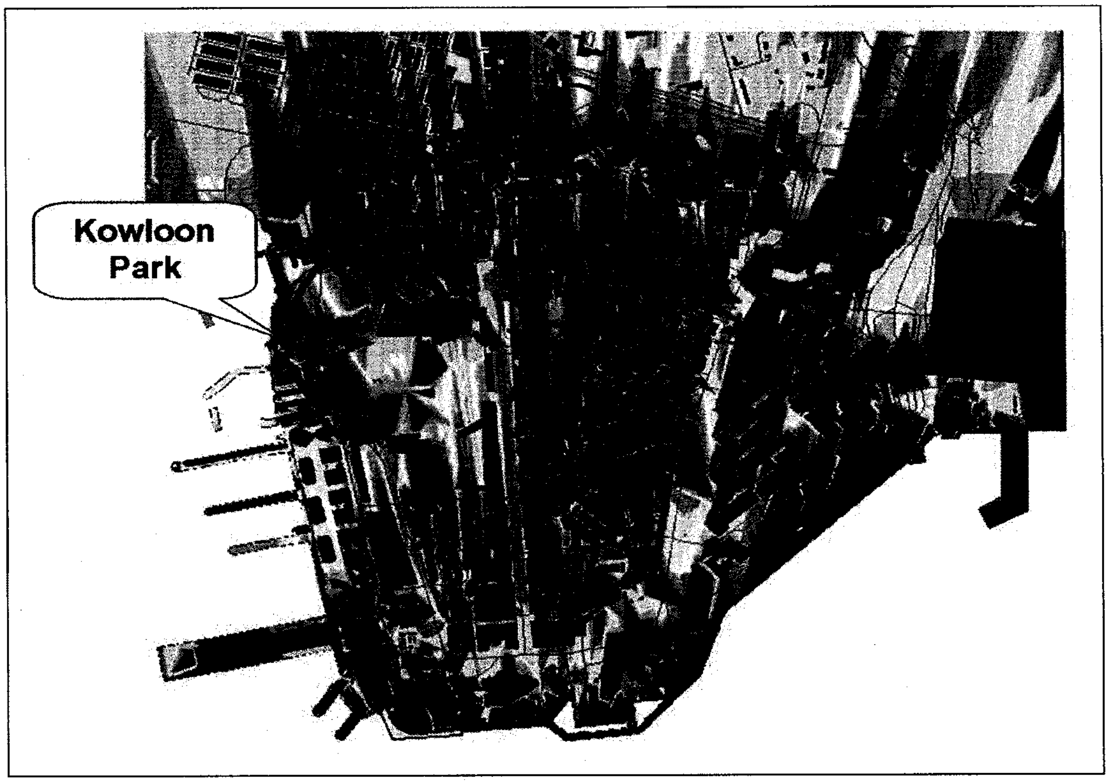


**Figure 4.11: Kowloon Park with Higher Visibility**

Source: author.

**(4) Distance Analysis**

Visibility analysis provides a general frame for analyzing "which area and how much can firework display will be seen?". Through this analysis, event managers may define the region that this event is going to be involved, and suggest the corresponding traffic arrangement. However, pedestrians as the participant in this event, seek to obtain visual effect which is related with the distance from a view of optical principal of human eyes. From the analysis result (Figure 4.10), it is easy to find that there are several areas which have same visibility value but different distances to display site. It is necessary and reasonable to differentiate these areas with their distances to attractor. Synthesis distance with visibility analysis, five level of viewshed at each cell with a size of human body is extracted focusing on the pedestrianziation area (Figure 4.12). This integrated area, depicts the general partitions of different viewshed areas that attract the pedestrians movement. In other words, it is the attractiveness analysis that each grid cell pulls on pedestrians. Spatial effects by buildings on pedestrian movement have been quantified and will be used in the behavioral modeling and simulation.

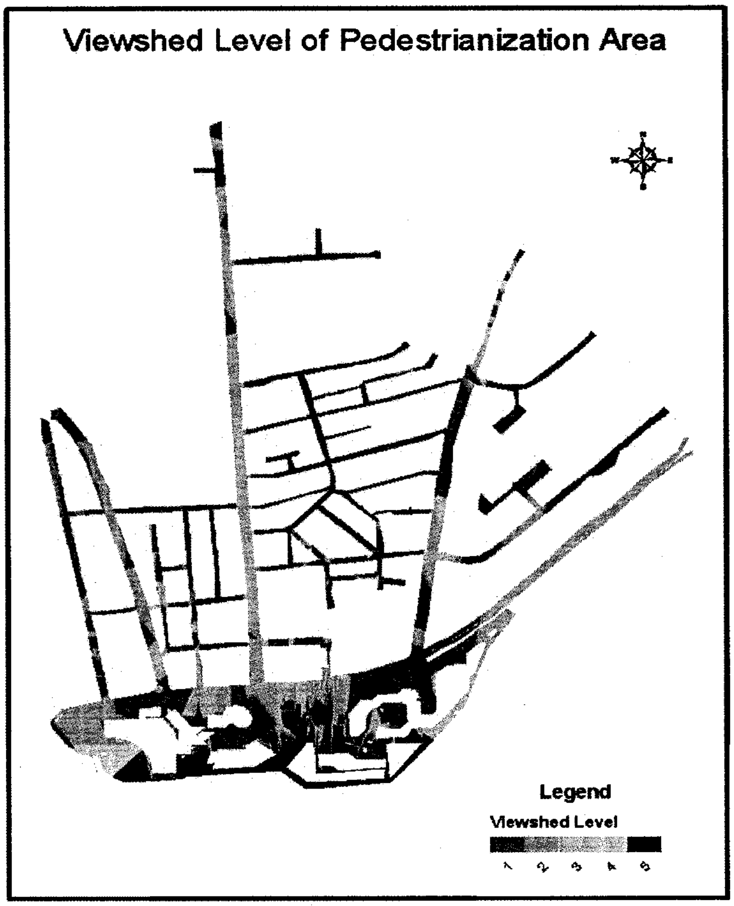


**Figure 4.12: Viewshed Level of Pedestrianization Area**

Source: author.

**(5) Result**

Viewshed value is finally stored with the structure of both visibility value and distance value (Figure 4.13). Each grid represents the standing area of each pedestrian. Pedestrians will first search for grids with the highest visibility value and then search for grids with the lowest distance value when they need make decisions on their headings.

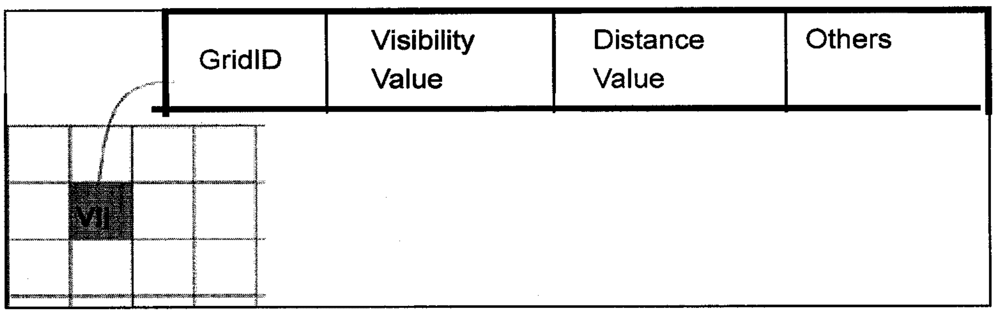


**Figure 4.13: Data Structure of Viewshed Value**

Source: author.

In certain extent, viewshed value reflects the density of crowds. According to the partitions by police department, the whole TST area involved in this event is divided into 3 zones with different crowd density (Figure 4.16, right picture). The darker color means the denser people in the region, which is consistent with the analyzed viewshed map (Figure 4.14, left picture). This further verifies the buildings effects on crowd behavior.

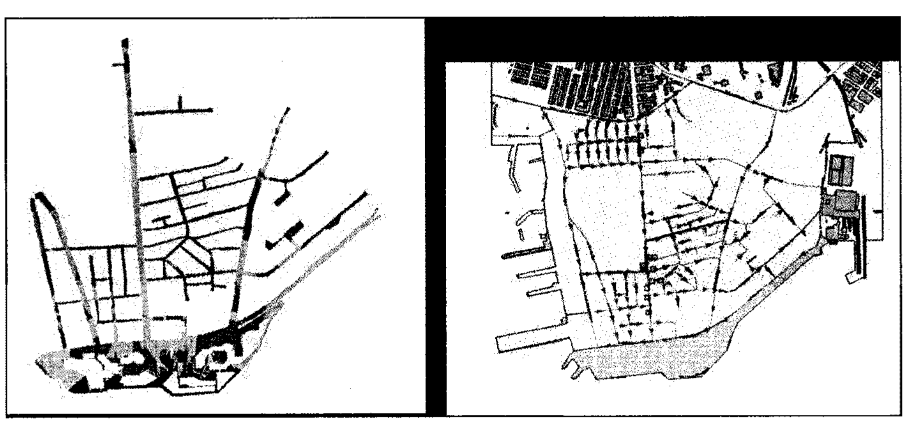

**Figure 4.14: Comparation of Visibility With Crowd Density,** (the left figure shows the detail visibility of each position, the right figure shows the approximate density distribution)

Source: author.

#### 4.3.3.2 Visibility by Road Exits

While in the dispersion phase, when exits that guide crowd leaving the area become attractors that drive crowd behavior, pedestrians' visibility is represented through their cognition of exits. Traditional cognition of geographic space is considered to be represented by cognitive map formed in human brains and people behave guided by this map. However, this cognition in large outdoor event is obviously affected by interactions between crowds. In a crowding environment, behavior of pedestrian is largely restricted within surrounding circumstances and exhibits a feature of path-following, especially in this phase of mass dispersion. As static geographic points, exits may be cognized by pedestrians when they are in the visual field of humans. If crowds are located within these fields, they will select one of the exits to disperse, if not, they are likely to follow people surrounded until they get to these fields. The visual fields can be calculated as isovist fields which are defined as the set of all points visible from a given vantage point in space (Benedikt, 1970; Turner, 2001) (Figure 4.15). It is originally used in architectural analysis from view of individual visibility to achieve quantitative description of spatial environment. Improved as visibility graph, this analysis method was found useful for explaining the relationship between spatial morphology and human movement especially within buildings, such as the Tate Gallery (Batty, Conroy et al, 1998; Turner et al, 2001).

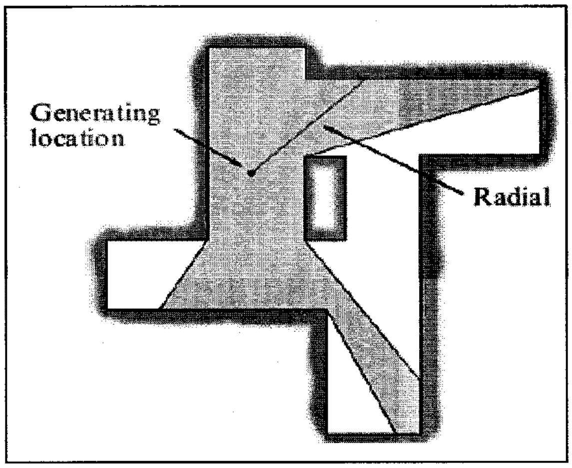


**Figure 4.15: An Isovist Polygon**

Source: adapted from Turner (2001).

In the firework display, due to the complex transportation settings and road network, most people coming for the display normally cannot have the cognitive map for the exits only until they see those exits. Therefore, this visibility graph analysis is feasible to be used to figure out areas from which pedestrians can cognize the exits that they can disperse and provide data for model crowd behavior in dispersion and evacuation phase. Since there are totally 13 exits within this area, constrained by the edges of buildings and roads, their isovists can be represented as Figure 4.16, which also means that pedestrians who arrive any of cells located in these isovists polygons may cognize the exits and make selections under the guidance of cognitive maps formed then.

**Figure 4.16: Visibility by Road Exits**

Source: author.

For the focus area in this research is the pedestrianization area, visibility of road exits is figured out as Figure 4.17. Attractiveness of each exit to pedestrians is same, so the final result of visibility value on each grid cell is stored as 0 or 1. Cells with value 1 mean from which pedestrians can realize the exits, and cells with value 0 mean from which pedestrians cannot realize exits and may behave following others or randomly.

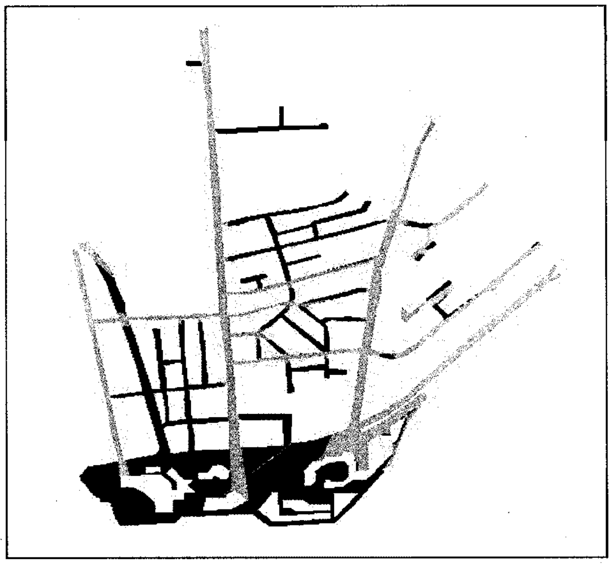

**Figure 4.17: Visibility Analysis Within Pedestrianization Area In Dispersion Phase**

Source: author.

### 4.3.4 Urban Morphology: Axial Map of Road Network

Urban built environment, especially buildings, exhibit effects on crowd movement in this local event, and represent as different visibilities or attractiveness at each ground cells. As another type of built objects in the environment of human activities, what and how about the effects on crowd behavior? Solving this problem may understand another driving force underlying crowd behavioral dynamics.

Crowding is the main feature in this event, and this phenomenon take place more easily at street junctions. Roads or streets are the activity environment that crowd movement happen, so investigating whether the morphology itself influence crowd behavior is helpful for decision making in the management. Hillier suggests a distinction between research programmes into the effects society has on space and those that look at the effects that space has back on society (Hillier 1984; Hillier 1998). The first strand of research inquires into the way in which society creates spatial structures for its own reproduction. Research of this kind seeks to answer questions about the mechanisms and rules by which buildings and cities are created for social needs. The second kind of research looks into the often-unintended social consequences that these spatial structures then have back on society. Once a spatial structure such as an urban area has been created, it seems to offer unexpected social potentials and problems. The way that people use an area depends not on what planners or architects might have expected but on these potentials offered by the spatial structure itself. What are the laws that govern the use of spatial structure that we find, however it was created and for whatever original purpose? This is the starting point for a research programme that attempts to isolate the independent role of spatial structure onto the functioning of society. One important way in which the environment might be shown to influence social activities is in the determination of pedestrian movement patterns. This is why it is of theoretical interest as well as practical use to develop models of this relationship.

Space syntax analysis (which represents and quantifies aspects of spatial pattern) has found that spatial configuration correlates powerfully with observed movement by both pedestrians (eg: Hillier et al, 1993, 1987, 1983; Peponis et al, 1989; Read, 1999) and drivers (Penn et al, 1998a; 1998b). Axial map is one of the approaches used to analyze the urban morphology's effect on human movement. The idea of a 'fewest line' axial maps was presented in the introduction of Hillier and Hanson's 'Social Logic of Space' as some minimal set of the fewest and longest lines of sight that cover some set of the "fattest convex spaces" in terms of their area perimeter ratio (Hillier and Hanson 1984, page 17). It is suggested as a method for reducing the complex continuous spatial network of cities into a set of component parts that could be subjected to analysis.

Using Axwoman, the extention of Arcview GIS, the axial map of TST area is drawn as Figure 4.18. And it is not difficult to find that road with higher connectivity result in more interactions between crowds (Figure 4.19). For example, Nathan Road is the road with highest connectivity, which is a main thoroughfare in reality. And according to the experiences from event manager, crowded phenomenon may be found more easily on this road.

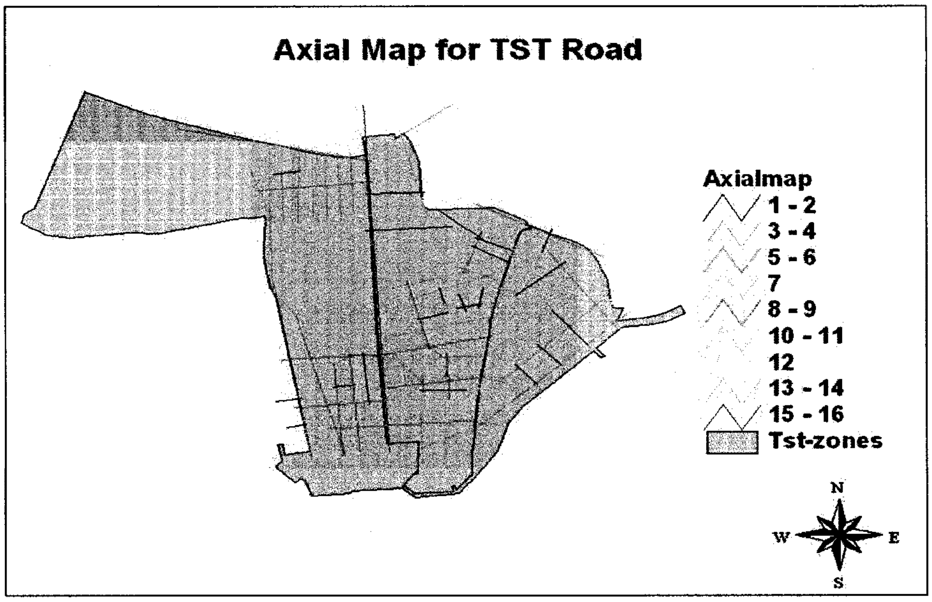


**Figure 4.18: Axial Map of TST Road**

Source: author.

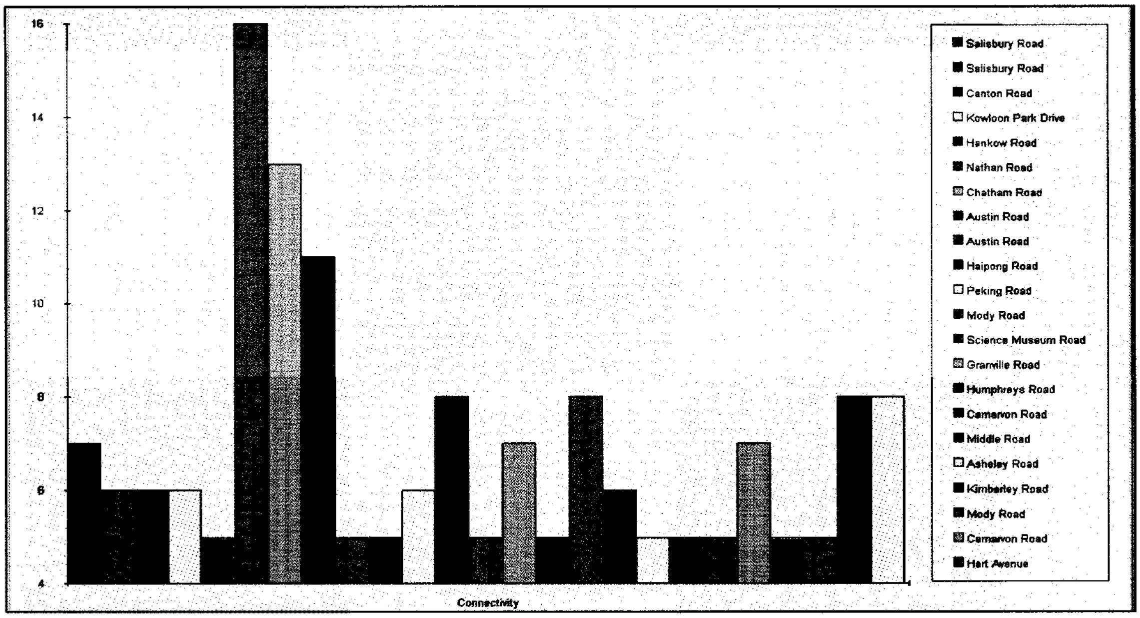


**Figure 4.19: Road Connectivity**

Source: author.

This method of representing urban morphology by using axial maps can be a good analysis tool for event manager to find the possible roads that need special attentions. It is also good for them to rationally arrange distributions of human resources and facilities according to the different levels of road features.

### 4.3.5 Spatial Controls

Many of the events that are of interest in this domain cannot be separated from explicit controls. For example, in the firework display, as crowds get bigger and denser, pedestrianization area is guaranteed through using mills barriers to block the roads and close the entrances of buildings to prohibit pedestrian passing. As the different features of buildings shapes will result in probable safety issues, they are also controlled by police. Crowd behavior is therefore affected by these controls. When modeling crowd behavior, these controls are unneglectable. However, these controls in the event are known or can be assumed, so modeling the actual situation with these controls in place is applicable. But as the purpose of this crowd behavioral model is to effectively manage crowds through examine and redesign these controls, then what we actually do is to begin our simulation with no controls. The situation in the absence of controls is firstly assessed, and then gradually controls are introduced to a level which meets the goals of safety. This means that data, calibration, prediction, and control (prescription) merge into one another; calibration must thus be structured around the whole cycle. When it comes to testing different controls, then the entire cycle must be run again for new controls imply different data patterns which as before are not available and must be generated. In a sense, spatial controls affect the crowd behavior and are the important components of the event, while they are designed as dynamic and their attributions can be set through interactive manipulations by users.

#### 4.3.5.1 Cordon Points

Cordons refer in this event to the barriers erected by event managers for closing streets and prohibiting entries. As scenes get more crowded, they are used to control the pedestrian behavior for ease of crowd congestion. Cordons will be set mainly in the phase of crowd arrival to prevent the large crowd inburst the pedestrianization area, and will be removed just before the starting of crowd dispersion. Cordons are also set according to the real crowded situation by managers. The distribution of cordon points is predefined by event managers as Figure 4.20.

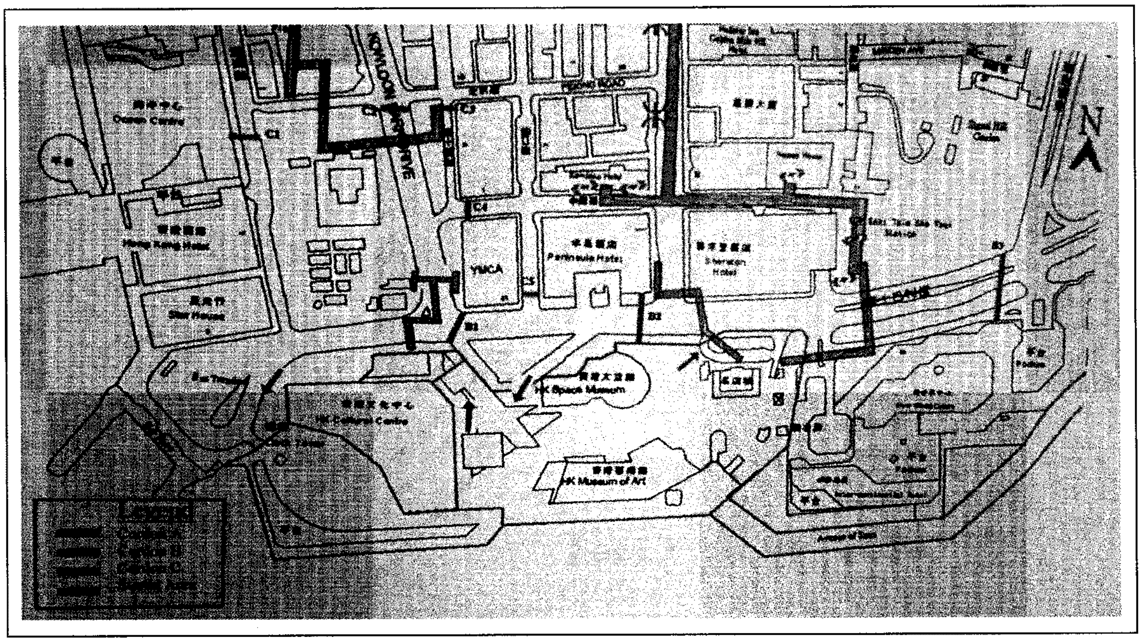


**Figure 4.20: Cordons Set in the Event**

Source: HKPFYT.

#### 4.3.5.2 Key Points

Key points mainly refer to controls from buildings due to their differences of physical infrastructure. They include main buildings, landings, stairs, subway crossings. Whether they are open or close will impact on crowd behavior and bring prodigious complicated interactions between crowds, which make the management work with huge risk of safety.

Except for private buildings in this area, much of the main buildings located in the event environment are for commercial or entertainment usage. Pedestrians may walk through these buildings to the viewing section which means widening the pedestrianization area, while at the same time will increase the interactions at the entrances. So, the entrances to the buildings can be open, close or only one-way permission. Although most of them are closed or set by managers before the event, it is still useful and necessary to inspect their setting.

Subway is another type of cordon points in this event. Since the use of subways in heavy crowd conditions is extremely dangerous, they are closed during the phases. Structure of subways is complex in dimensions normally with slopes or stairs and interlaced underground passages. The space it constitutes has beyond the scope of this research in an outdoor street environment, so its controls on crowd behavior will not be added during modeling and simulations. However, it is of great value for study human interactions in a subway environment.

There are also landings and stairs in the viewing area. Similar with subway structure, landings are risky area for viewing the firework, especially when they are located beside the sea. They are not allowed to get on the stages during the display. While stairs before buildings become good viewing sections that will attract large pedestrians, they will be strictly controlled with the density of population within this area due to the special physical structures.

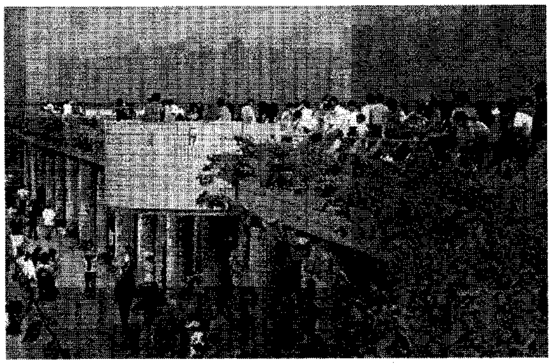

Figure 4.21a: Landing

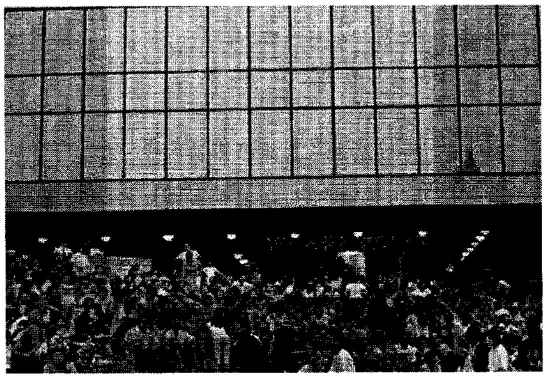

Figure 4.21b: Stairs

**Figure 4.21: Key Points in the Events**

Source: author.

#### 4.3.5.3 Guidance from Event Managers

Interventions from event managers comprise another kind of spatial controls that will affect the crowd behavior. During these three phases, almost at each junction of roads, there is at least one policeman to control the crowd movement to avoid congestions. Commanders also will consider directing crowds within their managing zones.

Guidances from event managers will take actions on pedestrian's route choice or change their directions. For example, there is a "viewing shadow" formed by the New World Center, which blocks the fireworks display location. This shadow runs in a line between the edge of the New World center, and the junction of Salisbury Road, and Mody Lane. Managers will control this section and guide crowds not entering this area.

## 4.4 Summary

### 4.4.1 Some Suggestions on Preparations for Crowd Management

By far, the image of this outdoor event has been depicted that it is a kind of spatial events involving large number of participants moving over a short period of time. In these events, people move rapidly to various attractions where the focus of interest is mainly on the attraction and not on others attending the event. Interactions between people, however, do occur through crowding and flocking behavior while the geometry of the environment has an important constraining effect on how people move.

Although the event of "firework display" in this research exploration is perhaps a one-off spatial event, issues of mobility and interactions between participants or objects in the environment are all same for the crowd management problems. Although crowds behave individually, still there have common features found through representation of their behavioral dynamics. The fascination of crowd psychology lies in the fact that it seeks to account for behavior that shows clear social coherence – in the sense of a large amount of people acting in the same manner despite the lack of either preplanning or any structural direction (Reicher, 1984, P.1). These features provide suggestions and foundations for crowd management and decision making, especially at the period of preparing or planning such an outdoor event.

First, crowd behavior is driven by event nature. The motivations of events make participants behave different types, whether homogeneous or exited, whether ordered or aggressive. Each type of crowd behavior may result in different possible consequences. Acknowledgement of such information is very useful for event managers make preparations before practical management and take notice of them in the process of the events evolution. Second, these events normally have predefined objects that become attractions by large number of pedestrians. These attractors turn into bonds that make crowding a predominant phenomenon connected within this energized human system composed of pedestrian movement. Attractiveness of these can be analyzed to know the probable behavior of crowds, like their general directions, possible crowded sections, and etc. Thirdly, crowd behavior is largely affected by built urban morphology, which mainly put up visibility differences by buildings and road networks. This factor directly affects the behavioral modules of crowds in such events. Spatial analysis on such relationship between crowd behavior and urban built environment quantifies the relative values of visibility and shows the details for modeling crowd behavior. And analyzing space syntax of the urban built environment through axial map reveals the possible roads or road junctions where crowded phenomenon will be produced more easily and remind event managers take care of these sites. However, fourthly, this kind of events is subject to considerable spatial controls mainly from whether buildings are open or closed, whether road is blocked by mills barriers or not, and interventions from event managers, and all of these spatial controls will affect the crowd behavior and bring different emergent situations.

### 4.4.2 Crowd Dynamics as Knowledge Base for Management

As one of the important components for crowd management, data environment stores all the information useful for co-operative work between event managers. Knowledges discovered through exploration on crowd dynamics become valuable information for the management. Not only the exterior behavioral process can be stored, more important are the underlying driving forces that produce such procedure of crowd behavior. This knowledge offer foundations for management system, and act as references for different types of outdoor events.

### 4.4.3 Hints on Crowd Behavioral Modeling and Simulation

Crowd behavior in such events make themselves dynamic system because of the movement, which also breaks down when the phenomena that we observe cannot be classified into categories from which general relationships can be inferred or deduced (Batty, 2002). Dynamics becomes the most important in such disaggregate human system whether it is an recreational events that involve ordered pedestrian movement or it is a political rally that involves high risk safety problems on crowding. When interactions become the connections of the human system, analysis from top-down simulation which usually depends on articulating relationships between system aggregates, is unable to capture the richness in structure and dynamics that many system displays. There is an increasing recognition that systems must be understood from the bottom-up for many systems function and maintain their structure in this manner. The way local actions generate emergent structures which have order at more global levels is particularly important to many functioning spatial systems such as the way traffic behaves in networks, the way suburbs and edge cities develop, and the way highly segregated residential areas coalesce within the urban fabric. This is part and parcel of complexity theory which espouses the idea of decentralized functioning and thinking as the basis for new ways of simulation and policy analysis (Johnson, 2001). Consequently, this type of outdoor spatial events has become an increasingly feature of urban cities and it is important to solve the safety issues that is generated by pedestrian movement using ways from bottom-up.

Agent-based modeling has been one of the most popular approaches to analyze intelligent social society from bottom-up. Explorations on crowd dynamics in the firework display also show the hint at feasible way of modeling and simulating crowd behavior through this individual approach. Based on these dynamics explored in the event, crowd behavioral modeling and simulation will be developed in the following two chapters. First, formal models for crowd movement in the event are developed focusing on the combined effects by urban morphology and social-psychological factors that crowds themselves possess. Second, through integration and simulation, spatial controls will be gradually introduced in the simulation of crowd behavior to find out different results under different scenarios, which will provide an interactive interface for geo-collaborative crowd management.

# CHAPTER 5 MULTI-AGENT PEDESTRIAN MODELING FOR OUTDOOR EVENTS (MAPMODE)

## 5.1 Introduction

Dynamics explored and analyzed in the former chapter revealed the relationships between crowd behavior and spatial environment, while as a complex system, interacting crowds may create emergent organizations at a higher level through their individual interactions, which cannot be found out only by observations on existed happened events. Modeling gives us a method for looking at both history and future. There have been a lot of modeling approaches used in pedestrian modeling, showing the growing interest in pedestrian modeling and simulation in the scientific community. For example, the first international conference on Pedestrian and Evacuation Dynamics took place in 2001 in Duisburg, Germany (Schreckenberg and Sharma, 2002). However, the emergence of higher-level organization from the interactions of lower-level units is whacking in the case of group behavior because we are the lower-level units, and the higher-level organizations typically emerge spontaneously, without our knowledge (Goldstone and Janssen, 2004). It is a growing realization across the social sciences that one of the best ways to build useful theories of group phenomena is to create working computational models of social units and their interactions, and to observe the global structures that these interactions produce. In the past few years, the use of agent-based models of pedestrian behavior has grown and shown its abilities to build intelligent social structure from the "bottom-up".

"*Models do not explain history, but they may tell us where to look* (Bowles, 2001)". As a feasible approach to model the crowding situations in outdoor events from a disaggregate view, multi-agent based modeling is adopted as a solution to both looking into individual pedestrian behavior and collective crowding phenomena emerging from individual interactions. In following sections, multi-agent pedestrian models for outdoor events (MAPMODE) are proposed. Elements in MAPMODE are defined first following the theories on agent-based modeling, a generic pedestrian behavioral model is built for crowded outdoor events, and three types of models are established and explained in detail based on the case of firework display. They are model for crowd arrival, model for crowd dispersal and model for crowd evacuation.

## 5.2 Model Definition

Generally speaking, an agent is a computer system that exists in some environment and capable of sensing and acting in this environment in order to meet its objectives (Wooldridge, 2002) (Figure 5.1). Agents exist in some space and can be designed to represent any entity. Agents have sets of attributes that describe their condition and characteristics that govern their behavior. Agents can, in many instances, "communicate" with other agents as well as with their environments which is called interactions. Agent behavior is driven by transition rules. Any number of rules can be devised to govern the activities of agents: goals that agents seek to satisfy, "preferences" that agents might be regarded as possessing (e.g., "likes" and "dislikes" for certain spaces), etc. Time proceeds iteratively through discrete steps.

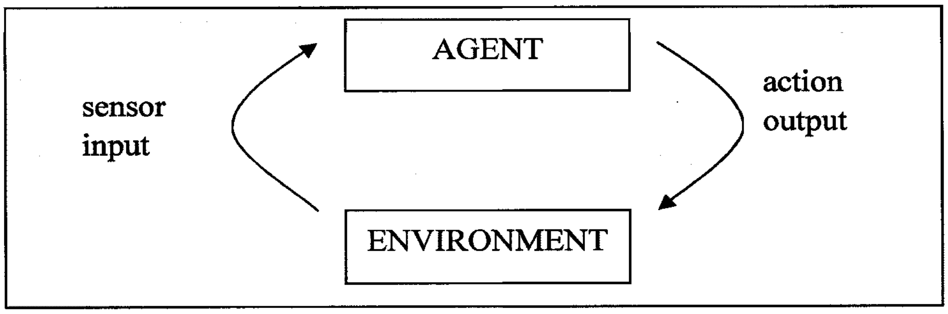


**Figure 5.1: An Agent in its Environment**

Source: adapted from Wooldridge (2002).

### 5.2.1 Agent

Theoretically, any identity can be viewed as an agent. The event of "Firework Display" can be represented by a few groups of agents which have individual features of behavior and interact with each other. According to the different functions they take in the event, 7 types of agents have been defined, which are:

- **Pedestrians Agents (*P*)**: who are main participants in the outdoor event and the main research focus of this work. Their interactions are complex and originate from actions and reactions with themselves and other agents in real time.
- **Policemen Agents (*L*)**: who are main event managers that interact with other agents, but have restricted activity region.
- **Attractors Agents (*A*)**: that are objects attracting pedestrians movement. During the formation process, attractors are the fireworks which produce different levels of viewsheds in the area. In the dispersion and evacuation process, exits are the attractors that lead pedestrians away from the area.
- **Roads Agents (*R*)**: on which crowd behavior takes places. They can be set open or close to allow or forbid pedestrian's movement.
- **Buildings Agents (*B*)**: although they are fixed objects, but they can be managed by event managers to permit or forbid pedestrians entry. When they are set closed, they can be viewed as blocks, and when they are set open, it can be seen as an additional behavioral space for pedestrians.
- **Facilities Agents (*F*)**: which are objects that event managers use to manage the crowds and release crowding.
- **Emergencies Agents (*E*)**: They are agents that created in the evacuation process if emergencies. They have own growing behavior, and pushes participants away from them as soon as possible.

Agents have their own attributes and behavioral features generalized from information we have collected from historical events. Table 5.1 illustrates their attributes designed within MAPMODE, and characteristics of their behavior. Data sources of agents' behavior can be observed from on-site, analyzed through spatial analysis, or modified by users.

| Agent | Representation | Attributes | Behavior | Data Sources |
|---|---|---|---|---|
| ***P*** | Pedestrians | Gender;<br>Age;<br>Starting Speed;<br>Maximum Speed;<br>Goal;<br>Direction; | Flexible;<br>React in real-time; | Can be observed, analyzed or modified ; |
| ***L*** | Events Managers | Information sent or receive;<br>Restricted random walking; | Flexible;<br>React in real-time;<br>React according to information; | Can be observed or modified; |
| ***A*** | Events or Road Exits | Location;<br>Values; | Fixed or dynamic; | Can be analyzed or modified; |
| ***R*** | Roads | Name;<br>Width;<br>Situation; | Fixed; | Can be observed or modified; |
| ***B*** | Buildings | Name;<br>Situation; | Fixed; | Can be observed or modified; |
| ***F*** | Facilities | Location;<br>Situation; | Movable | Can be observed or modified; |
| ***E*** | Emergencies | Type;<br>Dynamics; | Fixed or movable;<br>React in real-time; | Can be observed, analyzed or modified; |

**Table 5.1: Agent Attributes**

Source: author.

As the main research objects in MAPMODE, Agents ***P*** have their starting speed and maximum speed, their goals and accordingly directions to goals. Although it will not be considered in this thesis work, ***P*** have behavioral differences due to their gender and age. ***P***'s behavior is completely flexible, not because they act and react with physical environment but also they have flocking behavior because of psychological affect between crowds and are affected by spatial controls. However, their origins and destinations can be analyzed.

Agents ***L*** have relatively simpler behavior in this event, because their responsibility is mainly to manage crowds. They only behave in a restricted area for their duties. They receive or send messages from co-ordinators and transfer these messages to ***P***.

***L*** mainly work as guidances or controls to ***P*** and interact with other agents in real-time.

Agents ***A*** can be event itself or exits to the area. They have geographical locations and values that show their attractiveness to ***P***. Their behavior can be fixed or dynamic. For example, fireworks in this event are fixed, while exits can be controlled as open or close. Moreover, if attractors in an outdoor event are parades which have their own walking route or speed, they are viewed as dynamic. Information on ***A*** can be analyzed.

Agents ***R*** have features of name, width and situation. They can be controlled as open or close by ***L*** and have interactions with ***P***.

Agents ***B*** have similar attributes with ***R***, and interact with ***P***. When their situation is set to be close, they act as obstacles to pedestrians, and when open, they act as available spaces on which crowd are allowed to behave.

Agents ***F*** have pre-defined locations and will change their situations by ***L***. Furthermore, their situations can also be analyzed or set by users.

Agents ***E*** may have different dynamics as their distinct types. They can be a fixed crowding or a growing fight. In this research, we restrict E as a type of static agents which will push ***P*** away from them as soon as possible. Their information can be set and analyzed.

### 5.2.2 Space

Agents are located within spaces. From a human psychological perspective, one very important factor that influences an individual's social behaviors and decision making is the notion of personal space. According to Ashcraft and Scheflen (1976), "Man is a territorial animal very much like his fellow creatures. He defines a space and marks it out for his particular use. He draws visible and invisible boundaries which he expects others to respect. He will defend a territory against the intrusions of others." The respect of personal space functions as a social rule to keep safe distances among individuals. Since pedestrian agent is the main object that we focus on in the modeling, each space is represented with an array of cells with area of 50×40cm$^2$, which is the rough average area of Hong Kong people. So, spaces are:

$$S = \bigcup_{i=1}^{n_i} \bigcup_{j=1}^{n_j} C_{ij}$$

$i,j$ – index of cells $C$

$n$ – the total number of cells, $n = n_i \times n_j$

Cells have attributes, *type* and *value*. *Type* means the agent type that is located within a cell, thereby

$$C_{ij}(Type) \in \{P, L, A, R, B, F, E\}$$

Each cell is associated with only one agent type. Since *P*, *L* and *F* are moving agents on cells, and may overlap with *R*, it is considered to replace *R* if in such conditions. So, cells with pedestrians are represented as $C_{ij}(type) = P$, with policemen as $C_{ij}(type) = L$, with attractors as $C_{ij}(type) = A$, with Roads as $C_{ij}(type) = R$, with buildings as $C_{ij}(type) = B$, with facilities as $C_{ij}(type) = F$, and with emergencies as $C_{ij}(type) = E$. Meanwhile, *Value* means the attractiveness of each cell, which in this research represents the viewshed value ($V_{ij}$) of each cell. $V_{ij}$ is analyzed and calculated by visibility analysis in Chapter 4. Therefore,

$$C_{ij}(Value) = \begin{cases} V_{ij}, & if\ C_{ij}(Type) \neq B \\ -\infty, & if\ C_{ij}(Type) = B \end{cases}$$

### 5.2.3 Interaction

Interactions between agents decide the growing process of crowd behavior. Potential interactions in the event are mainly from those between pedestrians and those between pedestrians and other agents. Figure 5.2 illustrates existing interactions between agents.

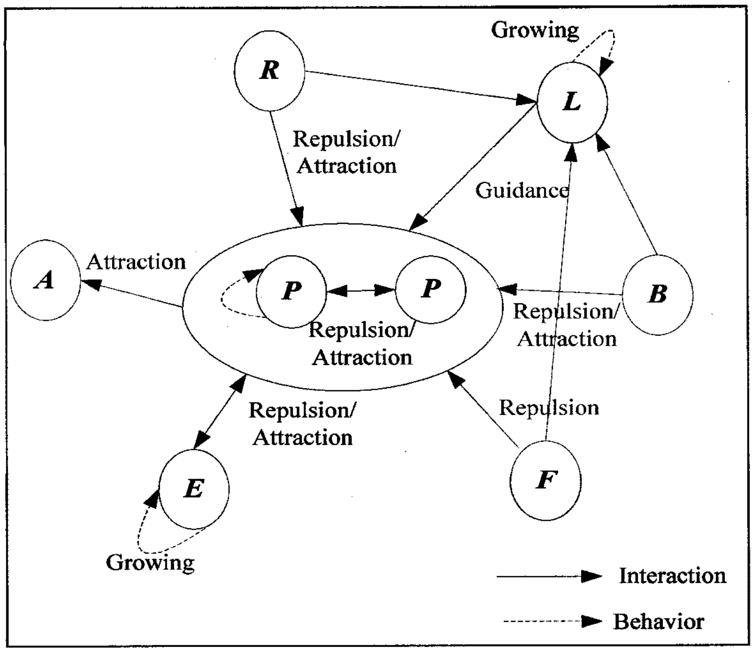


**Figure 5.2: An Illustration of Agent Interactions**

Source: author.

Interactions between pedestrian agents are primary flocking behavior or path-following behavior formed as crowd effects. Interactions between *A* and *P* are represented as attraction of *A* to *P*, and bring values of cells. As fixed physical environment in this event, *R* and *B* may work as attracting or repulsing *P*. If road is set as closed, it will forbid pedestrians movement on its surface; and if it is set as open, it will attract pedestrian according to its attractiveness value produced by attractors. Similarly, if a building is set as close, it works as blocks to pedestrians, and if it is set as open, it will allow pedestrian's entry. Besides the collision avoidance, interactions between *P* and *L* may be guidance which will directly affect pedestrian's route choice or movement especially at road intersections. Pedestrians will adjust their behavior according to messages received from *L*. *F* act as repulsion to *P*. When *F* are set, they will block pedestrians movement. Another type of interactions are represented between *E* and *P*. In most cases, *E* keep *P* away from them, while in some special cases, they may attract *P* as well, for example, a performance. Above interactions affect crowd behavior and bring part of crowd behavioral exhibitions.

Interactions in this event also include interactions between *L* and *R*, *B*, *F*. As a kind of special participants in this event, *L* behave basic reactive behavior as avoidance with *R*, *B* and *F*. Meanwhile, as event managers in this event, *L* interact with *R*, *B*, *F* through changing their situations as open or close to keep management on *P*.

### 5.2.4 Time

Dynamics of crowd behavior are intrinsically temporal. We define $t = 0, 1, \ldots, T$ as the time that pedestrian takes each step. As three phases are considered in this work, T is composed of the time needed for the arrival phase ($T^1$), time needed for the dispersal phase ($T^2$), time needed for the evacuation phase ($T^3$), and time for the display which is a constant ($\varepsilon$) (Figure 5.3). And in each time period of $T^k$, $t$ can be viewed as relative time from $t_0$ to $T^k$. So the total time period during the event is:

$$T = \sum_{k=1}^{3} T^k + \varepsilon$$

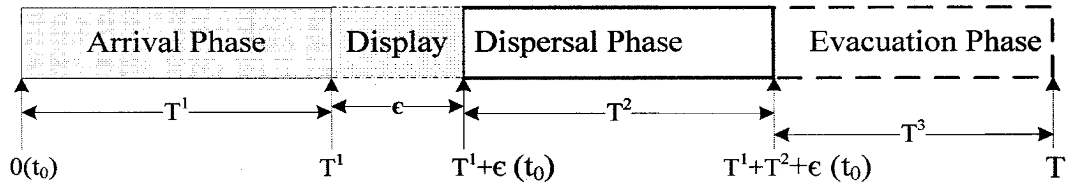


**Figure 5.3: Time in the Event**

Source: author.

Consequently, spaces can be further represented as:

$$S(t) = \bigcup_{i=1}^{n} \bigcup_{j=1}^{m} C_{ijt}$$

which also means that cells have been expressed with dimensions on both spatial and temporal. Each cell has attributes of agent type $C_{ijt}(type) \in \{P, L, A, R, B, F, E\}$ and value $C_{ijt}(value)$. So, if $C_{ijt}(type) = P$, then it means a pedestrian is located within a cell at time *t*, and will interact with other pedestrians; if $C_{ijt}(type) = L$, then that means a policeman is located within the cell at time *t* and pedestrian will receive or not receive his messages and interact with him; if $C_{ijt}(type) = A$, then at time *t*, the cell is occupied with an attractor; if $C_{ijt}(type) = R$, then it means that the road agent is signaling that a cell is available for a pedestrian to move to; if $C_{ijt}(type) = B$, then it is considered that a building agent as a block is unavailable for walk and will interact with pedestrian; if $C_{ijt}(type) = F$ ,then there is a facility agent existing in a cell and a pedestrian or a policemen can not move on it; and if $C_{ijt}(type) = E$, then an emergency agent is located within the cell and pedestrian interacts with it as a block or an attractor.

## 5.3 A Generic Pedestrian Behavioral Model in Crowded Event

We adopt Hoogendoorn and Bovy's (2001) theory on pedestrian behavior that three mutually dependent levels are implemented when individual pedestrian take actions. They are:

- **Strategic level**: in which pedestrian chooses his departure time and activity set;
- **Tactical level**: in which pedestrian schedules his activity, chooses his activity area and make route choices to activity area;
- **Operational level**, in which pedestrian takes his walking behavior and interact with his environment.

Based on above theory, for the firework display, a generic pedestrian behavioral framework is illustrated as Figure 5.4. When individual pedestrian takes first step at time $t_0$ for his movement to attractions, he needs to justify his surrounding environment, he chooses an optimal route (*r*) from route set ($U_2$) which are formed according to destination set ($U_1$), and takes his individual walking behavior. Pedestrian walking behavior results from interactions with crowd environment, and at the same time become input/output to the crowd environment which will re-affect pedestrian's destination choice and route choice at time $t_k$. As components of crowd environment, pedestrians act and react with this circumstance with advances of time.

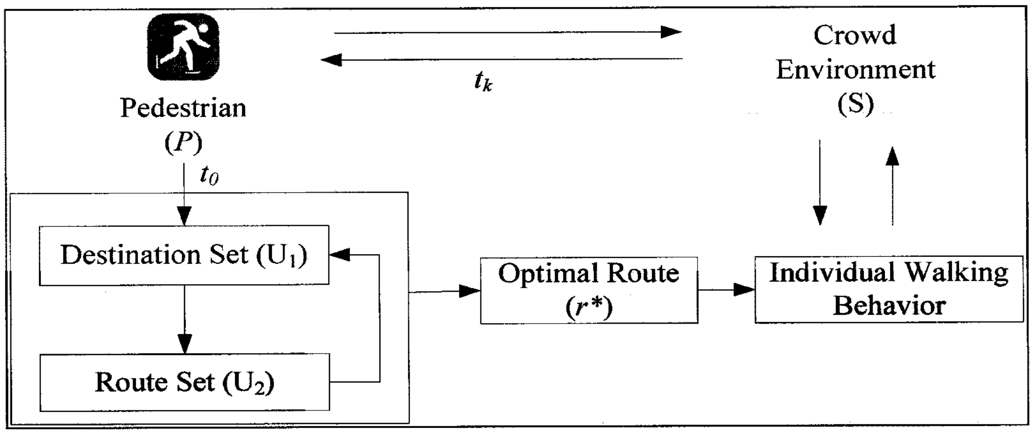


**Figure 5.4: A Generic Pedestrian Behavioral Framework**

Source: author.

### 5.3.1 Destination Choice

We assume that the main and the only goal of pedestrians in this event is to participate in the firework display, although a few of them may come into this area for shopping, eating or others. Attractors are the general destinations for pedestrian movement. We define $m$ as the number of attractors in the event, $A_i$ ($i$=1,2, ..., $m$)as objects of attractors, so the set of attractors ($\Gamma_A$) can be represented as following:

$$\Gamma_A = \bigcup_{k=1}^{m}\{A_k(t)\} = \{C_{ijt}, where\ C_{ijt}(type) = A\}$$

Therefore, the destination set is expressed as:

$$\text{U}_1 = \Gamma_A$$

### 5.3.2 Route Choice

Pedestrian behavioral route is based on the road network within this area. It is assumed that each pedestrian has the historical knowledge of the topology of the environment, which means that he knows the general location of attractors and has formed cognitive maps of a set of routes ($r$) from his located point to attractor points at time $t$ (Figure 5.5). For each individual pedestrian $P$, it is defined that the route from $P$ to $A_i$ is expressed as $\overline{PA_i}$, which is a set of routes from point where P is located to point where $A_i$ is occupied. For the total routes ($\cup_2$) from which individual pedestrian can select, it can be expressed as following:

$$\cup_2 = \bigcup_{j=1}^{z} r_j = \bigcup_{i=1}^{m} \overline{PA_i}$$

$z$ —total number of routes from P to A, $z \geq m$

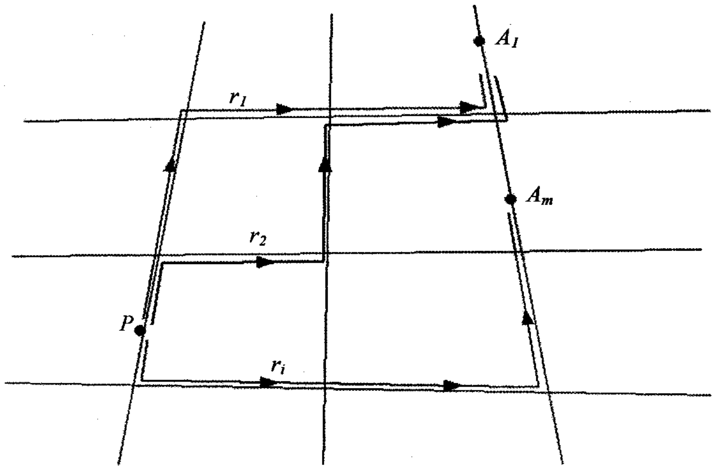


**Figure 5.5: Network-Based Route Set**

Source: author.

For each set of $\overline{PA_i}$, there might be more than one route that is accessible for pedestrian to pass through. Routes can be calculated by professional GIS software based on the road network with the event sites. While at the tactical level, an optimal route should be selected by pedestrian before he operates his behavior. If there is no additional information received from policemen ($L$), this selection is stochastic from the route set. So,

$$r^* = Random(\cup_2)$$

But if there are guides from $L$, pedestrian will walk along the route (direction) that policeman sends.

### 5.3.3 Random Walking Behavior

Pedestrian agent adopts random walking in his environment when destination is defined and a route is selected. This random walk means that pedestrian always tries to choose randomly for his next step. In this model, there are 8 directions that each pedestrian can select for his next step. That means: for each individual pedestrian *P* at time t,

$$P.Location(t) = C_{ijt};$$

the next position of *P* will be:

$$P.Location(t+1) = Random\{C_{i-1,j-1}, C_{i,j-1}, C_{i+1,j-1}, C_{i-1,j}, C_{i+1,j}, C_{i-1,j+1}, C_{i,j+1}, C_{i+1,j+1}\}$$

Actually, when route is selected before pedestrian takes his step, this random walk is constrained within the direction range of his selected route. That means the probability of pedestrian selecting directions of $\{C_{i-1,j}, C_{i-1,j+1,} C_{i,j+1,} C_{i+1,j+1,} C_{i+1,j+1,}\}$ is higher than that of $\{C_{i-1,j-1}, C_{i,j-1,} C_{i+1,j-1}\}$. Figure 5.6 shows the basic concept of this random walking. So, we use function of *RandomWalking()* to represent the pedestrian's random walking behavior, that is:

$$P.Location = P.RandomWalking()$$

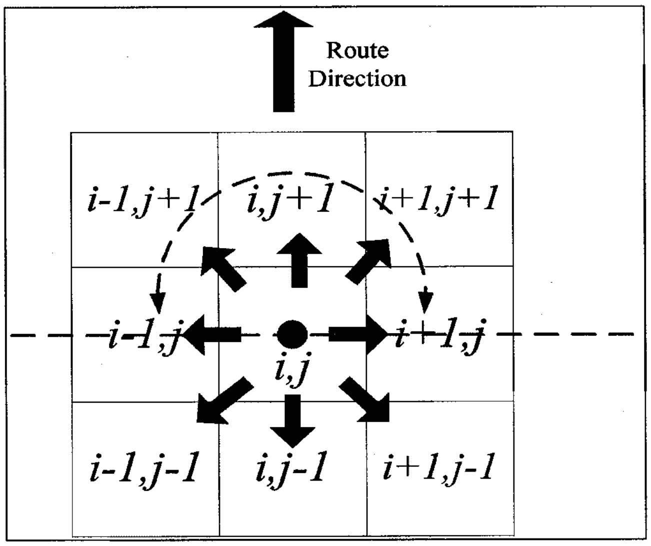


**Figure 5.6: Pedestrian's Random Walk**

Source: author.

While in a crowded environment, this random walk is very limited, due to the limited walkable spaces. Pedestrian behaves naturally to avoid collision with obstacles or surrounding people, or form certain behavioral modes with other pedestrians.

### 5.3.4 Collision Avoidance

This behavior gives a pedestrian agent the ability to maneuver without running into an obstacle or other agents. Its implementation is achieved by monitoring pedestrian's sensory input and reacting to possible collisions. For example, if a pedestrian agent detects obstacles both in front and on the right but not on the left, then it steers toward the left. So,

$$\textit{If } P_t.Location = C_{i,j} \textit{ and } C_{i\pm1,j\pm1,t}(type) \neq R \textit{, then}$$

$$P_{t+1}.Location = Random(\bigcup\{(C_{i\pm1,j\pm1}), where\ C_{i\pm1,j\pm1,t+1}(type) = R\})$$

### 5.3.5 Flocking Behavior

Except for the individual behavior that pedestrian may present, one of the collective behavior that crowd will follow is the flocking behavior. This flocking behavior further limits the pedestrian selecting his direction for his next step. Reynolds (1987) is the first to apply the flocking to describe the crowd effect. The basic idea of flocking is: one or more individuals follow another moving individual designated as the leader; generally the followers want to stay near the leader, without crowding the leader, and taking care to stay out of the leader's way (in case they happen to find themselves in front of the leader); in addition, if there is more than one follower, they want to avoid bumping into each other. The function of this flocking behavior has been concluded using agent-based approach based on that idea. Here, it is represented as: $P_t.Location = P.Flocking()$

### 5.3.6 Pedestrian Behavioral Framework

Spatial-temporal behavior of pedestrians in the event is the combination of pedestrian's destination choice, route choice, random walking, collision avoidance, and flocking. Figure 5.7 outlines the general pedestrian behavioral model in outdoor event. For each individual pedestrian taking his every step forward to his goal, he first senses the orientation of attractors, and compute multiple routes to attractors. Then, he makes decisions and judgments, selects randomly or compulsorily one available route, and adjusts his walking speed and heading. Third, he takes steps according to certain rules. During this operational level, he checks whether he is located in his destination until he achieves his behavioral goals.

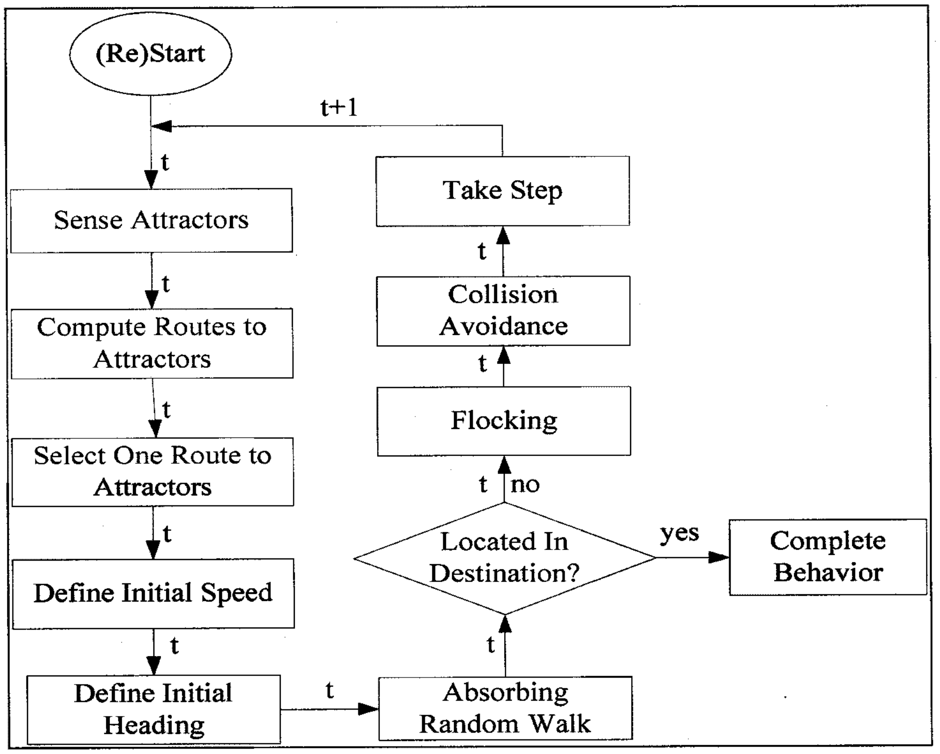


**Figure 5.7: An Outline of Pedestrian Behavioral Model**

Source: author.

The general pedestrian behavioral framework in outdoor event provides a generic process for crowd's interactions with their environment. However, pedestrians will exhibit different behavioral modes in three event phases.

### 5.3.7 Data Structure

Data model formed in MAPMODE depicts the attributes of agents and their spatio-temporal relationship. Following Figure 5.8 illustrates the objects and relationships in data model. There are mainly 7 types of objects in data model which represent 7 types of agents in MAPMODE. Their locations are directly relational with *Cells* which represent agent's activity spaces. One of the attribute "value" of Cells is relational with "Viewshed", and this "Viewshed" will affect *P*'s destination choice. Another attribute "Influence" of Cells only makes senses when emergencies appear. For agent *P*, there are main 5 functions set for control *P*'s behavior. They are functions of *Direction()* which define and adjust pedestrian's directions, *Location()* which calculates pedestrian's locations, *RandomWalking()* which controls pedestrian's random walking behavior, *Flocking()* that controls pedestrians social behavior, and *Disappear()* that means pedestrian leaves the area.

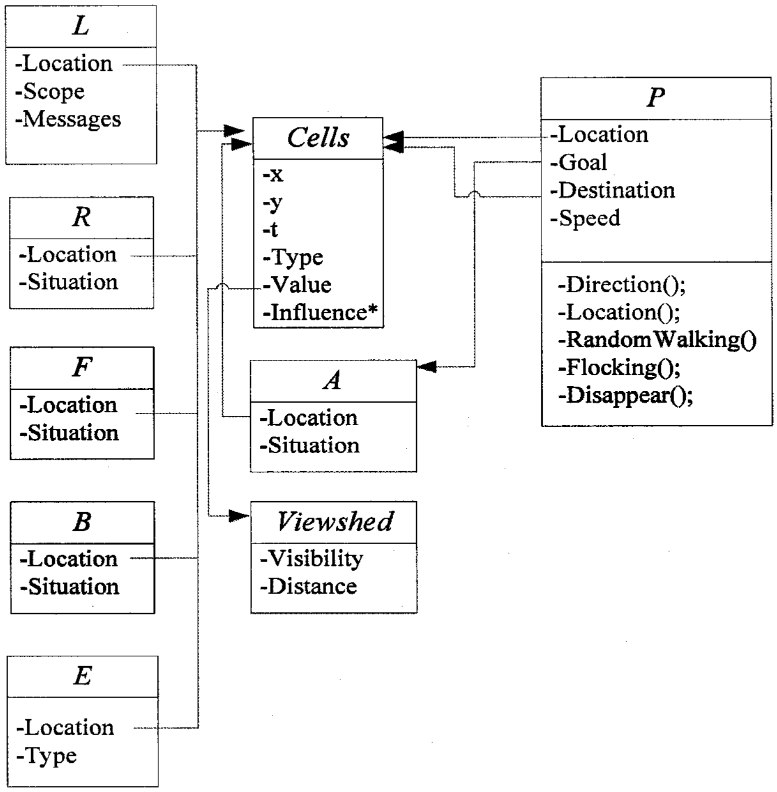


**Figure 5.8: Data Structure in MAPMODE**

Source: author.

## 5.4 Model for Crowd Arrival

### 5.4.1 Completion of Pedestrian Behavior

In the phase of crowd arrival, pedestrian will finally select one position to stop to view the firework display. His behavior will be considered completed until he finds a satisfying viewpoint which is decided by the viewshed value that cells have at that time. Viewshed value produced at each cell by the fireworks makes pivotal functions on pedestrian decisions. As depicted in chapter 4, fireworks produce different levels of values for each cell, and it is assumed that pedestrian always wants to find a cell which has the highest visibility value at time *t*. So, final destination set ($\cup_3$)of pedestrians will be represented as:

$$\cup_3 = \{C_{i_0,j_0}, where\ C_{i_0,j_0}(value) = Max(C_{ij}(Value)),$$

$$with\ \ 1 \le i_0, i \le n_i \quad and\ \ 1 \le j_0, j \le n_j\}$$

If a pedestrian finds a satisfying destination and completes his behavior, it is considered that the cell where the pedestrian is located is not available any more and its value will be changed as -∞. This process of destination choice can be explained by using a sketch map as Figure 5.9:

Pedestrian chooses cells with highest value at time *t*;

If he arrives his destination set, he will randomly select one and stand on the cell;

The cell with attribute P will change its *value* as -∞;

And this process can be explained as following:

$$if\ C_{ij}(type) = P\ and\ C_{ij} \in U_3;$$

then $C_{ij}(value) = -\infty$; $U_3 = U_3 - \{C_{ij}\}$

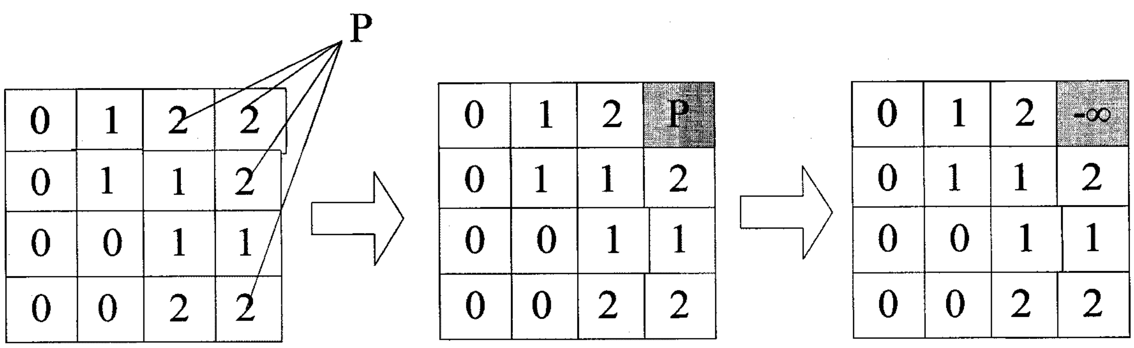


**Figure 5.9: Sketch Map for Destination Choice**

Source: author.

### 5.4.2 Behavioral Model for Crowd Arrival

In this phase, pedestrian spatio-temporal behavior can be characterized as Figure 5.10. First, at the strategic level, each pedestrian is generated at his starting point, and senses locations of himself and fireworks. During this period, pedestrian sets his goal as moving to view the fireworks and tries to arrive a satisfying viewpoint. Second at the tactical level, after sensing the locations, a series of routes to fireworks are computed and one of those is selected for taking walking behavior. At the same time, in case *P* selects a route, he has decided his direction of movement and prepares for movement by absorbing a random walking plan. Third, while at the operational level, *P* will step forward after interacting with his surroundings and following certain behavioral rules as collision avoidance and flocking. *P* will complete his behavior if he finds a best viewpoint.

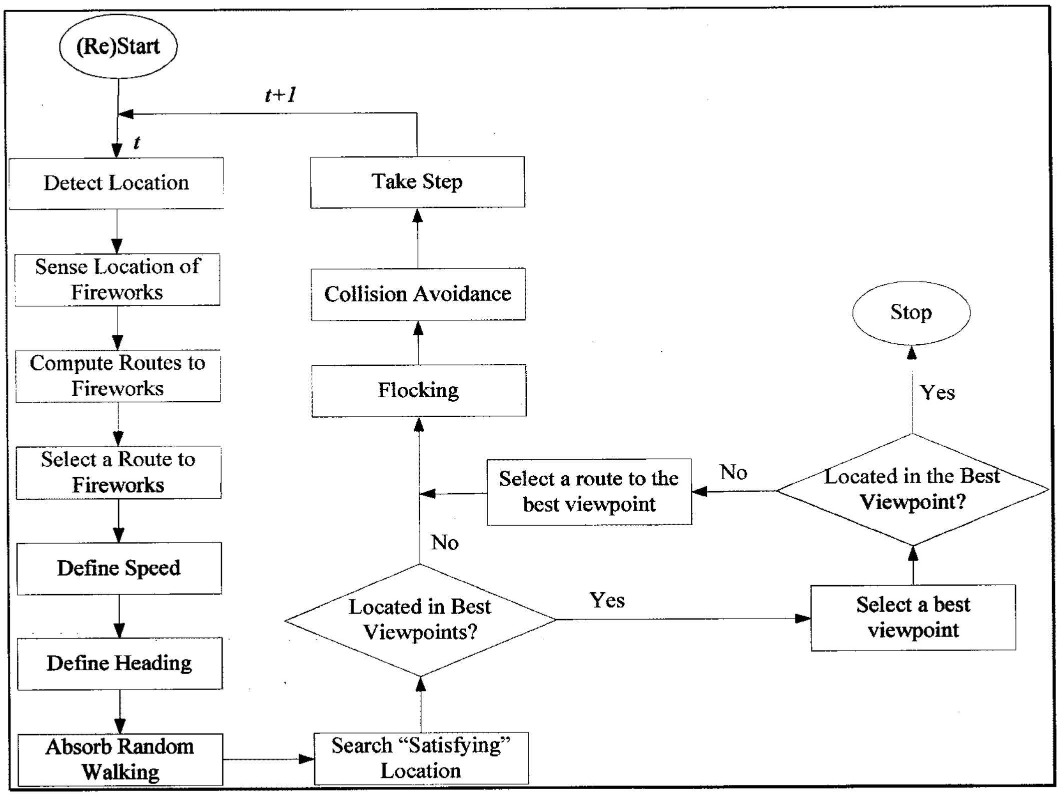


**Figure 5.10: The Pedestrian Behavioral Model for Crowd Arrival**

Source: author.

### 5.4.3 Pedestrian Interactions in Arrival Phase

Interactions between agents in this crowd arrival phase can be illustrated by Figure 5.11. At the beginning of this phase ($t_0$), pedestrians appear at their starting points as certain speed, Roads and Buildings are located as the physical environment in the event, but with their situations of open or close. Attractors-fireworks in this phase are located within spaces as their known positions. Policemen begin their duties at their respective presidial zones. And facilities-mainly the miller barriers-are prepared with pre-defined locations. Policeman wander within his duty area, estimate the population density and send guiding information to crowds. If policeman thinks the density is over the threshold and may result in safety problems, he sets up blocks which will temporary release crowded situations through affecting pedestrian's movement. Each pedestrian senses the locations of fireworks, make choice on a route to attractors and move to a best viewpoint that he can arrive. During his process of movement, pedestrian change his behavior real-time through interactions with roads situations, buildings situations, facilities that event managers set, policemen who manage crowds, and his partners. These interactions will be completed until pedestrian finds a satisfying viewpoint to the fireworks.

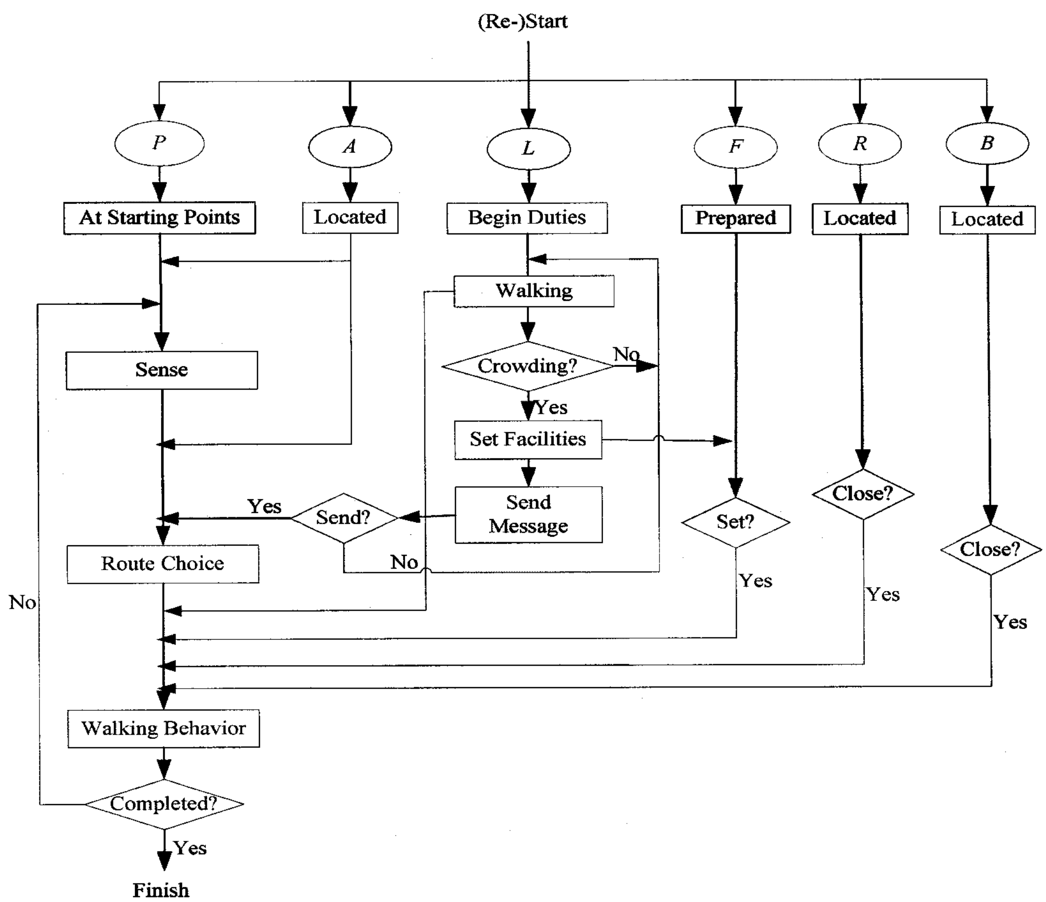


**Figure 5.11: Interactions in Crowd Arrival Phase**

Source: author.

### 5.4.4 Pedestrian Behavioral Rules in Arrival Phase

Combined with the framework of pedestrian behavior and interactions between agents, Figure 5.12 represents the pedestrian behavioral rules that have formed. These rules can be depicted as following. It should be noticed that these codes are not exactly the programming languages, but they describes the general process that is followed when implementing them.

$$C_{ijt} = P_t.Location;$$

$$if\ C_{ijt}(value) \in \bigcup_3;$$

$$P_{t+1}.Location = Random(C_{i,j}, P_{t+1}.Location);$$

$$if\ P_{t+1}.Location = C_{i,j},\ \ then\ C_{i,j,t+1}(Value) = -\infty;\ \ \bigcup_3 = \{\bigcup_3 - C_{ij}\};$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq F;$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq B;$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq L;$$

$$P_{t+1}.Location = P_{t+1}.Flocking();$$

$$P_{t+1}.Location = P_{t+1}.RandomWalking();$$

**Table 5.2: Behavioral Rules for Pedestrian Arrival**

Source: author.

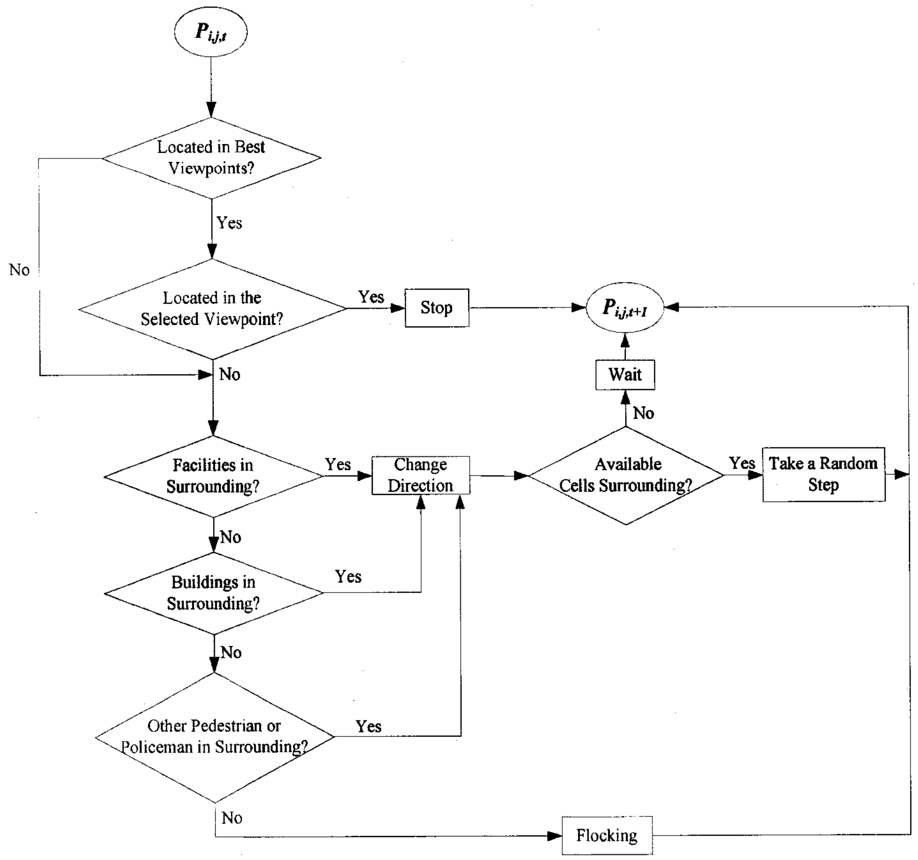


**Figure 5.12: Behavioral Rules for Crowd Arrival Phase**

Source: author.

## 5.5 Model for Crowd Dispersal

### 5.5.1 Completion of Pedestrian Behavior

In this dispersal phase, exits to this area become the attractors that lead crowd behavior. If pedestrian arrives each of the exits, it is viewed as he completes his behavior and disappear. So the final destination set ($\cup_4$) is:

$$\cup_4 = \bigcup_{i,j=1}^{n} \{C_{ij}, where\, C_{ij}(type) = A\}$$

### 5.5.2 Behavioral Model for Crowd Dispersal

Spatio-temporal pedestrian behavior in the phase of crowd dispersal can be characterized as Figure 5.13. First, at the strategic level, pedestrian detects locations of himself and exits, and makes his behavioral goal as leaving this area as soon as possible and moving to exits. Second, at the tactical level, pedestrian senses whether he is now in the visual field of exits, which also means that whether a pedestrian can view the locations of exits. If yes, *P* computes routes to exits and randomly selects one of those routes for starting his movement. While if no, *P* prepares to start his movement by following other participants. Third, at the operational level, *P* takes each step after considerations with collision avoidance and crowd effects. It is considered that *P* completes his behavior if he arrives on exits and disappears from this area.

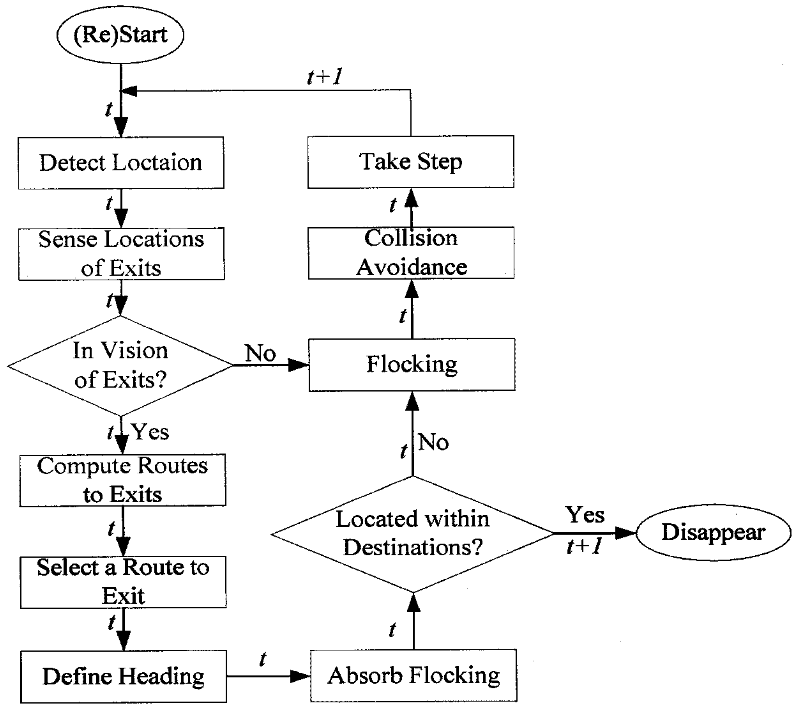


**Figure 5.13: The Pedestrian Behavioral Model for Crowd Dispersion**

Source: author.

### 5.5.3 Pedestrian Interactions in Dispersal Phase

Interactions between agents in this dispersal phase can be represented by using Figure 5. 14. With start of this phase at time $t_0$, pedestrians are located within spaces with their initial speed 0 at $t_0$. Attractors-exits in this phase-are pre-defined and located at geographic positions. Roads and buildings are both located with their initial situations. Policemen are on their duties and prepare for managing crowds in this phase. Facilities are prepared as well since they will be removed just before the starting of crowd dispersal. If it is considered so crowded to endanger safety, *L* set *F* to temporarily stop *P*'s movement and release crowding. At the same time, *L* may send messages to *P*, and try to guide their directions and route choice. *P* sense the existences of *A*, make judgement on whether he can view the exact positions of *A*, make route choices under interactions with both *A* and *L*, and take his movement behavior by synchronously interacting with *P*, *R*, *B* and *F*.

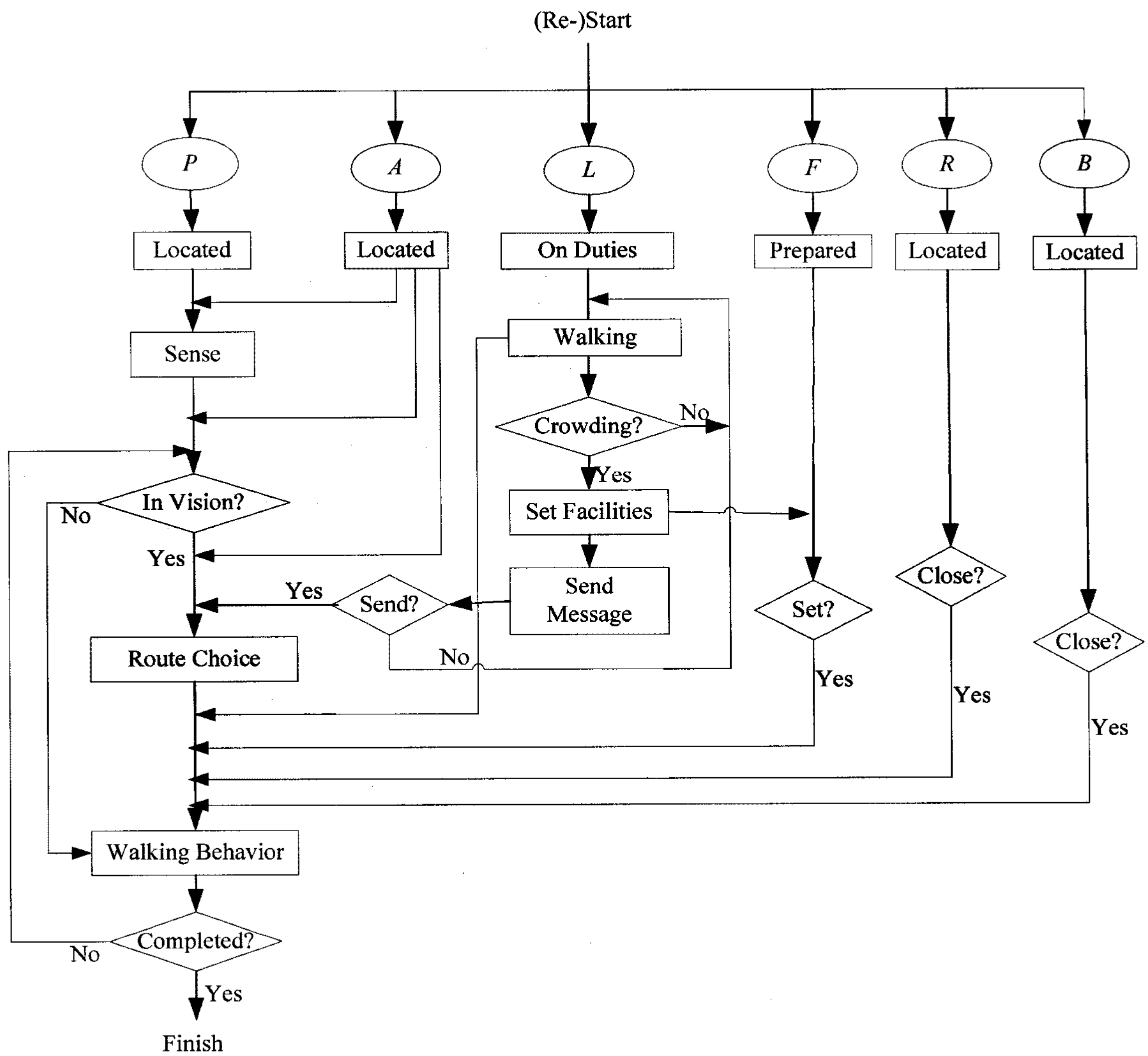


**Figure 5.14: Pedestrian Interactions in Dispersal Phase**

Source: author.

### 5.5.4 Pedestrian Behavioral Rules in Dispersal Phase

Rules that pedestrian follows in this dispersal phase are as Figure 5.15. As in this phase, cells value is divided into two levels, 1 which can be viewed or sensed by pedestrian and 0 which is not in vision of pedestrians, rules can be expressed as Table 5.3.

$$C_{ijt} = P_t.Location\,;$$

$$if\ C_{i,j}(value) = 1\,;$$

$$P_t.Direction() \in \bigcup_4$$

$$if\ C_{i,j}(type) = A\,,$$

$$P_{t+1}.Location = P.Disappear();\,;$$

$$if\ any\ C_{i\pm1,j\pm1,t+1}(type) \neq R\,;\quad P_{t+1}.Location = C_{ij}\,;$$

$$else\ \ if\ any\ C_{i\pm1,j\pm1}(type) \neq F$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq B$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()\,;$$

$$P_{t+1}.Location = P\,.RandomWalking()$$

$$if\ C_{i,j}(value) = 0\,,$$

$$if\ any\ C_{i\pm1,j\pm1,t+1}(type) \neq R\,;\quad P_{t+1}.Location = C_{ij}\,;$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq F$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq B$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()$$

$$P_{t+1}.Location = P.RandomWalking()\,;$$

**Table 5.3: Pedestrian Behavioral Rules in Dispersal Phase**

Source: author.

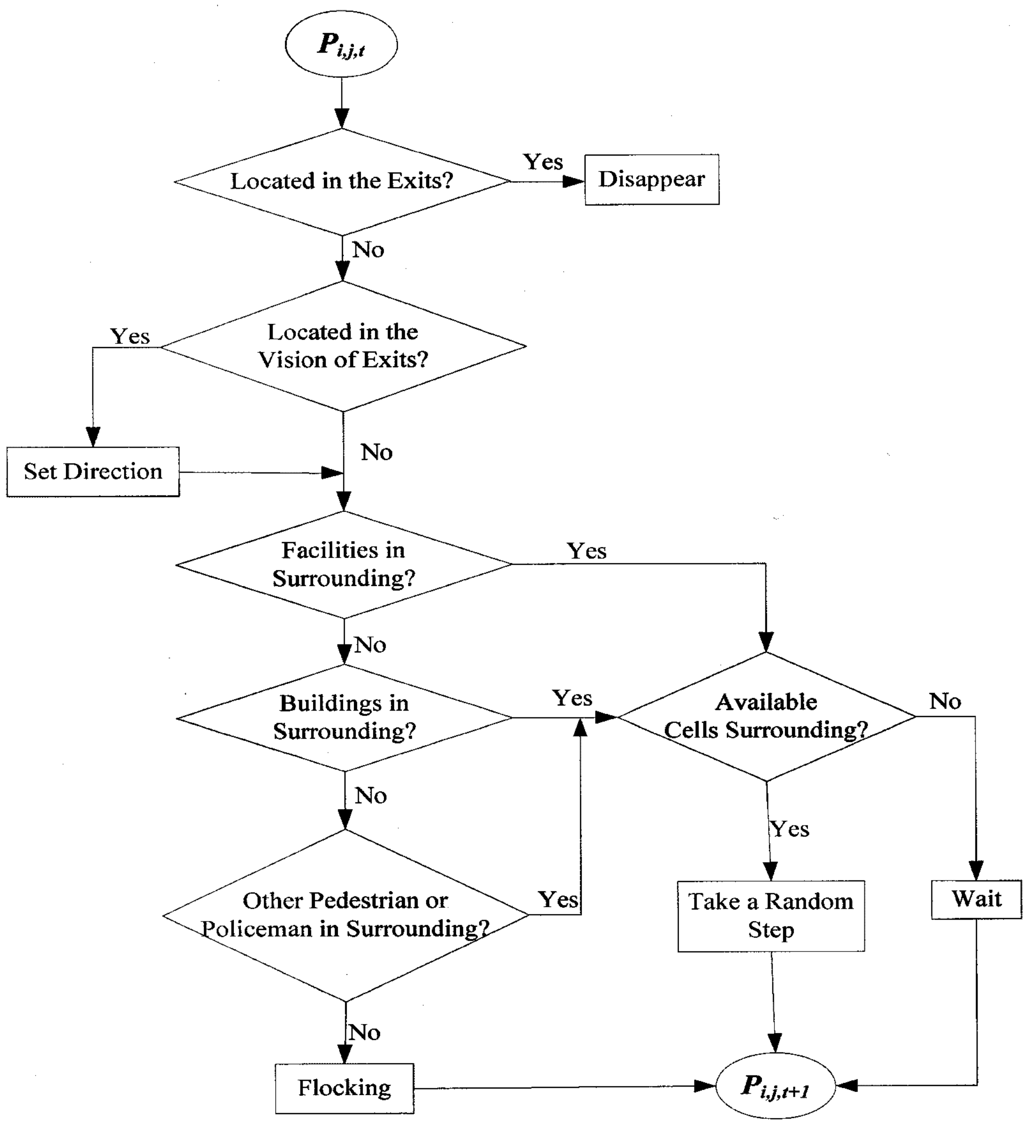


**Figure 5.15: Pedestrian Behavioral Rules in Dispersal Phase**

Source: author.

## 5.6 Model for Crowd Evacuation

### 5.6.1 Effectiveness of Emergencies

This evacuation phase is for preparations if there are any emergencies happened. In this research, we limit the emergencies within a type of small events that will push pedestrians away from them, for example, the small fights, road interruption, or others that may have negative effects on crowds. However, emergencies can be any identities in different cases. *E* is a type of new agents in this phase, has its own growing behavior and will influence all kinds of other agents. And the effectiveness of *E* (expressed with *I*), that is the visibility of pedestrian to *E*, is also calculated using visibility analysis. The value of *I* is added as an attribute in C using *Influence*. That is to say, in this phase, *C* is represented as $C_{i,j}(Type, Value, Influence)$. If at time *t*, a pedestrian is located within the influence region of emergencies, it is said that $C_{ijt}(Influence) = 1$; if not, that means $C_{ijt}(Influence) = 0$.

### 5.6.2 Destination of Pedestrian Behavior

When emergencies appear, pedestrian tries not to walk into the influence area that emergencies produce. Therefore, pedestrian needs select one route or direction to leave the area, with avoidance to select a direction to the emergencies. Here, set of *E* can be described as $\bigcup_{j=1}^{k} E_j$, with k as the total number of emergencies. And we define $\overrightarrow{PE}_j$ as directions from *P* to *E*. So, the routes set ($\cup_5$) can be represented as:

$$\cup_5 = \cup_2 - \bigcup_{j=1}^{k} \overrightarrow{PE}_j = [\bigcup_{i=1}^{m} \overrightarrow{PA}_i \mid \bigcup_{j=1}^{k} \overrightarrow{PE}_j]$$

### 5.6.3 Pedestrian Behavioral Model for Evacuation Phase

Spatio-temporal pedestrian behavior in this evacuation phase is characterized as Figure 5.16. Pedestrian makes his movement following three different levels. At the strategic level, *P* detects locations of himself, attractors and emergencies. And *P* makes his goal in this phase as leaving this area as soon as possible through trying his best for away from emergencies. At the tactical level, pedestrian needs make judgments on four conditions. Firstly, if pedestrian is located within both visions of exits and emergencies. Pedestrian tries to find routes that lead to exits but away from emergencies as well, and then randomly select one. If there is a route selected, *P* prepares for walking. If there is no available route, *P* absorbs to wait at his location until he finds one. Secondly, *P* is located in vision of exits but not in influence of emergencies. In this situation, *P* computes routes to exits, tries to select one route that can avoid moving near emergencies, and prepare walking. Thirdly, *P* is located in influence of emergencies but not in vision of exits. In this case, *P* prepares walking by selecting a direction that can be away from emergencies and follow other pedestrians. Fourthly, if *P* is location neither in vision of exits nor in the influence of emergencies, *P* prepares his walking following other pedestrians. At the operational level, *P* takes his walking behavior according to his route choice and direction choice in the tactical level, and interacts with other agents to take each step. *P* is considered to complete his behavior and disappear from this area in case he finally gets to exits.

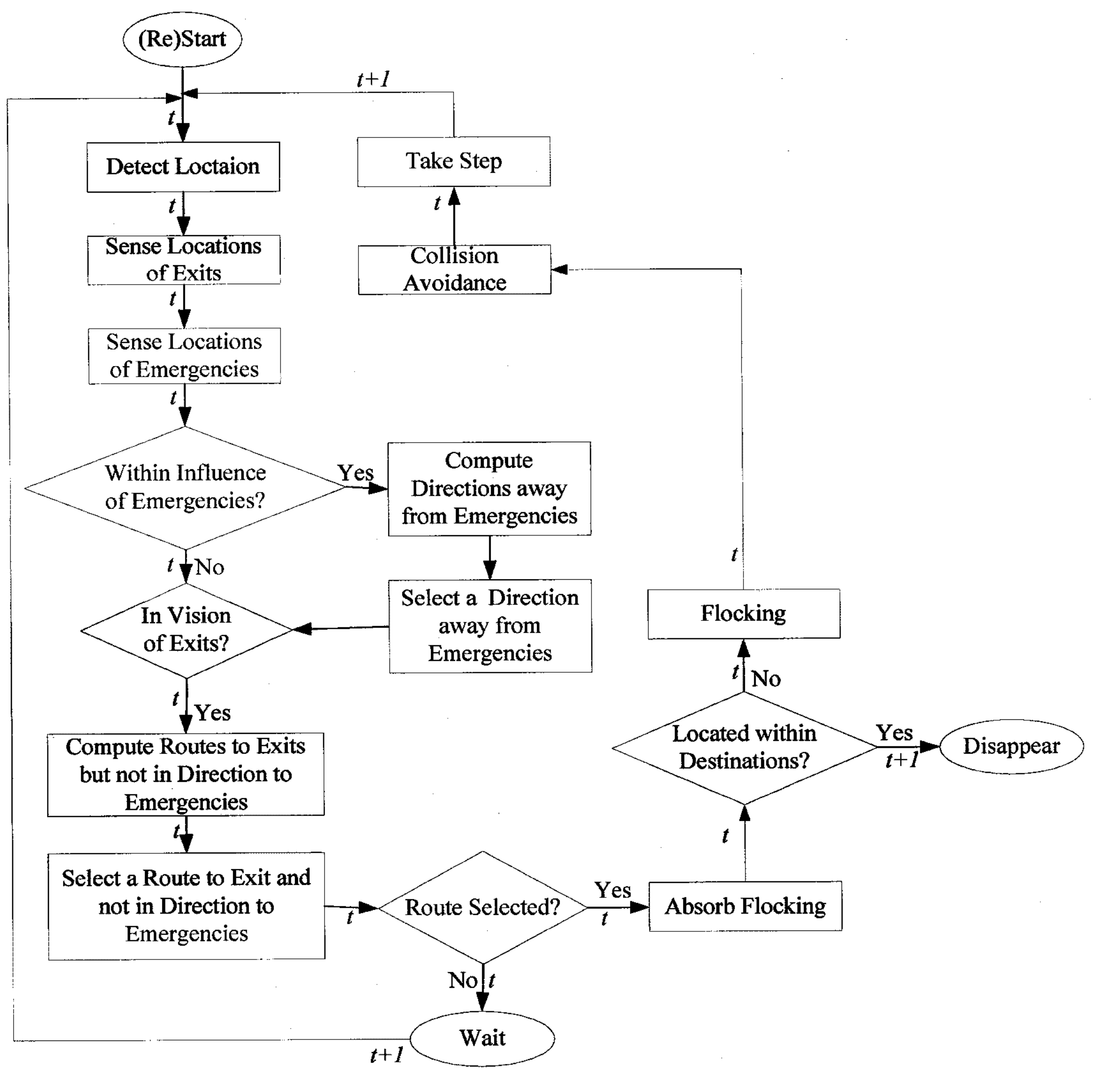


**Figure 5.16: Pedestrian Behavioral Model for Evacuation**

Source: author.

### 5.6.4 Behavioral Interactions

Interactions in this phase are still complex and exist between agents (Figure 5.17). At the beginning time ($t_0$) of this phase, pedestrians are distributed in spaces. Attractors and emergencies are located with their known positions. Roads and buildings are the physical environment with their situations at that time. As event managers, policemen are located within their duty region. And facilities are prepared with their locations predefined. Similarly with other two phases, policemen observe the crowd density and set up facilities to control pedestrian movement if when necessary. At the same time, policemen send information to pedestrians and affect and guide pedestrian route choice or direction choice. After sensing the locations of exits and realization of emergencies, *P* make decisions on the combined effects of *A*, *E* and *L*, and behave under the interactions with *E*, *L*, *F*, *R* and *B*.

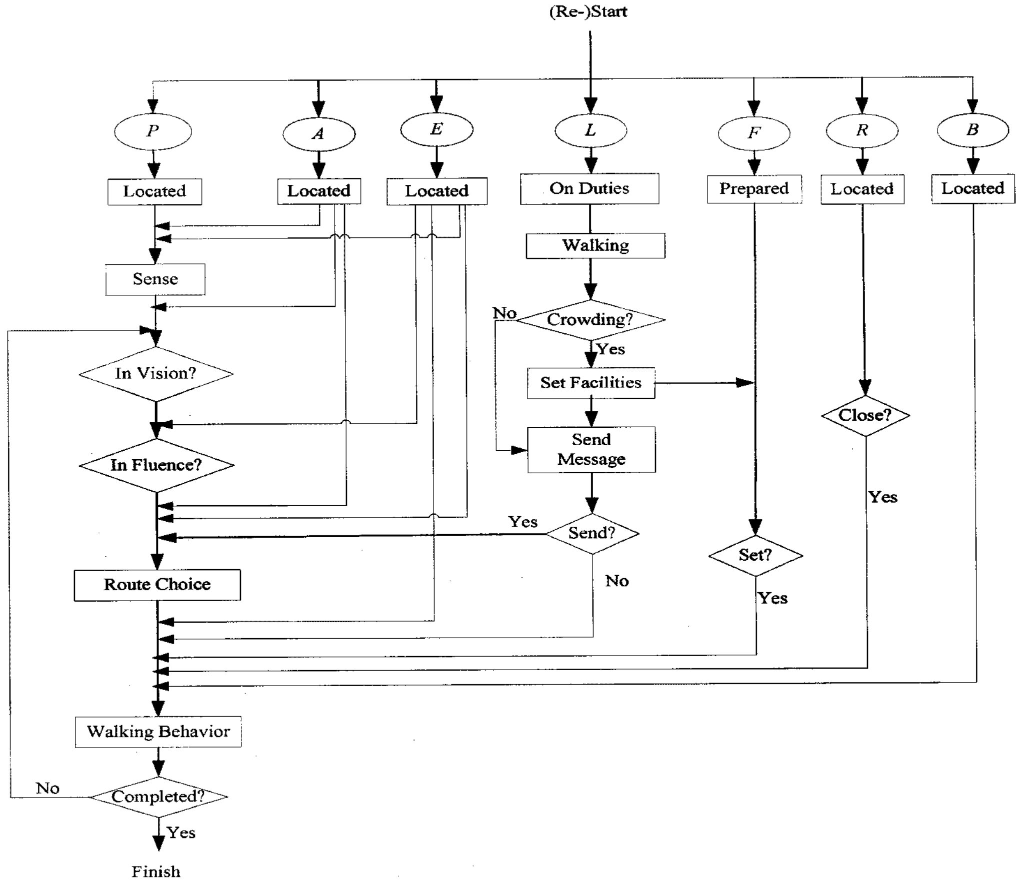


**Figure 5.17: Interactions in Evacuation Phase**

Source: author.

### 5.6.5 Pedestrian Behavioral Rules

Pedestrians may follow certain rules for making their movement behavior as Figure 5.18. And these rules can be represented by using sentences as Table 5.4.

$$C_{ijt} = P_t.Location;$$

$$if\ C_{i,j}(type) = A;$$

$$P_{t+1}.Location = P.Disappear();$$

$$if\ C_{i,j}(value) = 0 \,\&\, C_{i,j}(Influence) = 0,$$

$$if\ any\ C_{i\pm1,j\pm1,t+1}(type) \neq R;\ \ P_{t+1}.Location = C_{ij}$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq F$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq B$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()$$

$$P_{t+1}.Location = P.RandomWalking();$$

$$if\ C_{i,j}(value) = 0 \,\&\, C_{i,j}(Influence) = 1,$$

$$P_t.Direction() = \overline{\bigcup_{j=1}^{k} \overrightarrow{PE_j}}$$

$$if\ any\ C_{i\pm1,j\pm1,t+1}(type) \neq R;\ \ P_{t+1}.Location = C_{ij}$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq F$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq B$$

$$if\ any\ C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()$$

$$P_{t+1}.Location = P.RandomWalking();$$

$$\text{if } C_{i,j}(value) = 1 \; \& \; C_{i,j}(Influence) = 0$$

$$P_t.Direction() = \bigcup_2 ;$$

$$\text{if any } C_{i\pm1,j\pm1,t+1}(type) \neq R ; \quad P_{t+1}.Location = C_{ij}$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq F$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq B$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()$$

$$P_{t+1}.Location = P.RandomWalking() ;$$

$$\text{if } C_{i,j}(value) = 1 \; \& \; C_{i,j}(Influence) = 1$$

$$P_t.Direction() = \bigcup_5$$

$$\text{if any } C_{i\pm1,j\pm1,t+1}(type) \neq R ; \quad P_{t+1}.Location = C_{ij}$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq F$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq B$$

$$\text{if any } C_{i\pm1,j\pm1}(type) \neq L$$

$$P_{t+1}.Location = P.Flocking()$$

$$P_{t+1}.Location = P.RandomWalking() ;$$

**Table 5.4: Behavioral Rules in Evacuation Phase**

Source: author.

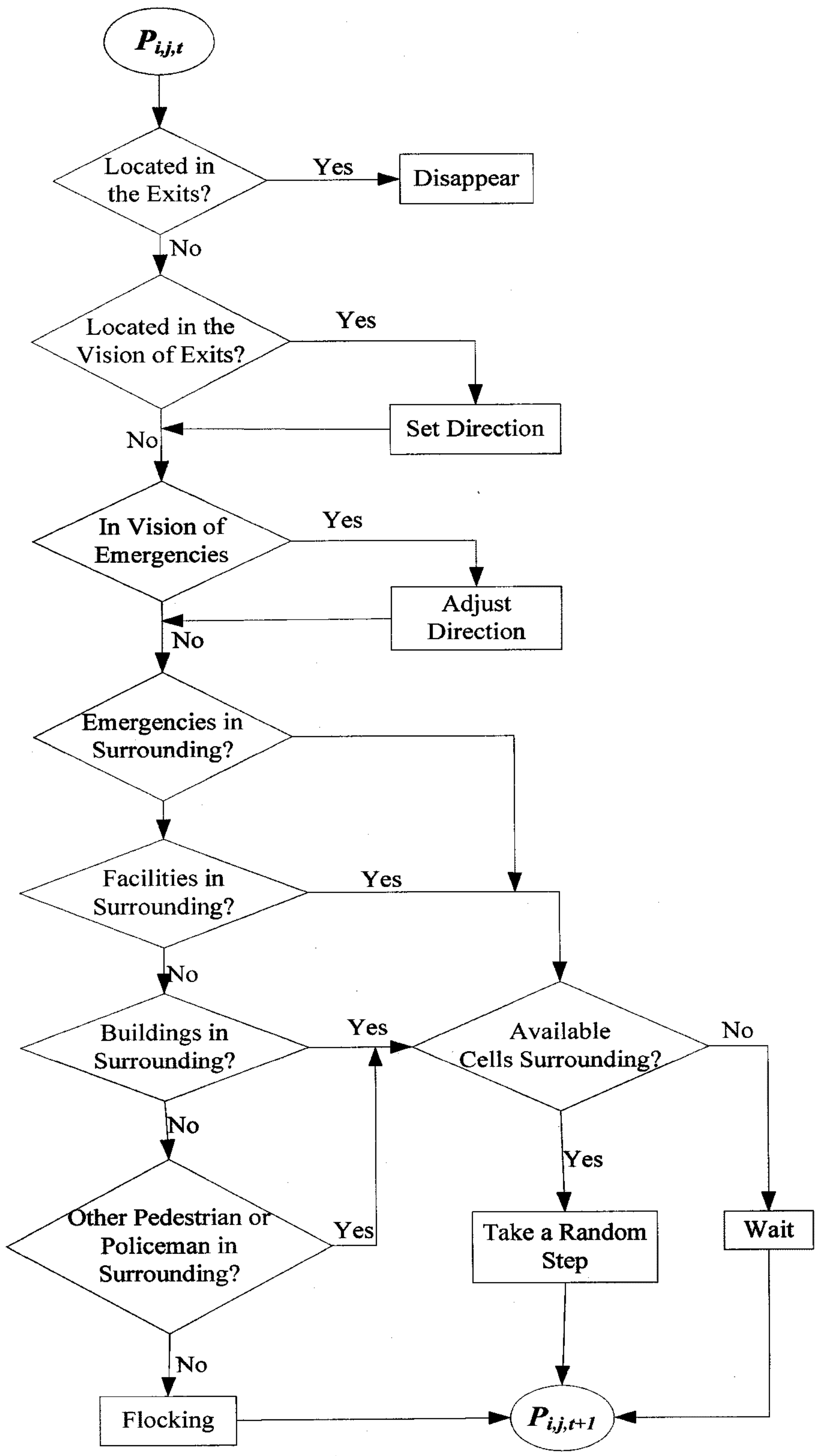


**Figure 5.18: Pedestrian Behavioral Rules in Evacuation Phase**

Source: author.

### 5.7 Summary

In this chapter, we have put forward MAPMODE based on three levels of pedestrian behavior. As basic elements in agent-based models, agents, interactions, temporal variances, and transition rules are discussed and synthesized in detail. Three specific models have been built to represent three phases formed in outdoor events, crowd arrival, crowd dispersal and crowd evacuation. It is necessary to point out that crowd behavior in evacuation phase may have much difference with cases. Because the psychological factors arise in crowds, different schemes may produce different results for evacuating crowds from fires, toxic gases or other terrorist events. However, we are not focusing on such emergencies since more detailed and complicated considerations need discussed, and psychological or behavioral theories take main effects rather than spatial-temporal on crowd behavior.

Models proposed here make a set of clearly simplifications to get them down to what we can handle. But those simplifications are dictated under assumptions on behaviors of most pedestrians in the event. Any type of modeling has difference between "real life" and our attempt to model it (Low, 2000). Perfect safety is Perhaps unattainable, but improved models of crowd dynamics can help to increase our safety in crowded situations (Low, 2000). Models are necessary to be evaluated. If models are evaluated as good, they are improved insights into why the vastly more complex real system behaves the way it does (Krugman, 1995). Therefore, the next chapter will integrate MAPMODE with GIS environment, and simulate crowd behavior with different scenarios. This integration will not only provide a platform for users to manipulate collaboratively but also provide visualizations for MAPMODE.

# CHAPTER 6 INTEGRATION AND SIMULATION OF CROWD BEHAVIOR (ISCB)

## 6.1 Introduction

As an alternative of modeling processes, agent-based modeling involves simulation, which is also a process of visualization. After exploration on and understanding of crowd behavior in the firework display in Chapter 4, we have already got knowledge of relationship of crowd behavior with their behavioral environment. They are mainly represented as data models which express theories predicting the structure of the real-world domains with entities and their attributes organized in interrelated sets (Raper and LivingStone, 1995). And MAPMODE we have developed in the former chapter abstracts the behavioral mode and process of pedestrians mainly from a perspective of individuals. They are process models that generally implicate theories predicting the exchange of the energy and mass over time within systems (Raper and LivingStone, 1995). Coupling spatial data models and agent based process models would be a great task for simulating crowd behavior in this case work. Simulation is defined as driving models of a system with suitable inputs and observing the corresponding outputs (Bratley, 1987). Information we have acknowledged, spatial environmental models and spatial-temporal crowd behavior models are the input within ISCB, and simulation results are carried out to generate different scenarios for examinations on crowd interactions. Evaluations and analysis of MAPMODE are accordingly acquired by explaining the outputs and comparing with practical phenomena. In this chapter, before implementing such ISCB, to satisfy the framework of geo-collaborative crowd management in large-scale outdoor events, the design of the infrastructure for ISCB, data flow in ISCB and interface of ISCB are introduced. After that, ten scenarios are generated as outputs for simulations of crowd behavior under different conditions. Through analyzing the outputs, suggestions on crowd management for the case event are summarized.

## 6.2 Design of ISCB

In ISCB, we use ArcGIS to store spatial data and models, AnyLogic to store the agent-based crowd behavioral models and simulations. The design of ISCB must meet the requirements of a geo-collaborative crowd management for outdoor events.

### 6.2.1 Infrastructure of ISCB

ISCB are carried out in a 2D virtual environment, composed with spatial environment where crowds behave, agent-based models that govern crowd behavior, simulations that visualize crowd behavior in different scenarios, and analysis based on simulation results (Figure 6.1).

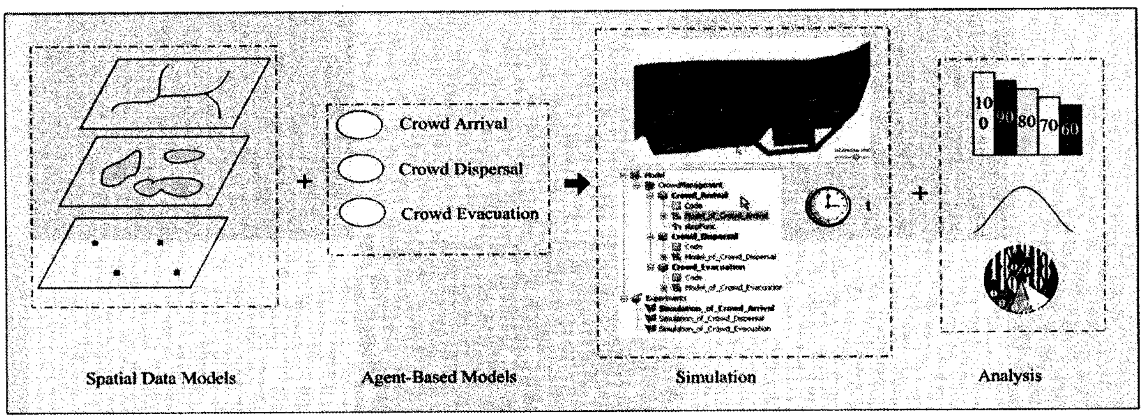


**Figure 6.1: Infrastructure of ISCB**

Source: author.

Stored in GIS, models of spatial behavioral environment are spatial data models that represent and store information on phenomena with spatial locations and/or extents (Lo and Yeung, 2002). The focus of data models in GIS has been on spatial, at the expense of temporal dimensions (Peuquet, 2002). In contrast, agent-based models make use of sophisticated representations of time and behavior, often at the expense of sophisticated representations of space and spatial relationships (Brown et al, 2005). ISCB needs combine both kinds of models together and visualize crowd behavior within spaces and with times. So, simulations in ISCB not only reproduce crowd behavior in real-world, but also generate scenarios used to assess MAPMODE by comparisons with real situations that have been discovered and recorded. Moreover, simulations provide platforms for event managers or users to estimate possible results under different pre-set conditions. Based on these results, analysis is made as outputs of figures, tables, reports or other formats.

### 6.2.2 Data Flow

As the base for ISCB, data is very important for implementations of the whole crowd management. Spatial database which mainly store the information on spatial environment and data models representing processes of crowd behavior are the two main imported data types in ISCB, and they will be calculated and exported as multiple formats for analysis. Figure 6.2 illustrates the data flow within ISCB. Spatial data and models stored in Geodatabase are the crowds' behavioral space and the input of ISCB. They are mainly stored as shapefiles in ArcGIS including the spatial locations and relationships of roads, buildings, event scope, spatial controls and visibility analysis. The spatial information in the formats of point, lines, polygons need to be transformed and transmitted to ISCB to provide as agents environment. As another type of input information in ISCB, crowd libraries are generated to describe crowd behavior in the event based on MAPMODE. In addition, libraries also include such information on populations as generations of the number of crowds, crowd behavioral speed, directions, and routes. Within ISCB, through simulations, input data is computed and calculated real-time to get statistics of crowd information on behavioral states or densities. Above data are implemented and achieved in the MAB platform AnyLogic. Result data is visualized and analyzed, and become the output of ISCB. Outputs data can be animations, figures, statistics, databases, excel tables, documents or reports.

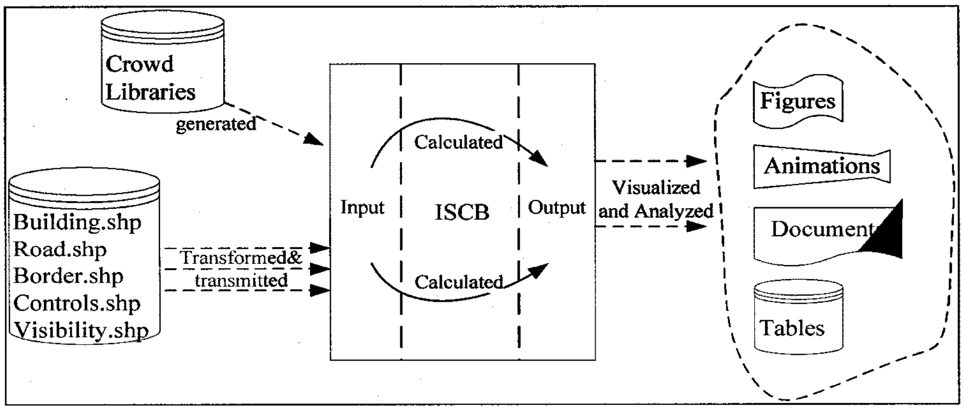


**Figure 6.2: Data Flow in ISCB**

Source: author.

### 6.2.3 Interface Design

Mainly for scientific explorations of crowd behavior in outdoor events, interface of ISCB provides an environment for visualizing MAPMODE, user controls, and illustrations of result analysis (Figure 6.3). Therefore, three modules are created, and they are the module of *User Control*, the module of *Model Visualization*, and the module of *Result Visualization*.

Module of *User Control* provides conditions for users to set different simulation parameters. It's mainly composed with three parts of controls: controls for population generation for initialization of crowd behavior, controls for spatial controls during the firework display like cordons setting, policemen setting, settings of buildings opening or closing, and controls for scenario simulations like roads closing/opening, emergencies settings, and crowd density changes. Module of *Model Visualization* mainly display crowd movement processes under different control settings for exploration of interactions between crowds in the events and dynamics emerged through interactions. Some of crowd collective phenomenon can also be displayed in this module, such as crowd density changes and speed changes. The third module of *Result Visualization* mainly displays real-time analysis results according to the computations of crowd behavioral models. It mainly displays variations of crowd behavioral attributions with the time lapse and statistics of population changes within event areas. It is noticed that this interface design only refers to the carryout of crowd behavioral simulations, while the implementations are achieved within the architecture of agent-based software AnyLogic which provides other part of interfaces to compile and run models.

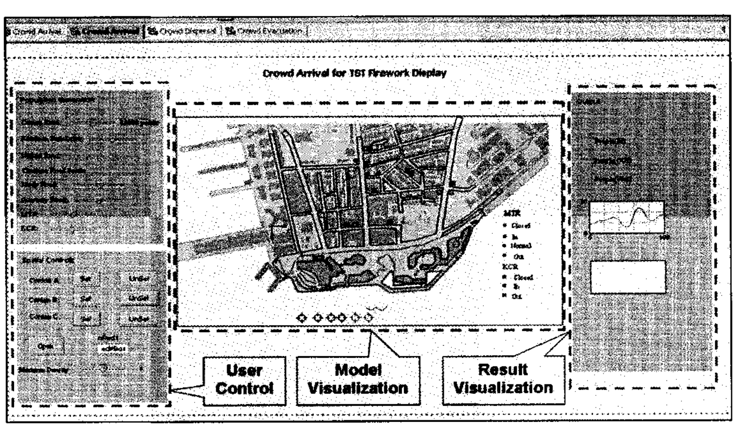


**Figure 6.3: Interface Design of ISCB**

Source: author.

### 6.3 Implementations

Implementations are based on the language Java and libraries integrated in AnyLogic.

#### 6.3.1 Project Structure

In ISCB, project *Crowd_Management.alp* is created for integrating all of the three pedestrian behavioral models and simulations based on those models. Structure of the project is illustrated as Figure 6.4. Figure 6.4a describes the project composed with models generated as *Crowd_Arrival.jar*, *Crowd_Dispersal.jar*, and *Crowd_Evacuation.jar*. Each simulation will also be generated based on each model that is respectively represented as *Simulation_of_Crowd_Arrival*, *Simulation_of_Crowd_Dispersal*, and *Simulation_of_Crowd_Evacuation*. Scenarios will be produced within any models through setting different controls by users. Figure 6.4b is the snap of ISCB.

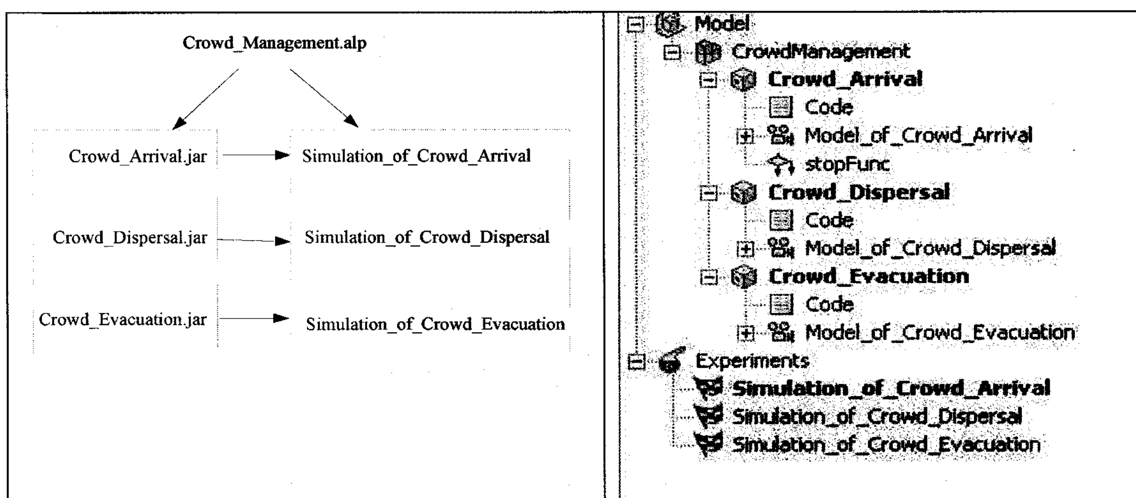


Figure 6.4a: Project Structure | Figure 6.4b: Snap of ISCB

**Figure 6.4: Project Structure of ISCB**

Source: author.

#### 6.3.2 Spaces

Crowd behavior is limited within their spaces. In ISCB, spaces are the behavioral environment for all the agents. Pedestrianization area is the space that crowds make movement in this ISCB, which includes the roads, buildings, and spatial controls. Figure 6.5 is the snap of agents behavioral spaces for the phase of crowd arrival.

MTR and KCR exits and road entrances to this area are those points where pedestrian agents are generated and starting moving to the spaces. In the implementation, *walls* are created as boundaries to limit crowd behavior in spaces.

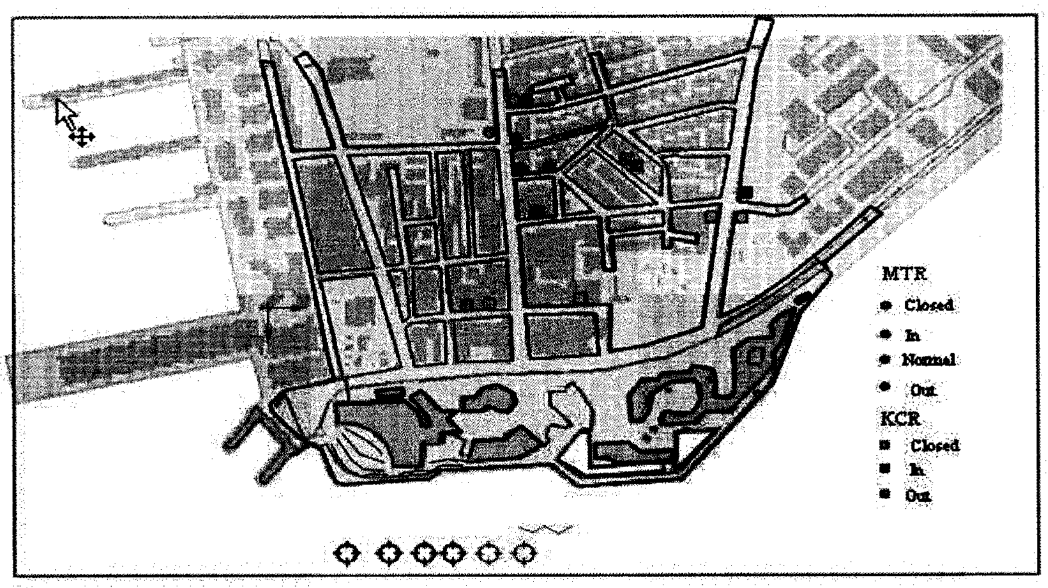


**Figure 6.5: Snap of Crowd Behavioral Spaces**

Source: author.

### 6.3.3 Population Generation

During the phase of crowd arrival, population will be generated from starting points as crowds who move to the event area for viewing the firework display. There are 6 entrances from roads and 2 sites where crowd generate and move into activity area. They are entrances located at Canton Road, Kowloon Park Drive, Nathan Road, Chatham Road South, Mody Road, Salisbury Road, and two sites MTR and KCR station which have totally 9 entrances that will generate crowds. Considering that it is feasible to calculate the number of people that MTR and KCR transport at the TST station and to measure the number at each road entrances, and it is possible that this information of population may vary with period of time and with different events, controls are set in ISCB for providing a modifiable population setting for users to compare different results that may produce. Eight parameters *CantonRdPed, KPDRdPed, NathanRdPed, ChathamRdPed, ModyRdPed, SalisRdPed, MTRPed,* and *KCRPed* are set for representations of the population that will be generated at each entrance.

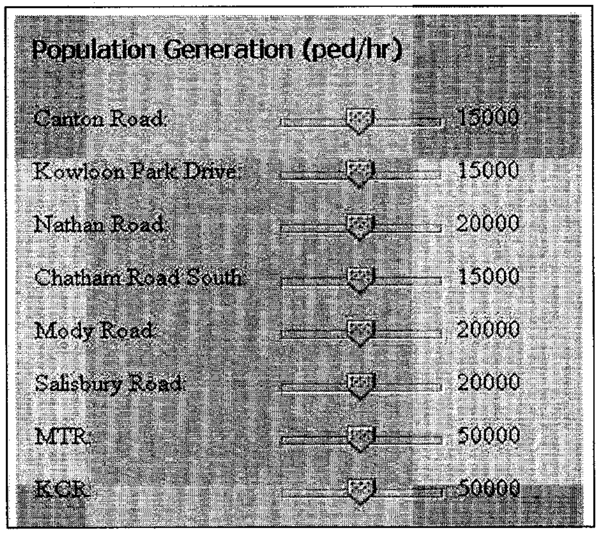


**Figure 6.6: Controls of Population Generation in ISCB**

Source: author.

For each pedestrian agent generated from entrances, it has attributions of speed, color, diameter, aggressiveness, initial direction, and etc. These attributions are alterable according to different conditions.

During phases of crowd dispersal and evacuation, the initial state of pedestrians is located within zones, so it is needed to generate population at the startup of simulation. Agent class *Ped_Out* is created specifically for these two phases, which is a subclass of *Ped* and inherit all the attributes and functions of class *Ped*. Generating pedestrians within certain area can be implemented by using following code and Figure 6.7 illustrated the scene of population generated within case study and with number of 2000.

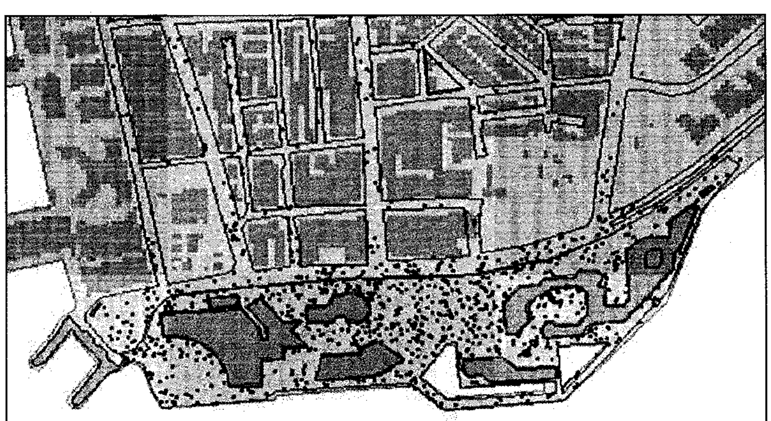

**Figure 6.7: Sketch Map of Population Generation during Phases of Dispersion and Evacuation**

Source: author.

### 6.3.4 Controls

Controls are inevitable components in the outdoor event used for releasing crowding and keeping safety. In the firework display, spatial controls include facilities that policemen will set, messages that policemen guide directions of crowd movement, and some important buildings that will be set open or close to allow or forbid crowd's passing through. ISCB provide three examples of controls for users to explore pedestrian behavior and their interactions with environment. Figure 6.8 displays the interface of controls set in ISCB. They are controls of "*Cordons*", the control of "*Police*", and the control of "*Buildings*". And three levels of control "*Cordons*" are prepared to temporarily control crowd movement to release crowded situation which are set as *Cordon A*, *Cordon B*, and *Cordon C*. If each of cordons is set, they will act as blocks on roads and crowds will change their movement directions.

For example, if "Cordon A" is set by users, by implementing "*Cordon_A.setOpen( true )*" cordon A will act as blocks that prevent pedestrians passing through, and pedestrians will try to find another direction to move to their attractions; while if "Cordon A" is removed by users by clicking button "Remove", pedestrians will continue to move as they want to their destinations by implementing "*Cordon_A.setOpen( false )*". The second control in the event is the event manager, mainly policeman, by sending messages to pedestrians to change their movement directions for releasing crowding in certain roads. In ISCB, if "*Police*" is set as sending "*Message*" in the controls, pedestrians who interact with policemen will move the direction according to the message. The third control in the event is some main buildings that will be set close to forbid pedestrians passing. In ISCB, we take the example of "*Cultural Center*" as simulating the different results if the building is set open or close.

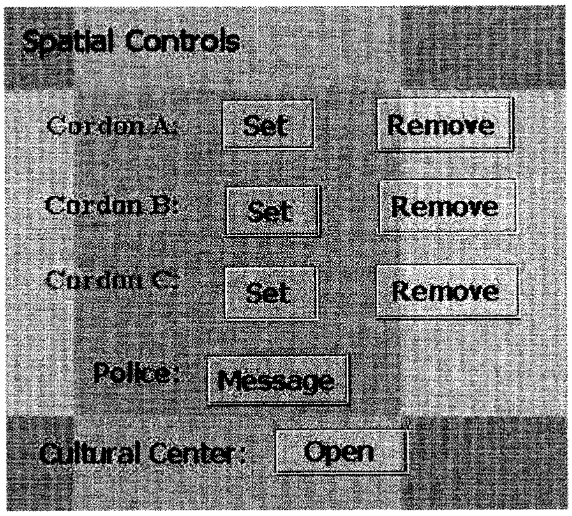


**Figure 6.8: spatial Controls in ISCB**

Source: author.

### 6.3.5 Output

For evaluating crowd behavioral models and analyzing crowd behavior, certain computation results need exported, such as animations, figures, or tables. Animations provide visual results of real-time processes of crowd movement based on MAPMODE and with different constraints of spatial controls. Furthermore, statistics of parameters which can be used to analyze crowd behavior and indicate decisions are calculated and displayed with time as well. In ISCB, indicators that have been computed are crowd population, crowd density and average time. At the same time, 5 main roads and 2 zones are selected as samples where contains complex crowd behavior. They are *Nathan Road*, *Kowloon Park Drive*, *Canton Road*, *Chatham Road*, *Salisbury Road*, *Seashore (Pedestrianization Area*), and *WaitArea* (Where pedestrians stop to view the display). Variables are defined to record the dynamics values (Table 6.1).

| Variable | Sample Site | Meaning | Implementation |
|---|---|---|---|
| *N_Pop* | Nathan Road | Number of pedestrians on Nathan Road | *Nathan.size()* |
| *N_Den* | | Density of crowds on Nathan Road | *Nathan.density()* |
| *N_T* | | Average length of stay of pedestrians on Nathan Road | *Nathan.getAverageTime()* |
| *KPD_Pop* | Kowloon Park Drive | Number of pedestrians on Kowloon Park Drive | *KPD.size()* |
| *KPD_Den* | | Density of crowds on Kowloon Park Drive | *KPD.density()* |
| *KPD_T* | | Average length of stay of pedestrians on Kowloon Park Drive | *KPD.getAverageTime()* |
| *C_Pop* | Canton Road | Number of pedestrians on Canton Road | *Canton.size()* |
| *C_Den* | | Density of crowds on Canton Road | *Canton.densitiy()* |
| *C_T* | | Average length of stay of pedestrians on Canton Road | *Canton.getAverageTime()* |
| *Ch_Pop* | Chatham Road | Number of pedestrians on Chatham Road | *Chatham.size()* |
| *Ch_Den* | | Density of crowds on Chatham Road | *Chatham.density()* |
| *Ch_T* | | Average length of stay of pedestrians on Chatham Road | *Chatham.getAverageTime()* |
| *Salis_Pop* | Salisbury Road | Number of pedestrians on Salisbury Road | *Salisbury.size()* |
| *Salis_Den* | | Density of crowds on Salisbury Road | *Salisbury.density()* |
| *Salis_T* | | Average length of stay of pedestrians on Salisbury Road | *Salisbury.getAverageTime()* |
| *Pedarea_Pop* | Pedestrianization Area (Seashore) | Number of pedestrians within pedestrianization area | *PedArea.size()* |
| *Pedarea_Den* | | Density of crowds on within pedestrianization area | *PedArea.density()* |
| *Pedarea_T* | | Average length of stay of pedestrians within pedestrianization area | *PedArea.getAverageTime()* |
| *waitAreaPop* | | Number of pedestrian waiting | *Waitarea.size()* |
| *waitAreaDensity* | | Density of pedestrian waiting | *Waitarea.density()* |

**Table 6.1: Variables for Output**

Source: author.

### 6.4 Scenario Generation and Model Evaluations

In contrast to induction and deduction, simulation is the third way of doing scientific study, especially in researches involving human activity. That's also why agent-based modeling and simulation is adopted in crowd behavioral modeling. Based on MAPMODE we developed in former chapter and implementations on such models, scenarios are generated step by step, first let pedestrians behave without any controls to analyze and assess possible phenomenon produced by crowd interactions, second to add spatial controls on crowd behavior, mainly the cordons and the messages that policemen send, and third to simulate and compare different outcomes when setting buildings different situation and setting different road situations. While it is important that the primary objective of scenarios simulations in this research is not to accurately predict or prove crowd dynamics, but to perform and discover possible sequences resulting from crowd behavior. In the social science, in particular, even highly complicated simulation models can rarely prove completely accurate (Axelrod, 1997). At the same time, for each time when we calculate our models, especially the agent-based models, results or processes we get through computations may probably different. However, the trends synthesized on these results are valuable for scientific researches on what we are interested in.

### 6.4.1 Simulation and Evaluation: Crowd Arrival

Crowd movement in the arrival phase is simulated in this section with different conditions. Both the crowd arrival model and functions of what we design for ISCB are evaluated. Results of different scenarios have been compared and analyzed.

#### Scenario 1: Crowd Arrival without Spatial Controls

In this scenario, pedestrians are generated from their starting points, based on different generating rate of number of pedestrians at each point. Each pedestrian randomly select his way to destinations to see the display. Spatial controls are not added in this scenario. Within pedestrianization area, crowds interact with each other with time elapse. Figure 6.9 displays the statistics of changes of crowd density, population and length of stay within sampling sites in this scenario.

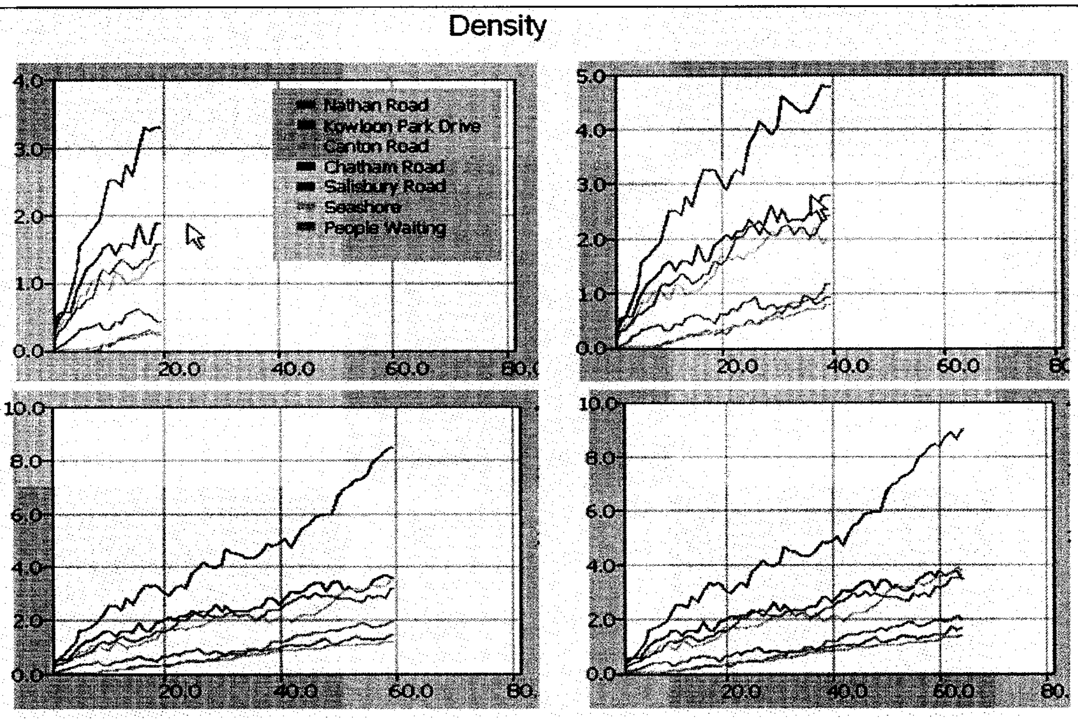


Figure 6.9a: Statistics of Density

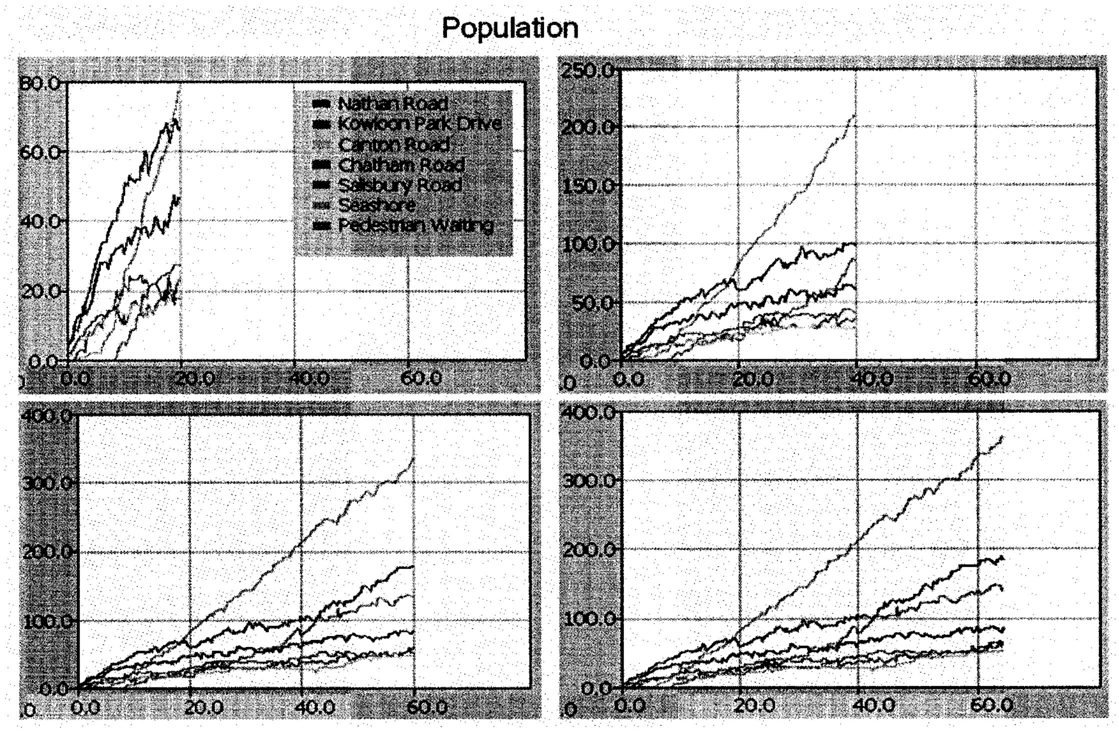


Figure 6.9b: Statistics of Population

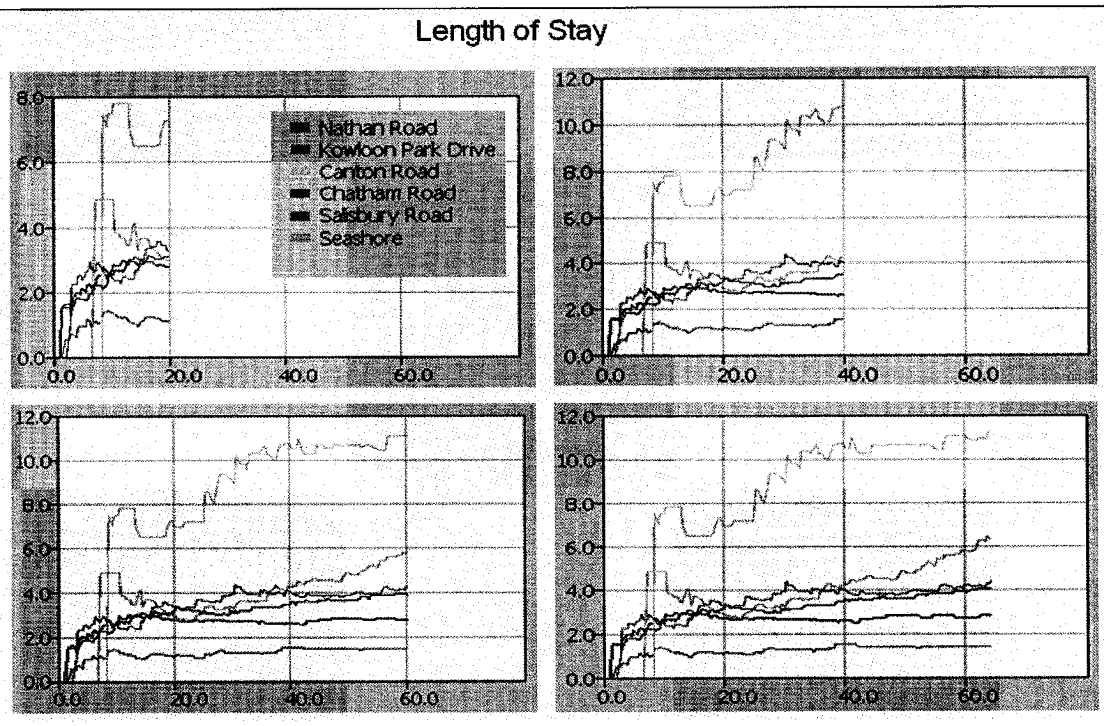


Figure 6.9c: Statistic of Length of Stay

**Figure 6.9: Statistics of Density, Population and Time of Delay**

Source: author.

Statistics of density changes on main roads and 2 zones (Figure 6.9a) reflect the increasing trends of crowd density with time. Within this scenario, *Nathan Road* becomes the most crowded road, density on Canton Road, Kowloon Park Drive and Chatham Road is also very high and increase fast with time, and as the connecting road between streets and seashore, Salisbury road appear not so crowded as other roads and keep almost same speed of density rise with that within seashore. At this period, pedestrians come through starting points and move to gather on seashore to view the display, thereby population on sampling sites are all increasing (Figure 6.9b), especially that within seashore. While at the same time, population of pedestrians who stop their movement and wait to view the display does not increase as much as that within seashore, which means that quite number of pedestrians are wandering within pedestrianization area, and may hesitating to select their most satisfied points. Statistics of Length of Stay records the average time that each pedestrian stay inside the specified area (Figure 6.9c). Pedestrians stay longest period of time on Canton Road, since it is a road directly reaching to attractors and there are not much branches of roads connected with. And Pedestrians stay shortest period of time on Salisbury Road, since it is a connecting road through which pedestrians try move to places where have best viewshed. Periods of time pedestrians stay on Nathan Road, Kowloon Park Drive and Chatham Road are similar, since they have similar options to select routes to arrive their destinations. Statistics of parameters on crowds show the rough process of crowd arrival without spatial controls, and testify the crowd behavioral model during the arrival phase. As a whole, population and density of crowds increase rapidly from the beginning of crowd generation, but keeping within a certain extent when reaching a threshold. Streets roads are places where policemen need more carefulness at the beginning of crowd arrival phase, while with more people arriving the zone of seashore, event managers should take care of people moving back and forth, and try guide them to stop moving and wait for the display.

As another type of output, animations of crowd arrival in this scenario further facilitate analyzing crowd behavior and evaluate crowd behavioral model. Figure 6.10 displays the snapshots of scenes at different time. Moreover, agent-based simulation reveals some details that are easy to be ignored when managing crowds. First, there are 3 sites which may involve much pedestrian activities and possess high risk of crowding, as labeled as site A, B and C. Site A is the intersection of Canton Road and Hong Kong Cultural Center, through which both directions of westward and eastward can lead pedestrians to reach to their destination. That will probably produce high interactions between pedestrians to choose routes. Site B and C are two areas that go to best viewshed zones. Most Pedestrians from street roads pass through the two sites to get to their destinations, after crossing Salisbury Road. At the same time, site B and C themselves hold highest viewshed value, which makes them two attractive sites for crowds assembling. Second, there is high possibility that crowds may jam on Nathan Road (Figure 6.10c). As a major thoroughfare involved within event zone, Nathan Road not only receive pedestrians from outside the zone, but the pedestrians coming by taking trains or subways. There are total 5 sources directly on this road, with one taking over the crowds from outside the event zone (from Jordon MTR Station and other pedestrians) and other four releasing crowds from MTR of TST station which takes half of population who arrive the zone by taking public transportation. Nathan Road also receives pedestrians coming across Zone 2 from Chatham Road. That's also why Nathan Road has been calculated to own the highest density if there are not any controls taken. Agent-based simulation reflects this phenomenon correctly. Third, site D (Figure 6.10c, red circle) also involves high interactions between pedestrians. It is an intersection between Chatham Road and Mody Road, and there are two KCR exits of TST Station located on this site. Also, this site D receives pedestrians from Chatham Road and Mody Road, crowds may either move along Chatham Road to Seashore or along Mody Road to Zone 2. But, the section of Mody road within Zone 2 becomes narrow suddenly which may result the jams of crowds on site D. Policemen should pay more attention on this site and guide crowds behavior if necessary. However, event managers should watch carefully on each road with increasingly pedestrians appearing within zones, while above referred need more careful attentions and guidance.

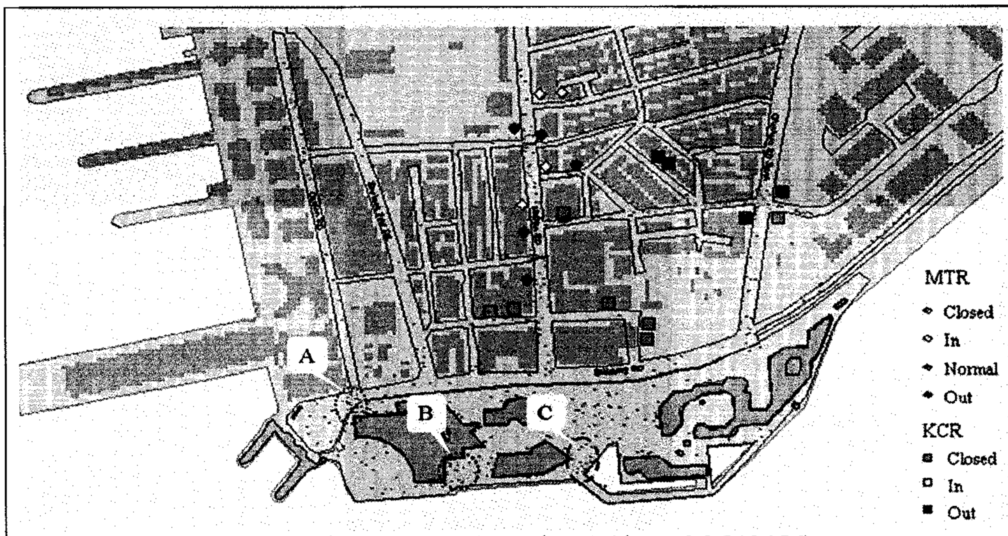

Figure 6.10a: Snapshot 1 (time=36.548456)

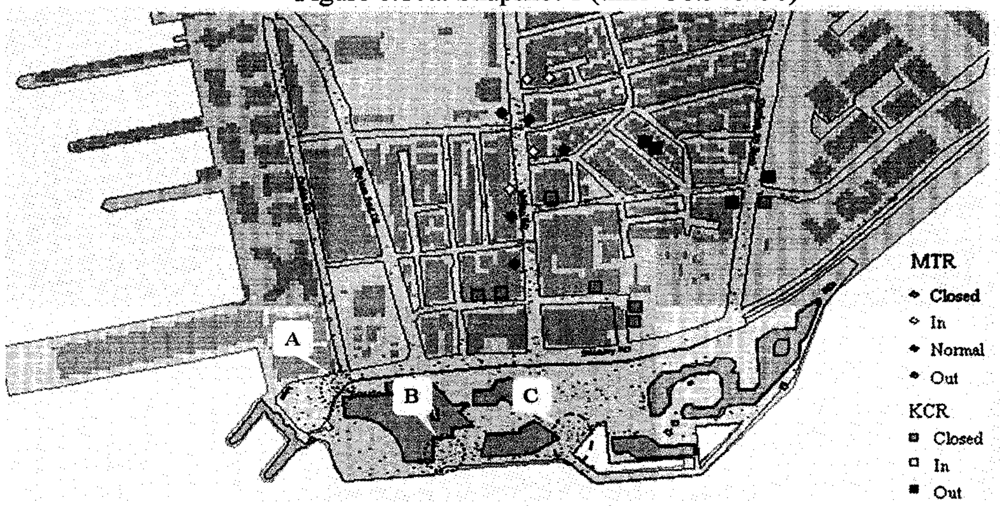

Figure 6.10b: Snapshot 2 (time= 47.366921)

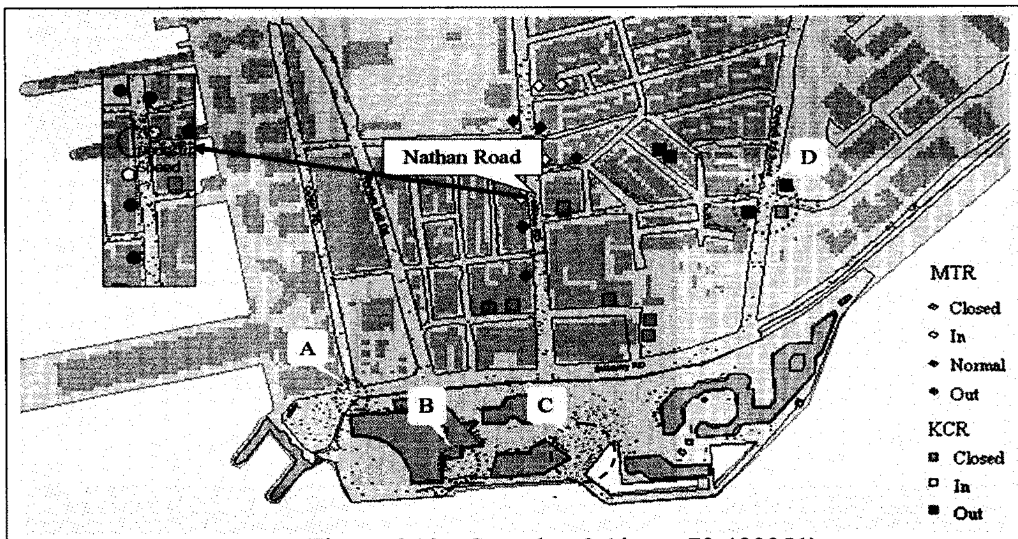

Figure 6.10c: Snapshot 3 (time= 73.489251)

**Figure 6.10 Scenario of Crowd Arrival without Spatial Controls**

Source: author.

### Scenario 2: Crowd Arrival with Policemen Control

Scenario of crowd arrival without any spatial controls shows the extremely crowding appeared on Nathan Road and Zone 2, which may be unsafe for crowd movement. Controls should be added to intervene pedestrian's route choice. As event managers, policemen should guide them move to roads those are not so crowded to release the crowding. Based on existing plan, pedestrians are guided to move within different zones, which means that they are guided to move westward within Zone 1 and eastward within Zone 2. So this scenario 2 simulates crowd movement affected by policemen control, that is to say if crowd density is found too high, policemen will send messages that guide their behavior in different zones, thereby keeping the crowd density within a safe extent. Figure 6.11 records the changing crowd density and population within sampling sits in this scenario.

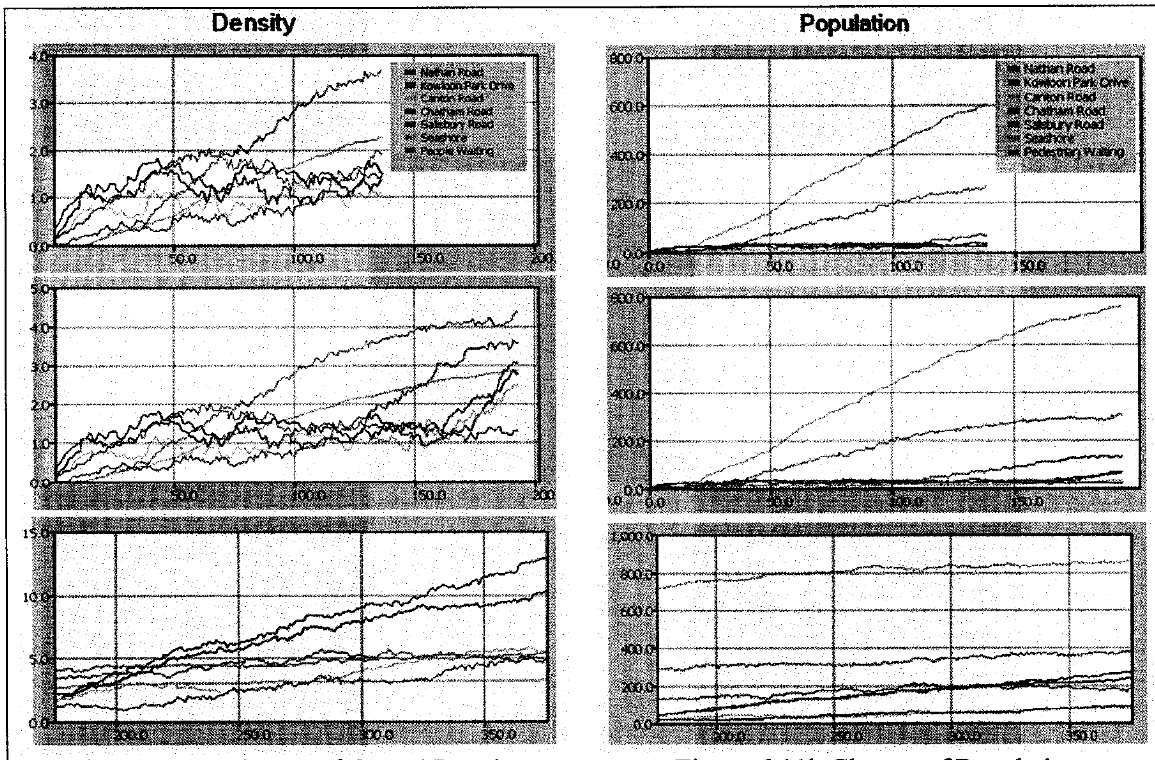


Figure 6.11a Change of Crowd Density

Figure 6.11b Change of Population

**Figure 6.11: Statistics of Crowd Density and Population in Scenario 2**

Source: author.

With controls from policemen on crowd density within zones, the crowding pressure on Nathan Road has been obviously released and gone shared with other roads. The number of pedestrians on each road also maintains within extent. With more pedestrians getting together within zones, density and the number of pedestrians within Seashore are getting increasing. From the statistics of density and population within sampling sites (Figure 6.11), there are possibly 3 phases formed with this scenario. The first is from t=0 to about t=140, crowds are guided moving safely within zones and reaching Seashore to wait for the display. Density and population within Seashore increase quickly, but still only part of pedestrians within Seashore stop to wait for the display, other part of people wander and try to find best places. This phase basically is kept safe for crowd movement, except for more attention needed on Seashore. The second phase is from t=140 to about t=200, with enough number of pedestrians within Seashore, crowds begin to form on roads, thereby density on each road starting increasing largely. And as the closest road to Seashore, density on Salisbury Road is getting quickly enlarged. More controls should be added except for policemen guidance, or there will be the third phase formed (t>250), within which density on each road may get enough high to arose high risk of crowd safety.

Animation of this scenario 2 also discloses an area that needs special attention (blue circle Figure 6.12). Crowds are easily formed from the early forepart of this scenario and keep until the end of phase. This area is located within Zone 2, people from Chatham Road, Mody Road and KCR or MTR station are probably guided to move through Mody Road to arrive their destination. But there are two branches which are easily be considered connected with Seashore, thereby attracting pedestrians move towards them. In fact, they are connected with a Garden and cannot get through to Seashore. Event managers should watch this area carefully and remind pedestrians of that.

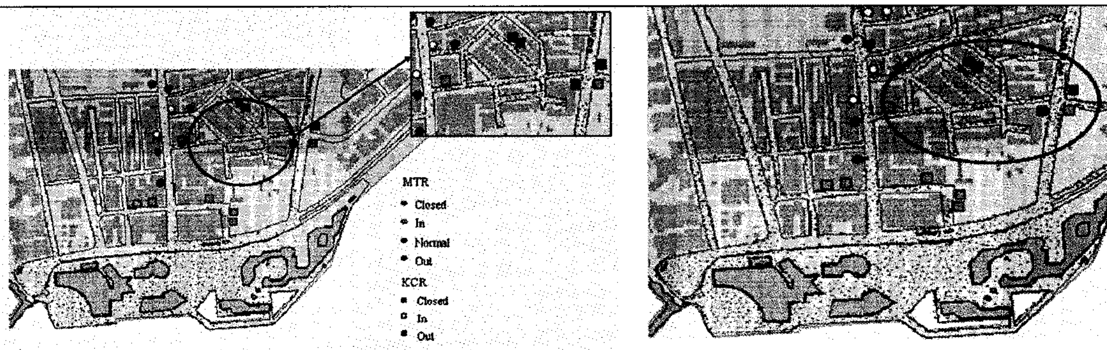


Figure 6.12a: Snapshot 2.1 Figure 6.12b: Snapshot 2.2

**Figure 6.12: Scenario of Crowd Arrival with Policemen Control**

Source: author.

**Scenario 3: Crowd Arrival with Controls of Policemen and Cordons**

The function of cordons is to temporarily stop pedestrian's movement and wait them until density in certain area is down. Based on existing information on cordons setting, this scenario simulates the scene of setting cordon A to prevent more pedestrians moving into the area when density in it has got high enough. Figure 6.13 shows the snapshot of putting Cordon A at specified location and computation result of density changes on sampling sites before and after the setting. It is found that the function of cordon has successfully blocked the movement of pedestrians and low down the speed of density increase within Seashore. But at the same time, setting of Cordon A increase the density on roads, especially that on Nathan Road and

Salisbury Road. That's because pedestrians still move forward to Seashore but be stopped and wait on Salisbury Road. While, pedestrians on Nathan Road is more encouraged to move westward within Zone 1 to reduce the density on it.

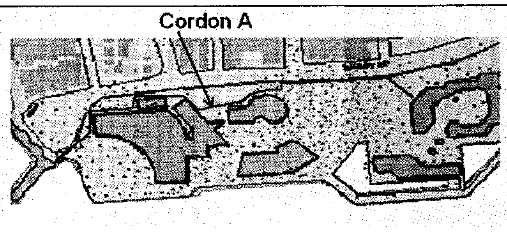


Figure 6.13a: The Begin of Setting Cordon A

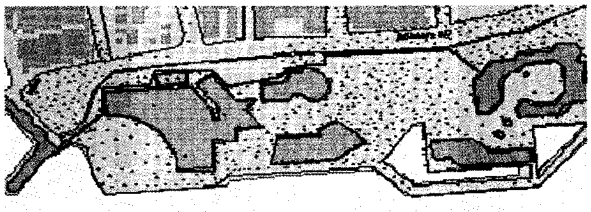

Figure 6.13b: Snapshot after Setting Cordon A

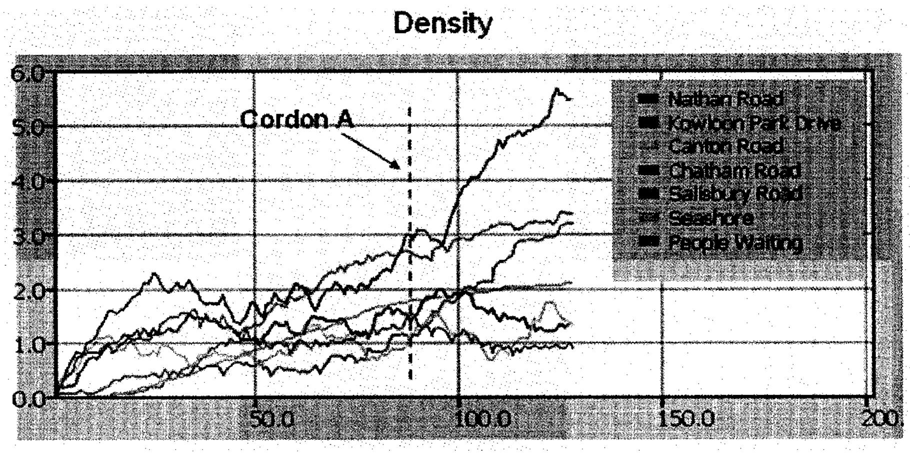


Figure 6.13c: Changes of Density Before and After Setting Cordon A

**Figure 6.13: Scenario of Crowd Arrival using Cordons**

Source: author.

Existing locations of cordons are mainly within Zone1, while the animation result shows that Zone 2 is also an area where it is easily to find the overcrowding phenomenon, especially the area spoken of in Scenario 2. One of the possible reason might be that most part of the whole population are coming out from Zone 2 due to the planning conditions of exits on KCR and MTR stations.

**Scenario 4: Opening Cultural Center During the Phase of Crowd Arrival**

There are buildings that can be passed through and mostly are shortcuts for pedestrians to arrive their destinations. Normally, they are close and not allowed to enter during the whole period. This scenario simulates the scenes if one building is open and evaluates the possibility of opening such buildings during the event. The main objective of this scenario is to simulate the scene and make this function work in ISCB, since real passages in the buildings are complicated. Figure 6.14 displays one of the snapshots for the animation (Figure 6.14a) and the records of the number of pedestrians who select to pass through the Cultural Center (Figure 6.14b).

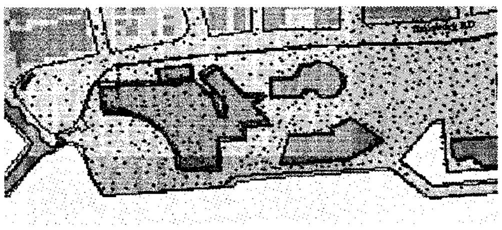

Figure 6.14a: Snapshot of Opening Cultural Center

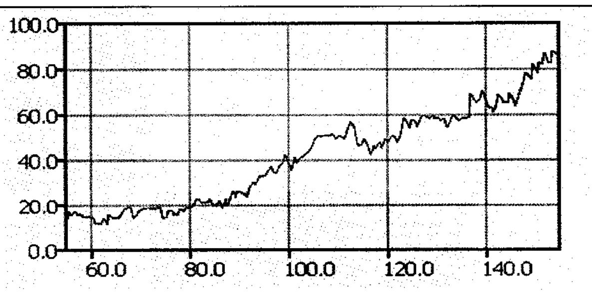


Figure 6.14b: Number of Pedestrians Passing through Cultural Center

**Figure 6.14: Scenario of Opening Cultural Center**

Source: author.

It is found that pedestrians like to select this building as shortcut to get to the sites which have high viewshed value, and the number goes up with the increasing of total number of pedestrians in Seashore. It will be not so secure enough when crowd density outside the building is too high to receive more pedestrians walking out of the building. Therefore, it is not advisable to allow passing through the building during the event, at least closing the buildings when having observed the crowd density within Seashore is high enough.

**Scenario 5: Changing Exit L4 & L3 From Exit N1 & N2 of KCR Station as "Out" During Crowd Arrival**

In the crowd arrival phase, it is obvious that Zone 2 produces much more population than other zones, causing the unbalance of the number of crowds which easily results in crowd jams. So in this scenario, we try to simulate the scenario that setting Exit F1 & F2 of the KCR station as "out" for allowing pedestrians coming out, and closing Exit N1 & N2 as "in" for only allowing pedestrians moving into. Exit F1 & F2 are located within Zone 1, which will hopefully change the generation of population, so this scenario tries to compare different results produced by setting different exit attributes. Figure 6.15 is the output of this scenario. Simulation results show that changing the situation of Exit L4 & L3 as "out" does not release the high density on Nathan Road, but increase that instead. As pedestrians coming out from Exit L4 & L3 have high probability to choose move toward to Nathan Road and enter the Seashore, and the time period it take them to move to the Nathan Road is shorter, both of which make Nathan Road becoming crowded in a short period of time. At the same time, most pedestrians from Nathan Road may select area between Hong Kong Space Museum and New World Center as their destinations due to the good visual fields there (Figure 6.15a). The computation result of the density change within sampling sites also indicates the extremely high density on Nathan Road (Figure 6.15b). Therefore, it is not advisable to open the Exit L4 & L3 during crowd arrival phase.

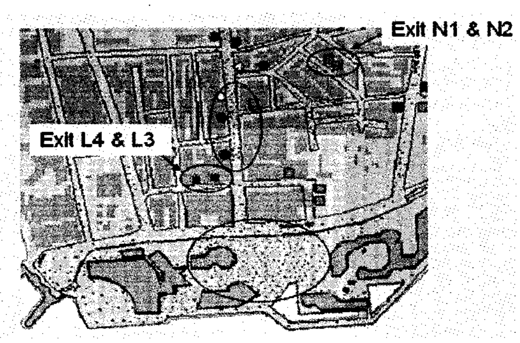


Figure 6.15a: Snapshot of Scenario 5

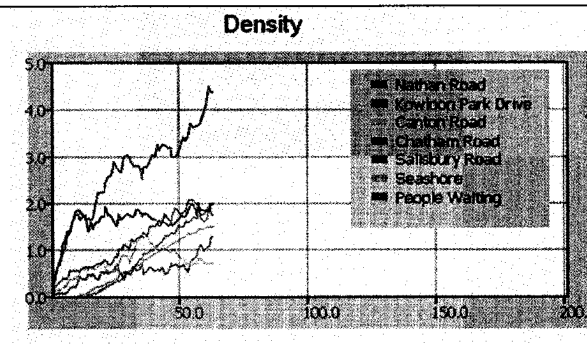


Figure 6.15b: Statistics of Density in Scenario 5

**Figure 6.15: Scenario of Changing Exit Condition**

Source: author.

### 6.4.2 Simulation and Evaluation: Crowd Dispersal

In this section, scenarios are generated to explore the crowd movement in the dispersal phase, thereby evaluating the crowd dispersal model we have already built and integrate in this phase by comparison with real scene. Compares are also made by simulating to add exits of KCR station that allow pedestrians in. At the start of crowd dispersal, pedestrians are generated and located within the whole pedestrianization area.

## Scenario 6: Crowd Dispersal with Spatial Controls

The intention of this scenario is to testify and evaluate the crowd dispersal model, and simulate the process of crowd dispersal in the event of firework display. Crowds are generated at the start of the simulation, and move to exits based on their behavioral model. Policemen control the density of crowds within their duties, and try to maintain a safe environment. Statistics of changes of crowd density, crowd population and duration of stay within 5 main roads and seashore have been done to evaluate the process (Figure 6.16).

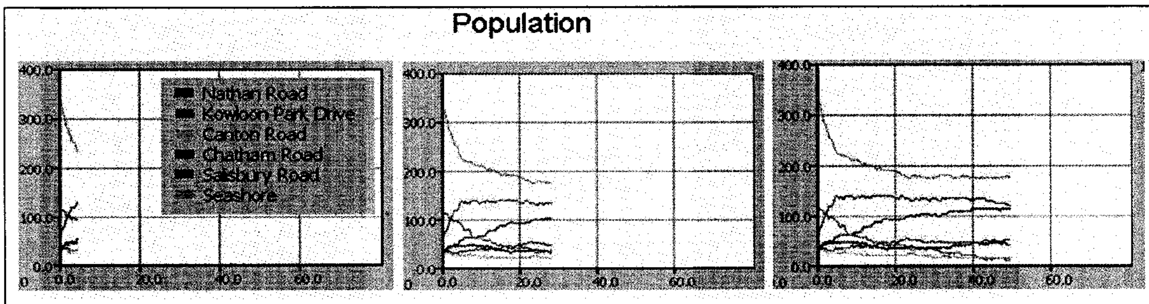


Figure 6.16a: Statistics of Population Change

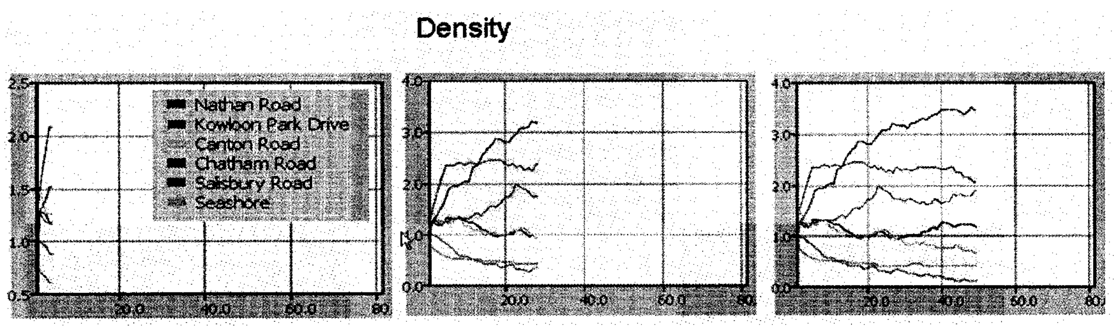


Figure 6.16b: Statistics of Density Change

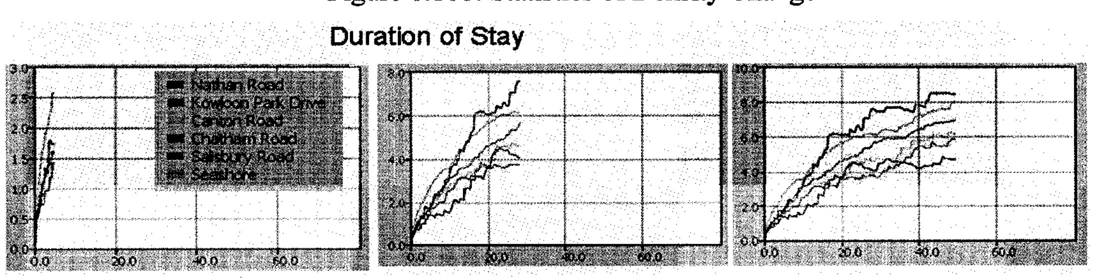


Figure 6.16c: Statistics of Duration Change

**Figure 6.16: Output of Crowd Dispersal Phase**

Source: author.

At the start of this dispersal phase, pedestrians are located within the whole area, with highest population in Seashore (Figure 6.16a). Then, pedestrians move based on the rules of dispersal model, randomly selecting an exit to leave the area if they are in view of exits, or following others if not. Therefore, the population within Seashore decreases rapidly, since they begin to move towards their different destinations. While the number of population within each road begins increasing, especially within Salisbury Road that is a connecting road between Seashore and Street Network. This situation continues until pedestrians begin leaving this area through transportation or road exits, thereby keeping the population within roads a balanced number, and a slowly decreasing number within Seashore. The change of density within sampling sites also explains the reliability of simulation of crowd dispersal phase (Figure 6.16b). At the former time period of dispersal phase, density on 5 main roads increases rapidly because large number of crowds within seashore try to move through roads to leave the area, especially the Salisbury Road and Nathan Road. There are totally 5 MTR exits located near Nathan Road, which attracted most of pedestrians selecting these exits to leave the area, thereby causing Nathan Road with high density. Crowd density on Kowloon Park Drive also presents an increasing density, since most pedestrians within Zone 1 may select passing through Kowloon Park Drive to reach exits on Nathan Road. Density within Seashore decreases with the reducing of crowds. Higher the density, the duration of pedestrians stay within sites becomes longer (Figure 6.16c). Within the former period of dispersal phase, pedestrians may need stay within area for a longer time, since exits cannot accept the inburst of large crowds. Especially within seashore, when crowds finish viewing the display and prepare dispersing, they will find it is hardly to move forward and need probably wait for a period of time to start moving. And the situation will be same on each road. Therefore, it is very important for event managers to watch on crowd behavior and prevent any accident which may result in disorders. The duration of stay within sites for pedestrians will maintain steady but still higher after a certain period.

Based on the statistics of parameters on crowds movement with time, it can be said that the simulation of crowd dispersal in terms of crowd dispersal model is accordant with the real-life situation and reliable. Animation of this scenario complementarily explains the process of crowd dispersal and further implies sites where need special attentions (Figure 6.17). The initial situation of dispersal phase is built on the default that crowds are located within their environment with a high density (Figure 6.17a), and then begin to move to exits. There are two sites where have been found in the simulation that are easily to be extremely crowded (Figure 6.17b, A and B). Site A is located on Nathan Road, where MTR stations C1 and D1 are located. These two stations may accept pedestrians from both Zone 1 and Zone 2, therefore interactions from both opposite directions of pedestrian flows are strong enough to form crowding. And site B is located at the interaction between Nathan Road, Salisbury Road and the Seashore. Seashore of this part is an area with highest viewshed value and is filled with large crowds, and moreover, most of the exits to the pedestrianization area are located on Nathan Road, most of crowds from Seashore select to follow this way to leave, thereby cause site B a vulnerable site. Cordons are hereby encouraged to be used to temporarily wait crowds and release high density within this site.

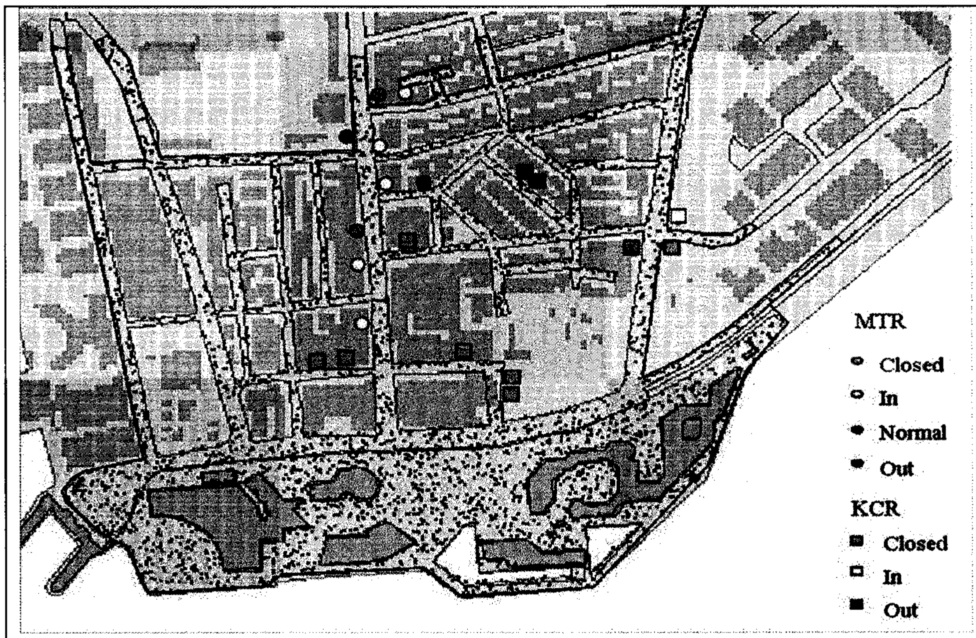


Figure 6.17a: Snapshot1 of Scenario 6 (t=0)

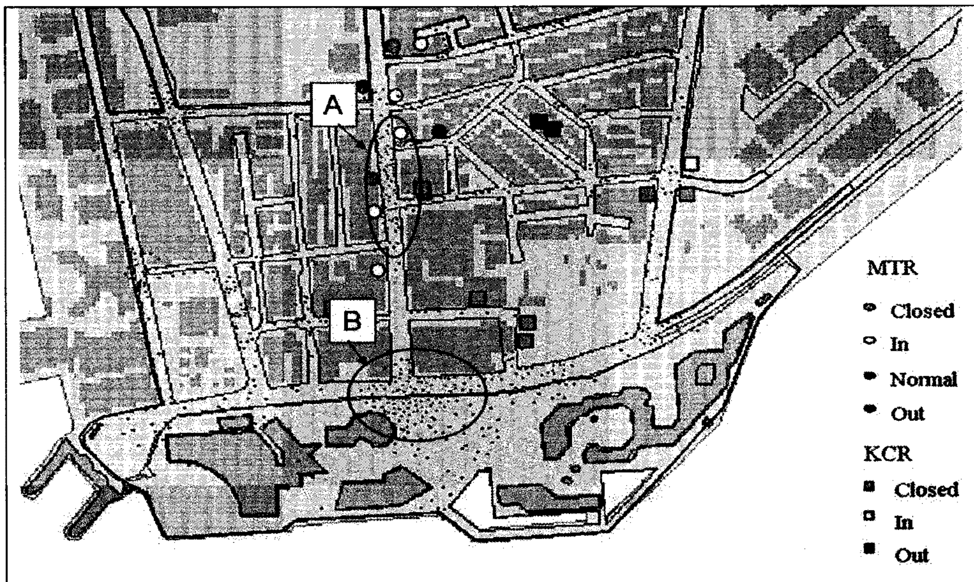


Figure 6.17b: Snapshot2 of Scenario 6 (t=79.00)

**Figure 6.17: Animation of Scenario 6**

Source: author.

**Scenario 7: Using Cordon B During Crowd Dispersal**

The objective of this scenario is to simulate crowd behavior under the condition of using cordons and to evaluate functions of cordons in ISCB. Cordon B are selected as the experiment objects to explore and compare the results related with crowd behavior. Figure 6.18 records the two snapshots at the start and after of setting cordons B. The main function of cordons B predefined by the police department is to decentralize crowds within different zones. At the beginning of dispersal phase, large crowds from seashore may try to move from there standing sites through Salisbury Road into different main roads which are obviously cannot accommodate too much population. And in order to keep pedestrians try distribute even on roads and avoid too much population selecting Nathan Road as there are many exits around the road, cordon B1 try to encourage pedestrians leave using Canton Road and Kowloon Park Drive, Cordon B2 tries to make pedestrians leave using Hankow Road through Salisbury Road, and Cordon B3 encourage pedestrians selecting Nathan Road and Middle Road, there by other pedestrians selecting Chatham Road and Salisbury Road North Section. Figure 6.18b displays the scene after setting cordon B that pedestrians are distributed evenly on spaces.

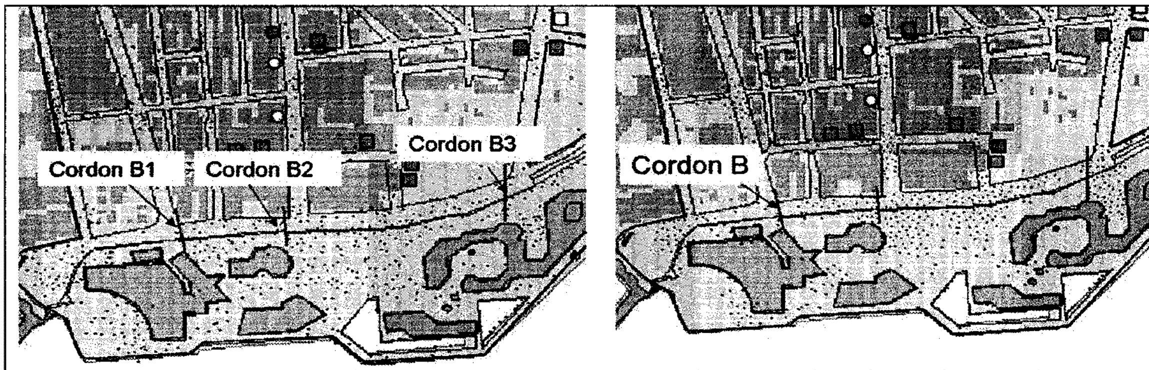


Figure 6.18a: Start Using Cordon B

Figure 6.18b: After Using Cordon B

**Figure 6.18: Using Cordons when Crowds Disperse**

Source: author.

**Scenario 8: Adding Exit L1 at KCR Station During Dispersal Phase**

As predefined by the Police Department, only one KCR exit is open for allowing pedestrians in to leave the area, it is simulated in this scenario that additional one exit is open to explore the changes of crowd dispersal behavior and evaluate the result of this what-if scenario. Exit L1 located on Middle Road is assumed to be open during dispersal phase, and Figure 6.19 displays the results of this scenario. The result shows that opening Exit L1 will not change the crowded situation and shorten the dispersal time period, but contrarily increase the chances of crowding at the intersection of Nathan Road and the Seashore. That may because opening the Exit L1 increases the probability of pedestrians choosing Nathan Road as exiting road to the area. The accumulation of crowds at the intersection goes against the safe release of crowd population within Seashore.

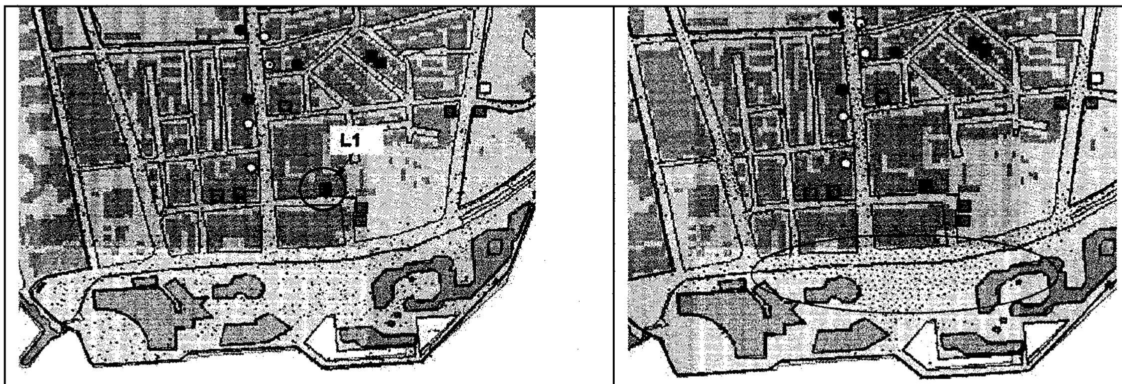


Figure 6.19a: Snapshot1 of Scenario 8

Figure 6.19b: Snapshot2 of Scenario 8

**Figure 6.19: Adding Exit during Crowd Dispersal**

Source: author.

### 6.4.3 Simulation and Evaluation: Crowd Evacuation

In this section, there are two scenarios are generated to explore the crowd movement in the evacuation phase when emergencies appear, thereby evaluating the crowd evacuation model built and integrated in ISCB. One scenario is made to test the capability of emergency road set on the Salisbury Road by police department, and the other simulate the results of when "*emergency*" agents appear on one road and block the road. At the start of crowd evacuation, pedestrians are also generated and located within the whole pedestrianization area with a high density. During the evacuation phase, pedestrians will select the closest exit if there are multiple exits in view of their vision, and follow others if not. However, at any time, emergency can come forth and evacuation model can be adopted and implemented in ISCB.

**Scenario 9: Crowd Evacuation using Emergency Exits**

North section of Salisbury Road is reserved by the Police Department as Emergency Route for vehicles or crowds passing when needed. Therefore, this scenario tries to test the function of emergency route predefined by the Police Department, and evaluate the crowd evacuation model we developed in the former chapter and the function of emergency route as well. Statistics are made on 5 thoroughfares, seashore, and emergency route in addition. The following figure 6.20 represents the output of statistics on crowd parameters within sampling sites.

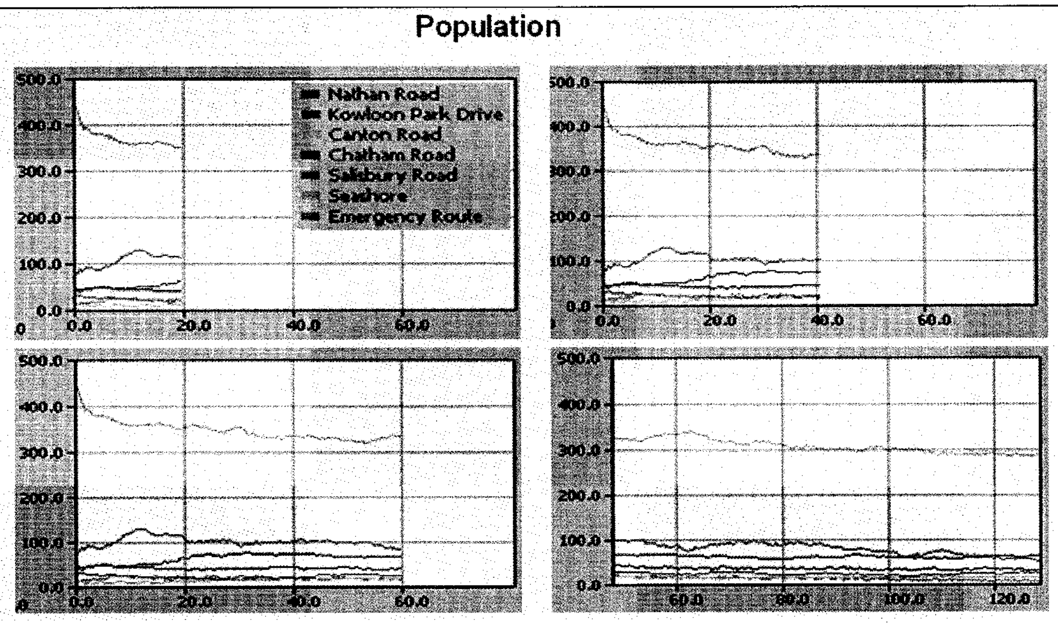


Figure 6.20a: Statistics of Population

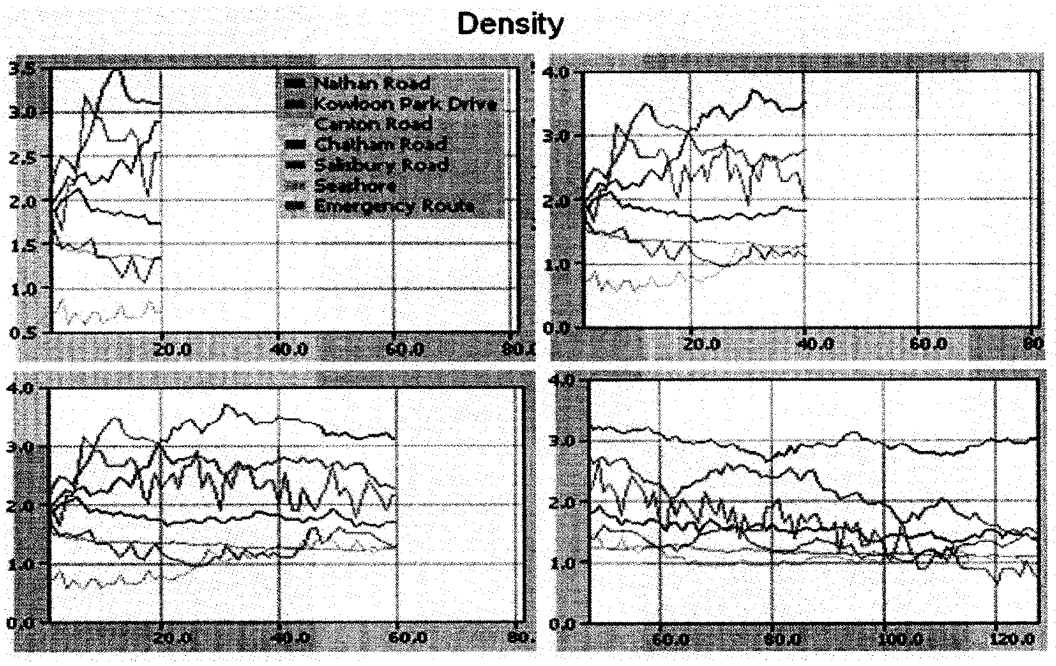


Figure 6.20b: Statistics of Population Change

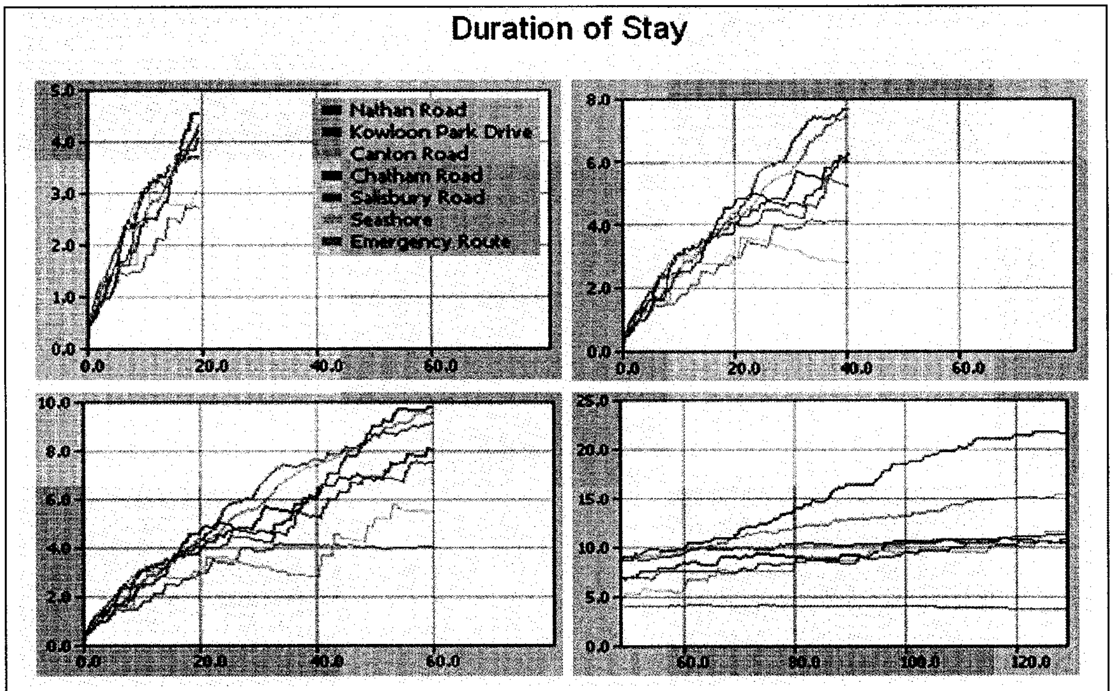


Figure 6.20c: Statistics of Duration of Stay

**Figure 6.20: Statistics of Scenario 9**

Source: author.

Statistics of population within sampling sites (Figure 6.20a) displays the changes of the number of pedestrians within areas. From t=0 to t=20 which is the beginning period of crowd evacuation, population within Seashore decrease rapidly while the number of pedestrians on Salisbury Road increase, which clearly explains that pedestrians begin moving to exits through Salisbury Road. Population within other thoroughfares maintains almost unchangeable. From t=20 to t=60, the number of pedestrians within Seashore decrease slowly which is the same with that on Salisbury Road. During this period, pedestrians may accumulate within certain sites, which cause the slowly disappear of pedestrians. And this situation will continue until the density of crowds within the whole area reaches a safe value, which also means the evacuation phase is completed. Density of crowds within each sampling site keeps almost same tones with the population change. Density on Salisbury Road increases at the beginning period of crowd evacuation, and decreases thereafter. Density on Nathan Road exhibits an increasing trends from t=0 to t=40, and decreases slowly during t>40. That's because most of the crowds choose the exits around Nathan Road to evacuate from the region. Duration of stay within sampling sites display an overall increasing trends due to the high density within each site. All of these three parameters decrease finally until the whole area reaches a safe crowd density.

Statistics on parameters during this evacuation phase basically evaluate the reliability of crowd evacuation model, while the animation of this scenario (Figure 6.21) displays the scenes of this simulation. During the former time period of crowd evacuation, pedestrians are located within area with a high density and prepare to select exits to leave the area as soon as possible (Figure 6.21a). As soon as they select their closet exit to leave, pedestrians move forward and crowding appear especially at intersections between Nathan Road, Salisbury Road and the Seashore. Emergency Route is used to evacuate pedestrians quickly (Figure 6.21b). Since this scenario is only to test the use of emergency route and no emergencies are simulated, the scene appears that crowds gather at Nathan Road while leaving the emergency route unused (Figure 6.21c). That's because pedestrians find the closest exit on Nathan Road and most of them would like to select exit there rather than exit on Salisbury Road which is farther. Therefore, it is suggested that event managers should remind people of selecting emergency route to evacuate crowds more quickly.

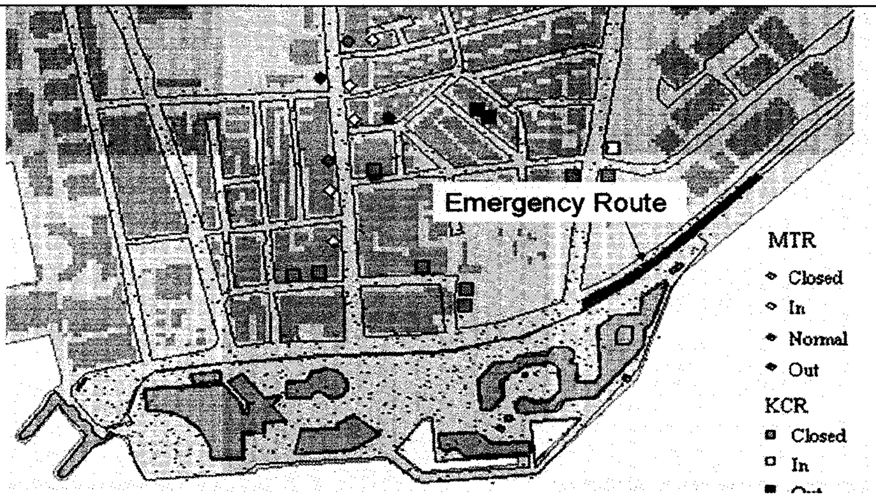


Figure 6.21a: Snapshot1 of Scenario 9 (t=1)

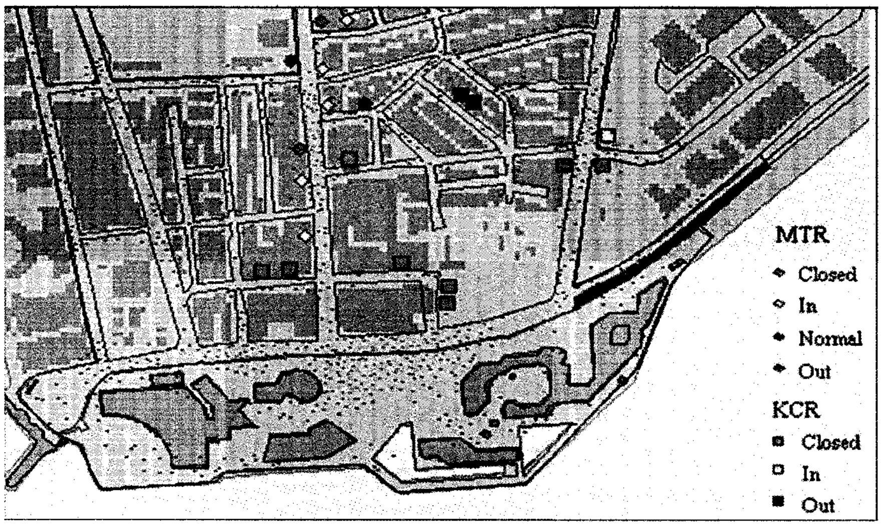


Figure 6.21b: Snapshot2 of Scenario 9 (t=16.000)

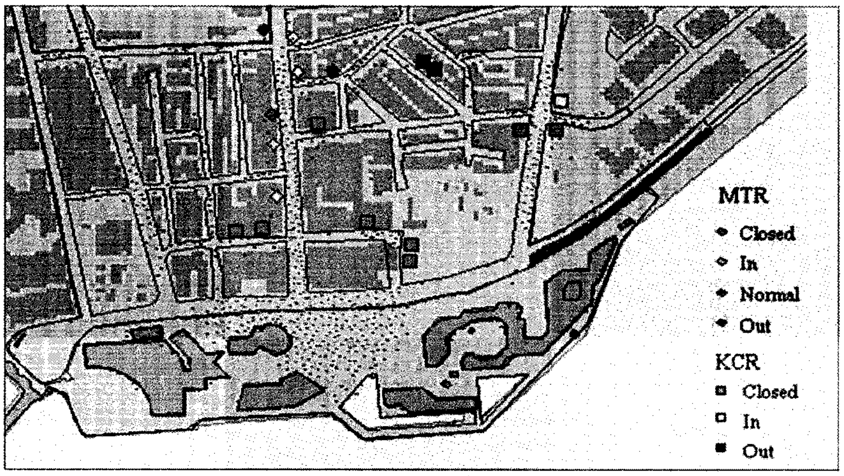


Figure 6.21c: Snapshot3 of Scenario 9 (t=68.000)

**Figure 6.21: Animation Results of Scenario 9**

Source: author.

**Scenario 10: Crowd Evacuation When Accident Appears**

In this scenario, we assume that one small accident happen within Seashore which is a high crowd density area. Pedestrians within the accidental area are required to stay stable within the effected area, and pedestrians outside the accidental area are restricted entering and leave away as soon as possible. Pedestrians still choose the closest exits to leave the whole area. Figure 6.22a displays the scenes of the appearance of accident and crowd movement thereafter which further evaluate the multi-agent crowd evacuation model. At the start of the appearance of small accident, the affected area is confirmed that will restrict pedestrians get closer to. Pedestrians select the closest exit and try get away from accidental area to leave the zones. Therefore, figure 6.22b displays the crowd behavioral results based on the evacuation model. The accidental area should be an area that crowds will gather and wait for leave through using Nathan Road, while crowds either select exit on Salisbury Road or moving around Cultural Center to leave by passing through Canton Road or Kowloon Park Drive. Statistics also shows that after the accident appears, although density within seashore decreases slower, density on Canton Road and Chatham Road increases rapidly, which explains that more pedestrians select to pass through those two roads to get way from the area.

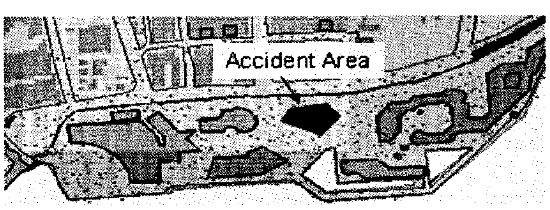


Figure 6.22a: Start of Accident

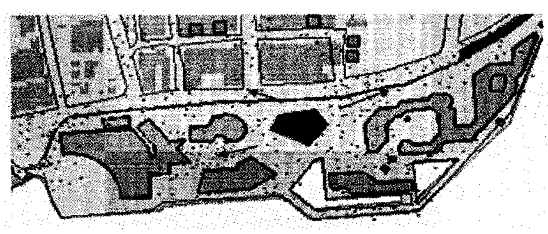

Figure 6.22b: Crowd Evacuation after Accident

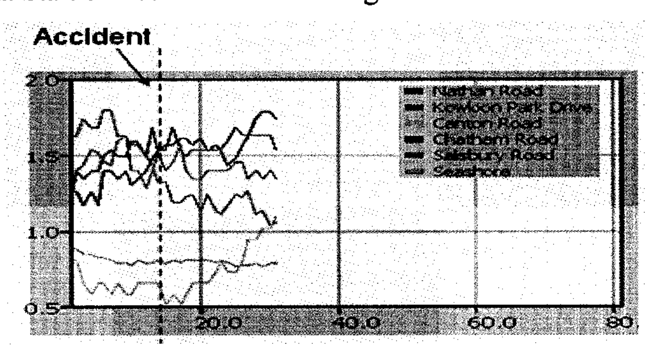


Figure 6.22c: Density Change Before and After the Accident

**Figure 6.22: Output of Crowd Evacuation When Accident Appear**

Source: author.

## 6.5 Summary and Suggestions

In this chapter, the design and implementations of integrating and evaluating MAPMODE to simulate crowd behavior within outdoor event are explained. And scenarios that can help explore and analyze crowd behavior through individual pedestrian's interactions are generated. ISCB provides valuable outputs by introducing spatial controls step by step. Ten scenarios are generated that typically represent crowd behavioral modes with different conditions. Although agent-based modeling employs simulation, it does not necessarily aim to provide an accurate representation of a particular empirical application. Instead, the goal of agent-based modeling is to enrich our understandings of fundamental processes that may appear in a variety of applications. Outputs of 10 scenarios depict the real-life processes of crowd movement in the outdoor event we are studying, and accordingly get evaluations on the reliability of MAPMODE by comparing those output with historical records of event processes. What's more, agent-based simulation helps to explore emergent phenomenon produced by interactions, which will possibly be blind spots during managing crowds. However, managing crowds for such large-scale outdoor events need considerations for multiple factors, based on scenarios generated from agent-based crowd behavioral models, following suggestions are proposed for event managers on managing crowds in the firework display.

### 6.5.1 Phases

There are obviously arrival phase and dispersal phase formed in outdoor event. It is found that it takes longer time for arrival phase than dispersal phase if no emergencies appear, which means that event managers should prepare to keep crowd safety longer time in arrival phase than dispersal phase. At the same time, there are more sites found that need special attention within arrival phase, which means that event managers should watch out extremely carefully within crowd arrival phase and guide their behavior at any time. It may owe to human cognition. In the arrival phase, due to the complex road network within study area, pedestrians normally have rough image of the orientation of attractors and choose their route randomly under rough guidance from policemen. Interactions between pedestrians and their surrounding environment are strong that need interventions. However, at the dispersal phase, when crowds are almost filled with the whole zones, pedestrians are easy to find their exits to leave the zones by themselves or by following other crowds. And the whole area is considered to be safe as long as the density decreased to certain threshold. Therefore, detailed and careful preparations for events are much important during crowd management.

### 6.5.2 Zones

There are 3 zones partitioned originally according to information got from TST Police Department, while it is found that there is much less complicated urban morphology with Zone 3 than Zone 1 and 2. For the crowd arrival phase, there are more roads that can lead to most crowded area (Seashore) within Zone 1 than those within Zone 2 and 3. And for the dispersal or evacuation phase, there are also more roads in Zone 1 that can receive large population from Seashore and lead them leave the area. But there will produce largest number of pedestrians within Zone 2, since it is an area including all the exits of KCR and MTR that pedestrians come out from TST Station that are pre-set by event managers. So to release crowds within Zone 2 during the arrival phase, managers should encourage pedestrians move to their destinations by crossing Zone 1, which will alleviate the pressure of high density of crowds within Zone 2. And during dispersal or evacuation phase, managers should encourage crowds select roads within Zone 1, which may help them leave the area quickly.

Seashore becomes a specific zone where has most number of population and highest crowd density. However, there are only parts of sites owning high viewshed value for display. Still, crowds will gather within this area and try their best to move to their best sites, which result in very high interactions between pedestrians and increase the vulnerability of crowd safety within the Seashore area. So, it is suggested that Seashore can be partitioned as an individual zone which will need specific attention on crowd behavior, so that 4 zones are formed to reduce confused duties within Seashore. Personnel that manage crowds in this event can be distributed according to extent of possible interactions within each zone.

### 6.5.3 Roads

Road intersections are sites having high crowd interactions. Pedestrians need make route choice on intersections, and event managers should guide or remind crowds to make available selections to release high density on certain thoroughfares. Special attention should be paid on roads where originate population, like Nathan Road and Chatham Road, since there are public transportation on those two roads.

### 6.5.4 Main Buildings

Main buildings are not suggested to be open during the event time period, especially those are located within Seashore. Simulation of opening Cultural Center during crowd arrival phase shows that at the beginning part of the phase, it can be open, and pedestrians who select to pass through the building to reach their destinations take up quite a high percentage of the total population within seashore and increase much quickly. It will be danger when the density of crowd outside the building is high. At the same time, area around the Cultural Center is also a site with highest viewshed for the display, so it is strongly recommend that main buildings should be close during the whole time-period.

### 6.5.5 KCR and MTR stations

KCR and MTR are the two main public transportation vehicles by which pedestrians come out into the event zones. Although they are not our concerns of crowds movement within subway stations in this research work, it is very necessary to pay attentions to the areas around the exits due to the overflow of large crowds. Simulations of each scenario have already showed the incidental jams produced by crowds.

In conclusion, the main objective of this research is to provide a framework for geo-collaboratively managing crowds for large-scale outdoor events. By integrating multi-agent crowd behavioral models, the simulations have ensured the reliabilities of MAPMODE and the feasibility of providing a platform for geo-collaboration during the work on the same geographic problem of crowd behavior for different users.

# CHAPTER 7 CONCLUSIONS

As introduced in the first chapter, the main objectives of this thesis work are to find the dynamics of crowd behaviors in large-scale outdoor events and to provide a framework for managing crowds in such events. These have been achieved through MAPMODE that are developed here. Based on the study of the case event of "Firework Display in Hong Kong TST area" which is a frequent outdoor event, this research explores the dynamics of crowd behaviors by emphasizing the effects of spatial environment on pedestrian movement, develops and simulates crowd behavior focusing on interactions between different objects involved in the event, and builds a rational framework for crowd management on such outdoor events. Crowd behaviors have attracted increasing interests from researchers and demanding suggestions and solutions are required by outdoor event managers. So this research has provided an alternative means to current behavioral research on crowd and pedestrian dynamics with an attempt to use multi-agent based approach and integrating human spatial cognitions to build a computational model of crowd behaviors. In spite of limitations on data quality, it is a feasible framework to serve as a platform for communication and decision-making for the relevant players. Future works are necessary to extend the geo-collaboration for managing crowds in large-scale outdoor events.

## 7.1 Significance

### 7.1.1 Conceptualizing Crowd Management for Large-Scale Outdoor Events

As outdoor events are becoming frequent happenings in modern urban cities, crowd management is also getting more important in both scientific researches and practical applications. There has been much focus on crowd management in indoor environments, like a building, mainly from the engineering point of view concerning how to safely and quickly evacuate occupants in the events of a fire or other emergencies. Most of these researches emphasize mainly on the design of buildings or facilities. This research argues that crowds in outdoor events should also be paid attention such as crowds in parades, recreational events, or pilgrimages. Means for a systematic management of crowds in outdoor events are still absent, particularly in reference to computational models of crowd dynamics. Through the works completed here, crowd management for large-scale outdoor events have been conceptualized through an analysis of crowd behavioral dynamics for the implementation of geo-collaboration on crowd management.

This research has firstly gained an insight into the nature of outdoor crowds, focusing on the relationship between pedestrians' spatio-temporal behaviors and urban built environments. It was found that urban spatial morphology has great effects on human behaviors. That is represented as pedestrian visibility differences contained by urban terrain and road networks. These differences can be analyzed and calculated through establishing detailed urban spatial models and exhibiting viewshed differences by geographic terrain and isovist differences by urban road networks. Quantified visibility differences make it clear for managers to estimate and evaluate possible crowded levels within event-affected areas. In virtue of spatial analytical tools, crowd modeling and crowd management have been improved by viewing from the perspective of spatial information rather than only from the points of engineering or environmental psychology. Besides, crowd behaviors are a result of interactions that not only exist among individual pedestrians but also between individual pedestrian and his behavioral space. Interactions arise from the beginning of the strategic level of pedestrian behavior and disappear at the completion of pedestrian behavior. It has implied a dynamic process of spatio-temporal behaviors and interactions. Dynamics of outdoor crowds can be acquired through further understanding of behavioral interactions between each component within the events.

Secondly, this research has also gained an insight on managing crowds based on development phases. Due to the characteristics of a short duration and a large number of participants of large-scale outdoor events, crowding may emerge at any time-period and any position. Most of the current researches on crowd modeling have put more emphasis on human evacuation from emergencies than the emphasis on how crowd is formed and dispersed in normal situations. This research has proposed three comparably important phases for building crowd behavioral models, including the phases of crowd arrival, crowd dispersal and crowd evacuation in emergencies. Within each phase, owing to distinct goals and environmental settings, crowds behave differently. In addition, the use of spatial database integrated with spatio-temporal models for these three phases has given rise to improved functions at all of the environmental, pedestrian and emergency management for outdoor events.

Thirdly, as group works are the principal mode for management, moving crowd management towards geo-collaboration is necessary and inevitable. The framework for a geo-collaborative management of crowds has been proposed in this work, which is composed of data environment, visualization environment, interface environment and user environment. The framework is developed for data environment which stores information and knowledge of individual behaviors and their behavioral space. It provides a visualization environment for different end-users to simulate processes of crowd behaviors and events evolvement, and support decisions-making with multi-modal and multi-mode interfaces. Geo-collaboration will support dialogues for groups at the same/different places and same/different time, and provide communications between users for coordinated work.

So, specifically in this work, conceptions of crowd management for large-scale outdoor events have shed lights on:

- new viewpoints from the spatio-temporal perspective on crowd behaviors and their interactions;
- extensions on crowd dynamics within both normal and emergent situations;
- explorations on crowd behaviors from both aggregate and disaggregate views;
- proposal of geo-collaborative management of crowds to support decision-making;
- improvements on understanding human behaviors with the help of contemporary development of Geographic Information Sciences both theoretically and technically.

The framework for geo-collaborative crowd management is expected to be applicable to any outdoor events in solving the problem of efficiently managing large pedestrians movement in a short period of time. It is hoped to release the pressures from the absence of practical knowledge on and tools for crowd management, particularly when concerns are growing in developing an appropriate science to deal with safety, crime and leisure.

### 7.1.2 Agent-Based Modeling of Emergent Systems

Emergent systems indicate that interactions among simple parts can produce complex phenomena (Epstein, 1996; Johnson, 2001). By this definition, the whole of one system is more than the sum of its parts because of the interactions between the parts. Thus they cannot be simply reduced into the pieces of the system, since an emergent phenomenon may have properties that are decoupled from the properties of the parts (Bonabeau, 2002). The characteristics of emergent phenomena make them difficult to understand and predict because emergent phenomena can be counterintuitive. Human systems like crowd dynamics are one kind of emergent systems whose involved factors are mostly "soft"; for example, potentially irrational behavior, subjective choices, and complex psychology. These factors are difficult to quantify, calibrate, and sometimes justify. Although there may exist a major source of problems in interpreting the outcomes of simulations, it is fair to say that in most cases agent-based modeling is seemingly the only way to deal with such situations. In agent-based modeling, a system is modeled as a collection of autonomous decision-making entities called agents. Each individual agent assesses its situation and makes decisions on the basis of a set of rules. Repetitive and competitive interactions among agents are the feature of agent-based modeling. The power of a computer is relied upon to explore behavioral dynamics beyond the reach of pure mathematical methods. Even a simple agent-based model can exhibit complex behavior patterns and provide valuable information about the dynamics of the real-world system that it emulates. In MAPMODE, an outdoor event of a firework display is described as a combination of interactions between seven types of agents: pedestrians, policemen, attractors, roads, buildings, facilities and emergencies. The ISCB tries to simulate crowd behavior based on their behavioral interactions thereby acquiring the possible emergent phenomenon of crowding and achieving the goal of managing crowds through scenarios. By modeling and simulating the behavior of the system's constituent units and their interactions, agent-based modeling captures emergence from the bottom up when the simulation is run. It is found that this agent-based modeling approach provides additional information on crowds that cannot easily be observed or be estimated only through collective analysis. Scenarios generated in Chapter six have been evaluated and demonstrated advantages of such

MA approach, which help improve knowledge on crowd behaviors in a case event that is not easily explored through observations and analyze in Chapter four.

The agent-based approach is also able to capture an emergent phenomenon and thereby provides a natural description of emergent systems. For example, if individuals behave following certain specific rules then crowds as a whole will exhibit some particular properties. How does the heterogeneous micro-scale of individual pedestrian behavior generate the global macroscopic regularities of the whole crowd system? There has been research preoccupied with static equilibria to summarize the relationships while time dynamics has essentially been ignored. But human behavior is a nonlinear and nonequilibrium dynamics. MA approach helps to overcome these problems and has been applied in this work in describing crowd behavioral processes. It depicts the whole crowd system from the perspectives of its constituents. In addition, it not only simulates the spatial change of agents, but also the temporal evolvement of an event. MAPMODE in this work naturally simulate the three phases of crowd movement and event processes, and provide support for better decision-making. This MA approach is also flexible for users to study and communicate. For example, it is easy to add or delete agents in MAPMODE and set different attributes for agents, like setting road situations as close or open. Users can set facilities via the user-friendly interface, like adding mills barriers on roads to temporarily bar pedestrian's movement. Furthermore, it is not difficult to revise parameters with agents given the natural framework for adjusting the complexity of the agents: behavior, degree of rationality, ability to learn and evolve, and the rules of interaction. Besides, the model can be stopped or resumed at any time to explore the changing system after each step without disrupting the structure of the model.

### 7.1.3 Empirical Modeling of Human Spatial Cognition

It is widely accepted that human behavior is driven by his cognition on the environment. Spatial cognition is concerned with the study of knowledge and beliefs about spatial properties of objects and events in the world (Montello, 2001). Cognitive structures and processes are a part of the human mind, which emerges from the brain and nervous system inside of a body. Spatial cognition includes the cognition of location, size, distance, direction, separation and connection, shape, pattern, and movement. There have been many models developed for cognitive processes in a geographic space, but most of them are conceptual or semantic due to the complex infrastructure of human thinking. Behavioral modeling is still mostly based on exterior representations. However, any research concerning cognitive maps should be philosophically, theoretically, and methodologically sound and these three features should be related strongly (Downs, 1970). To gain better insights into the whole process of spatial thought and behavior, it is necessary to integrate disparate theories into a more coherent whole. Hence, MAPMODE developed in this work for large-scale outdoor events has combined not only the long-term observations and experiences on pedestrian and crowd behaviors but also the psychological cognitive process of pedestrian decision-making and spatial cognition. Based on the investigations on historical events, it is assumed in MAPMODE that pedestrians who are participating in the case event have a general cognition of the locations and orientations of goals they are to achieve. But in dealing with discrete behavior of pedestrian movement, it has integrated the feature of "following the crowd" as represented by the flocking behavior. Not only is the pedestrian behavior modeled at the practical level, but also the strategic and tactical levels of pedestrian decision-making processes are integrated and simulated. First, each pedestrian agent is a decision maker, actively making decisions, setting goals, and guiding behaviors to achieve the goals. The goals are constantly changing based on the information that is continuously acquired. Second, behavior is a function of both the real and subjective worlds. Pedestrian behavior is constrained by spatial and environmental factors or human interventions. However, these constraints can be recognized and individuals have the capacity to use and process the information received from the environment to construct decisions. Third, the whole behavioral process is dynamic and embedded. Information is constantly recycled and reprocessed, with many problems and scenarios being processed in parallel. The whole cycle linking thought and behavior is thus in a constant state of flux. Fourth, pedestrian's cognition is both internalized and externalized. A pedestrian's next step is a reaction of the previous actions that change with the environment. Thus, the behavioral environment is dynamic and in a progressive state of changes with each time interval. Although it is impossible to model the exact "thinking" process of each individual, the proposed model is evaluated a natural and improved way of depicting pedestrian behavioral process under the general forces of cognition to surroundings. And this cognition has been integrated and represented as computational models of human behavior and empirically evaluated after simulating the crowd behavior.

### 7.2 Discussions

The models developed in this work may have limitations mainly in terms of data quality. Individual data is the foundation for agent-based modeling of crowd behaviors in this outdoor event, which means the more detailed the data, the better the models. Quality of individual data is first represented with a classification of pedestrians and agents. In MAPMODE, every individual is considered as similar irrational pedestrian and has similar drives for behavior. However, individuals do have differences due to their age, sex, nationality, ability and even in height and size. These differences may result in differences of spatial cognition among different individuals. The second limitation pertaining to data quality is about alternative behaviors. Our models are based on the assumption of the main goal that crowds have, while it is possible for pedestrians within the area to have second or third goal except for that, or whose main goal is not to participate the event. Models will be further improved if we have knowledge on the proportions of participants' different goals. The third data limitation arising from data concerns the source of information which comes mostly from event managers with little or no feedbacks from the real actors in such events, apart from ourselves who participated in the event. It is difficult to collect and compile statistics for each or sample population because of the large quantity and changing constitutes of each event. Feedbacks from participants on such a crowd management platform and crowd behavioral models may improve the efficiency and functions of this framework.

In addition, the case we have studied in this work is a typical outdoor event in urban cities, yet with relative simple interactions as well. Just as presented in chapter four, the recreational nature of a firework display dictates somewhat the crowd behavior which is mild mannered and easier to represent. The main objective of participants in this sort of event is clear and simplistic without much deviant behavior. The simplistic nature of the case event makes models and simulations more satisfactory because crowd behaviors are summarized and abstracted satisfactorily. However, each outdoor event has special features due to its different motivations, and also different types of crowds will appear in events. In the case of Hong Kong, different outdoor events with different objectives may impulse the formations of crowds with different types, for example, pageants held several times once a year for celebrations may attract exciting crowds, parades for protests may attract aggressive crowds, and congresses with demonstrators may invoke violent participants. All these outdoor events highlight the needs to manage crowds more effectively and efficiently. Given the dynamics of crowds in different events, the parameters of MAPMODE must be modifiable to accommodate variations.

Furthermore, models developed in this work adopt the MA approach and have been evaluated as informative for crowd management in large-scale outdoor events by comparing the simulated results with real situations. Since crowd behavior can be modeled by various methods, a number of models can be employed to analyze and simulate the pattern and process of crowd behavior. Although there are no existing methods found applied in the case that we are studying on, models of crowd behavior will be more comprehensive if contrasts and compares are made with different methods. In addition, trajectories of pedestrian movement are ignored in this simulated platform. Finding out the regularities of crowd behavior from simulation results will provide improved knowledge on pedestrian movement.

This work offers a starting point to look into crowd behavior and crowd management with individuals in mind and from a spatio-temporal perspective. It also brings about theoretical and technical issues needing considerations and explorations for future researches.

### 7.3 Suggestions and Future Work

#### 7.3.1 Collection of Pedestrian Information

Agent based modeling approach is driven by individual data sources, thereby rich individual data with good quality must be addressed to improve our models beyond what we have done here and in related work. So, it is very important to collect concrete individual information of pedestrian behavior as detail as possible. As pedestrian behavior is very complex that extends beyond the physical to the social and psychological, motivations, perceptions, personal attributes, and socio-economic status are all central to the decisions to engage in movement. This complexity raises issues for the number and type of data that should be included in future studies.

Demographic data are relatively easy to acquire and analyze, however, they are only one of many factors in walking behavior. Psychological and social factors are crucial to understanding behavior yet they are very difficult to monitor and evaluate objectivity. As a result, few studies try to understand the psychological and sociological reasons for walking behavior and are limited to quantifying the amount of walking behavior in various environments, controlling for different demographic status. As in stated in Craig et al.(2002), "research on physical activity and the physical environment is at the correlates stages, so it is premature to establish causal effects." These limitations point toward possible paths of future research.

As human behavior varies with personal attributes, it is also important to study the different behavioral dynamics for each type of pedestrians. It is worthy of collections of different behavioral information by distinguishing males or females, elders or youngers, nationalities, cultural differences, disabilities, or others. More detailed information make crowd behavioral models suitable for real-life. Due to these differences, it is suggested to try to notice and collect components of populations in outdoor events. It will be significant to acknowledge what types and how many types of pedestrian participate within the event. For example, for the firework display, we have already caught the information that family members and adults are the main members in the event, except for a few children and rarely old persons. But what is the general percentage of the whole crowds? If information on compositions are got held, MAPMODE will be further improved. Each type of events may have their different composing modules which may also vary with the discrete time, like, weekday or weekend, summer or winter. However, it is a long-term and persistent but essential task for future research if an efficient crowd management is necessary.

Methods for capturing pedestrian behavior are also necessary to study for future work. There have been many methods used to collect the information on pedestrian behavior, like photographs, taking videos, statistics, surveys and etc. Any of these methods will facilitate for capturing human movement, while it will be better to combine multiple ways for measuring behavioral dynamics. In recent years, there have also been two categories of surveying pedestrian behavior used in researches. They are surveys focused on walking as physical activity and surveys focused on walking as mode of transportation. Trip-based or activity-based diaries are the most frequently used method of capturing transportation-related walking behavior, even though they are usually primarily collected for the purpose of describing and forecasting automobile travel demand. The details (such as origins, destinations, and local land use characteristics) of pedestrian trips are lost when the data are aggregated to a traffic analysis zone, the spatial unit of most travel demand forecasting. Respondents are more likely to forget to record short trips in the diaries. These audit tools are inadequate for studies on pedestrian movement specifically interested in the outdoor event. Questionnaires are another type of methods for capturing pedestrian behavior, while it is arduous to make it in short period and with thousands of hundreds of people. How to do the questionnaires will be another issue for future work. Interviews also become useful for understanding pedestrian behavior. There has already been a study conducted for the Surface Transportation Policy Project which adopted the approach of phone interview to assess the perceptions of human behavior. However, this study has not compared the perceptions recorded in the interviews with actual walking behavior. With the development of technologies, CCTVs, GPSs, airphotos or event remote sensing images will detect crowd information in outdoor events. How to trace and analyze the information will also be the issue of future work.

### 7.3.2 Improving Models Applicable for Different Types of Outdoor Events

When agent-based models have been compared to empirical data, they have often been applied to case studies. A problem with case studies is that they are not genuinely replicable events, although role-playing games can sometimes capture their major elements. Like mentioned in limitations, this work has now constrained within only one type of outdoor event, MAPMODE need to be improved for different types of outdoor events, which can be made by enhancing the behavioral rules set for different types of pedestrians. Thus, more cases with different nature should be explored and analyzed to find the generalized crowd dynamics. Computational models provide simulations and suggestions for scenarios, while field observations are equally important for crowd management. They will inform and improve one another over several iterative cycles. Relatively simple laboratory situations can be constructed to involve groups of people to interact in idealized environments, according to easily stated behavioral rules. Experiments can bridge the often-noted gap between computational models and group behavior, because the assumptions underlying the experiments can be tailored to correspond almost exactly to the assumptions of the computational models. Thus the models can be aptly applied without sacrificing the concision of their explanatory accounts.

### 7.3.3 Full Geo-collaboration for Crowd Management

Managing crowds in large-scale outdoor events is a process of geo-collaboration. As proposed in conceptual framework, there will be five environment included within geo-collaborative crowd management. Technologies as the foundation are evolving rapidly everyday and will support geo-collaboration without doubt. User environment as the external communicator of information is indispensable for management. Data, visualization and interface are the most important concerns to achieve geo-collaboration. As we have discussed the future works on data, especially the pedestrian behavioral information, geo-collaborative visualization and geo-collaborative interface design give the possible directions for future works. Both of these two directions will have common issue on the design of human-computer interface (HCI). It is inevitable for crowd management if full geo-collaboration will be implemented.

New technologies has now made it possible for everyone to have access to pedestrian modeling information using different devices, such as large and high-resolution displays that can enable same-place collaborative work, and smaller and lighter devices that generate or use geo-referenced information anywhere and that are linked to wireless communications. But the ways users interact with such geographic information can be multiform. A substantial amount of research has been conducted in the general area of HCI, providing an initial foundation for understanding how humans interact with geospatial information. Although the new technologies pose an initial hurdle for users of geospatial applications, the fundamental challenge is how to support human interaction with the geospatial information itself. Although the HCI community has begun to examine the effectiveness of information visualization methods and tools, most studies have centered on information displays rather than on mechanisms for interacting with them (Chen and Yu, 2000). HCI problems results in two issues of how to present information to groups and how to design interfaces to facilitate group work. Open issues include appropriate interface metaphors and support for multi modal interaction. For example, Face-to-face communication relies on gestures and facial expressions. Some researchers believe that realistic avatars facilitate more open communications among participants (Oviatt and Cohen, 2000). HCI will be a big challenge for really moving crowd management towards geo-collaboration and become the most important for future work on geo-collaboratively managing crowds in large-scale outdoor events.

## Bibliography

AlGadhi, S.A.H. & Mahmassani, H.S., 1991, Simulation of Crowd Behavior and Movement: Fundamental Relations and Application, *Transportation Research Record*, 1320, pp:260–268.

ALPSIM, from http://www.vsp.tu-berlin.de/archive/sim-archive/projects/alpsim/, access on 2006/06/25.

Ando, K., Aoki, T., & Oto, H., 1991, Improvement of the Simulation System for Passenger flow, *Quarterly Review of the Rail Technical Research Institute Report*, Japan, Spring.

Aoki, T., 1994, The Simulation System of Passenger Flow, *Quarterly Review of Rail Technical Research Institute*, Vol 35, No. 2, May 1994.

Armstrong, M. P., 2001, *The Four Way Intersection of Geospatial Information and Information Technology*, White Paper Prepared for NRC/CSTB Workshop on Intersections between Geospatial Information and Information Technology, September 19, 2001.

Ashcraft, N., & Scheflen, A. E., 1976, *People Space: The Making and Breaking of Human Boundaries*, Anchor Press, New York.

Ashford, A., O'Leary, M. & McGinity, P. D., 1976, Stochastic Modeling of Passenger and Baggage Flows Through an Airport Terminal, *Traffic Engineering & Control* 17, 207-210.

Axelrod, R., 1997, Advancing the Art of Simulation in the Social Sciences, in Conte,R., Hegselmann R., & Terna, P. (Eds.), *Simulating Social Phenomena*, Berlin : Springer, pp. 21-40.

Bandini, S., & Worsch, T. (Eds.), 2000, *Theory and Practical Issues on Cellular Automata : Proceedings of the Fourth International Conference on Cellular Automata for Research and Industry*, Karlsruhe, 4-6 October 2000.

Batty, M. & Jiang, B., 1999, Multi-Agent Simulation: New Approaches to Exploring Space-Time Dynamics Within GIS, *CASA Working Paper Series,* Paper10, University College London : London.

Batty, M., & Conroy, R., 1998, *The Virtual Tate*, London: CASA.

Batty, M., & Longley, P., 1994, *Fractal Cities*, London: Academic Press Limited.

Batty, M., & Rana, S., 2002, Reformulating Space Syntax: The Automatic Definition and Generation of Axial Lines and Axial Maps, *CASA Working Paper Series*, Paper 58, University College London : London.

Batty, M., 1976, *Urban Modelling: Algorithms, Calibrations, Predictions*, Cambridge University Press: Cambridge.

Batty, M., 1997, Predicting Where We Walk, *Nature* 388: 19 – 20.

Batty, M., 2000, "A Slow Sort of Country!" Said the Queen, *Environment and Planning B: Planning and Design,* vol. 27, pp. 799 – 800.

Batty, M., 2001a, Agent-Based Pedestrian Modelling, Editorial, *Environment and Planning B: Planning and Design*, vol. 28, pp. 321 – 326.

Batty, M., 2001b, Exploring Isovist Fields: Space and Shape in Architectural and Urban Morphology, *Environment and Planning B: Planning and Design*, vol 28, pp. 123-150.

Batty, M., Desyllas, J. & Duxbury E., 2002, The Discrete Dynamics of Small-Scale Spatial Events: Agent-based Models of Mobility in Carnivals and Street Parades, *CASA Working Paper Series*, Paper 56, University College London : London.

Batty, M., Jiang, B., & Goodwin, M. T., 1998, Local Movement: Agent-Based Models of Pedestrian Flow, *CASA Working Paper Series*, Paper 4, University College London : London.

Benedikt, M.L., 1979, To Take Hold of Space: Isovists and Isovist fields, *Environment and Planning B*, vol. 6, pp. 47-65.

Benenson, I., & Torrens P. M., 2004, *Geosimulation: Automata-based Modeling of Urban Phenomena*, Hoboken, NJ : John Wiley & Sons.

Berlonghi, A. E., 1993, Understanding and Planning for Different Spectator Crowd, in : Smith, R. A. &Dickie, J.F. (Eds.), *Engineering for Crowd Safety*, London: Elsevier, pp.13-20.

Blue, V. J. & Adler, J. L., 1999, Using Cellular Automata Microsimulation to Model Pedestrian Movements, in Ceder, A. (Eds.), *Proceedings of the 14th International Symposium on Transportation and Traffic Theory*, pp: 235-254, Pergamon : New York, N. Y.

Blue, V. J. & Adler, J.L., 1998, Emergent Fundamental Pedestrian Flows from Cellular Automata Microsimulation, *Transportation Research Records* 1644, 29-36.

Blumberg, B., & Galyean, T, 1995, Multi-Level Direction of Autonomous Creature for Real-Time Virtual Environments, in *Proceedings of SIGGRAPH '95, Annual Conference Series, ACM SIGGRAPH*, pp.47-54.

Bokhary, J., 1993, *The Lan Kwai Fong Disaster on January 1, 1993 : Inquiry by the Honourable Mr. Justice Bokhary : Final report*, Hong Kong : Govt. Printer.

Bolt, R.A., 1980, Put-that-there: Voice and Gesture at the Graphics Interface. *ACM Computer Graphics,* vol. 14, no. 3, pp.262–270.

Bonabeau, E. , 2002, Agent-Based Modeling: Methods and Techniques for Simulating Human Systems, *PNAS*, vol, 99, pp: 7280-7287.

Bratley, P., Fox, B & Schrage, L., 1987, *A Guide to Simulation*, Second Edition, New York : Springer-Verlag.

Brown, D. G. et al, 2005, Spatial Process and data models: Toward integration of Agent-Based Models and GIS, *Journal of Geographical Systems* 7: 25-47.

Carstens, R. L. & Ring, S. L., 1970, Pedestrian Capacities of Shelter Entrances, *Traffic Engineering* 41, 38-43.

CASA website, http://www.casa.ucl.ac.uk.

Census and Statistics Department, 2000, *Hong Kong Population Projections 2000-2029.*

Chapleau, R., Allard, B., Trepanier, M., Morency, C., 2001, Origin-Destination Travel Survey Software: Cognitive and Technological Assistance, *World Conference on Transportation Research*, July 2001, Séoul, Corée, CD-ROM, 20 pages.

Chowell, G. et al, 2003, Scaling Laws for the Movement of People Between Locations in a Large City, *Physical Review E* 68, 066102.

Chrisman, N. R., 1998, Beyond the Snapshot: Changing the Approach to Change, Error, and Process, in Egenhofer, M. & Golledge, R. (Eds.), *Spatial and Temporal Reasoning in Geographic Information Systems*, Oxford University Press Oxford: New York, pp: 85-93.

Clifford, P., 1999, Tynecastle Football Stadium Crowd Movement Simulation, *Stadia and Arenas: Development, design and management, Stadia & Arenas 2000*, 16-17th June 1999, London Arena : The Concrete Society.

Couclelis, H., 1998, Geocomputation in Context, in Longley, P., Brooks, S.M., Mcdonnell, R. & Macmillan, B. (Eds.), *Geocomputation: A Primer,* New York: John Wiley & Sons.

Craig, C. L., Brownson, R.C., & Dunn, A. L., 2002, Exploring the Effect of the Environmental on Physical Activity: A Study Examining Walking to Work, *American Journal of Preventative Medicine*, 23 (2S).

Cristiano, C., 1998, Simulating with Cognitive Agents: The Importance of Cognitive Emergence, in *Proceedings of First International Workshop*, MABS '98, Paris, France, July 4-6, 1998, pp. 26-44.

Cullen, I., Godson, V., &Major, S., 1972, The Structure of Activity Patterns, in Wilson, A.G. (Eds.), *Patterns and Processes in Urban and Regional Systems*, London: Pion, 281-296.

Cutter, S. L., Richardson, D. B., & Wilbanks, T. J., 2003, *The Geographical Dimensions of Terrorism*, New York and London: Routledge.

Daly, P.N., McGrath, F., & Annesley, T.J., 1991, Pedestrian Speed/Flow Relationships for Underground Stations, *Traffic Engineering and Control* 32, 75–78.

Davis, D. G. & Braaksma, J. P., 1998, Adjusting for Luggage-laden Pedestrians in Airport Terminals, *Transportation Research A* 22, 375-388.

DeFanti, T. & Stevens, R., 1999, Teleimmersion, in Foster, I. & Kesselman, C. (Eds.), *The Grid: Blueprint for a New Computing Infrastructure*, pp: 131-155, San Francisco, Calif: Morgan Kaufmann Publishers.

Desyllas, J., Duxbury, E., Ward, J., & Smith, A., 2003, Pedestrian Demand Modeling of Large Cities: an Applied Example from London, *CASA Working Paper Series*, Paper 62, University College London: London.

Epstein, J., and Axtell, R., 1996, *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press: Cambridge.

Ferber, J., 1999, *Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence*, Addison-Wesley: Reading, MA.

Fisher, D. A., & Lipson, H. F., 1999, Emergent Algorithms: a New Method for Enhancing Survivability in Unbounded Systems, in *Proceedings of 32nd Hawaii International Conference on System Sciences*, CD-ROM, Institute of Electrical and Electronics Engineers: New York.

Frank, A.U., Bittner, S., & Raubal, M., 2001, Spatial and Cognitive Simulation with Multi-agent Systems, in Montello, D. (Eds.), *Spatial Information Theory: Foundations for Geographic Information Science*, Springer : Verlag, pp. 124-139.

Franklin, S. & Graesser, A., 1997, Is It an Agent, or Just a Program? A Taxonomy for Autonomous Agents, in Muller, J. P., Wooldridge, M. J., & Jennings, N. R. , *Intelligent Agents III: Agent Theories, Architectures, and Languages*, Springer-Verlag : Berlin, pp. 21 - 35.

Freundschuh, S. M. & Egenhofer, M., 1997, Human Conception of Spaces: Implications for GIS, *Transactions in GIS* 2, 361-75.

Fruin, J. J., 1971, Designing for Pedestrians: A Level-of-service Concept, in *Highway Research Record*, no. 355, Pedestrians, pp: 1-15, Highway Research Board : Washiongton D. C.

Fruin, J. J., 1993, *Crowd Management Information*, from www.crowddynamics.com.

Fruin, J.J, 1993, The Causes and Prevention of Crowd Disasters, in Smith, R.A. & Dickie, J. F., *Engineering for Crowd Safety*, Elsevier.

Fruin, J.J., 1971, *Pedestrian and Planning Design*, Metropolitan Association of Urban Designers and Environmental Planners.

Fukui, M., & Ishibashi, Y., 1999, Self-organized Phase Transitions in Cellular Automaton Models for Pedestrians, *Journal of the Physical Society of Japan* 68, 2861-2863.

Gahegan, M., 2000, The Case for Inductive and Visual Techniques in the Analysis of Spatial Data, *Journal of Geographical Systems* 2(1): 77-83.

Galea, E.R., *Use of Mathematical Modelling in Fire Safety Engineering*, Paper No 97/IM/25, The Fire Safety Engineering group, Centre for Numerical Modelling and Process Analysis, University of Greenwich, CMS Press : London.

Garbrecht, D., 1973, Describing Pedestrian and Car Trips by Transition Matrices, *Traffic Quarterly* 27, 89-109.

Gershenson, C., 2001, *Artificial Societies of Intelligent Agents*, Master's Thesis, Fundación Arturo Rosenblueth: Mexico.

Gimblett, H., Durnota, D. & Itami, R., 1997, *Some Practical Issues in Designing and Calibrating Artificial Human-Recreator Agents in GIS-based Simulated Worlds*, in Complex International Journal - Workshop on Comparing Reactive and Intentional Agents 3.

Gloor, C., Mauron, L. & Nagel, K., 2003, *A Pedestrian Simulation for Hiking in the Alps*, paper presented at 3rd Swiss Transport Research Conference, Monte Verita/ Ascona, March 19-21, 2003.

Gold, J. R., 1980, *An Introduction to Behavioural Geography*, Oxford University Press.

Goldstone, R. L. & Janssen, M. A., 2004, Computational Models of Collective Behavior, Trends in Cognitive Sciences, vol. 9, no. 9, Review, Elsevler.

Golledge, G. R. & Stimson, J. R., 1997, *Spatial Behavior, a Geographic Perspective*, Guilford.

Gong, J., & Lin, H., 1999, *Virtual Geographical Environments: Concept, Design, and Applications*, in Proceedings of the International Symposium on Digital Earth(ISDE), November 29 - December 2 , 1999, Beijing , China, pp: 369-375.

Goodchild, M. F., 2000, GIS and Transportation: Status and Challenges, *Geoinformatica*, 4(2), 127-139.

Gopal, S., & Smith, T.R., 1990, NAVIGATOR: An AI-based Model of Human Wayfinding in an Urban Environment, in Fischer, M.M, Nijkamp, P. & Papageorgious, Y. Y. (Eds.), *Spatial Choices and Processes*, pp: 169-200, North-Holland, Amsterdam.

Habraken, N. J., 1998, *The Structure of the Ordinary: Form and Control in the Built Environment*, Cambridge: MIT Press.

Hagerstrand, T., 1970, What About People in Regional Science? *Papers of Regional Science Association* 24: 7-21.

Haklay, M., O'Sullivan, D., & Goodwin, M. T., 2001, "So go downtowns": Simulating Pedestrian Movement in Town Centres, *Environment and Planning B: Planning and Design*, vol 28, pp :343-359.

Hankin, B. D. & Wright, R. A., 1958, Passenger Flow in Subways, *Operational Research Quarterly* 9, 81-88.

Health & Safety Executive, 2000, *Managing Crowds Safely*, HMSO.

Hearnshaw, H.M., & Unwin, D. (Eds.), 1994, *Visualization in Geographical Information Systems*, Chichester, England: John Wiley & Sons.

Helbing, D., & Molnár, P., 1995, Social Force Model for Pedestrian Dynamics, *Physical Review E*, 51: 4282–4286.

Helbing, D., & Molnar, P., 1997, Self-organization Phenomena in Pedestrian Crowds, in Schweitzer, F., *Self-Organization of Complex Structures: From Individual to Collective Dynamics*, pp. 569–577, Gordon and Breach : London.

Helbing, D., & Vicsek, T., 1999, *Optimal Self-organization*, New Journal of Physics 1, 13.1–13.17

Helbing, D., 1991, A mathematical Model for the Behavior of Pedestrians, *Behavioral Science*, 36: 298–310.

Helbing, D., 1992, A Fluid-dynamic Model for the Movement of Pedestrians, *Complex Systems* 6, 391-415.

Helbing, D., Farkas, I., & Vicsek, T., 2000, Simulating Dynamical Features of Escape Panic, *Nature* 407: 487 – 490.

Helbing, D., Molnar, P., Karkas, I.J., & Bolay, K., 2001, Self-organizing Pedestrian Movement, Environment and Planning B : Planning and Design, 28, pp. 361-383.

Helbing, D.,et al, 2002, Simulation of Pedestrian Crowds in Normal and Evacuation Situations, in Schreckenberg, M., Sharma, S. D., 2002, *Pedestrian and Evacuation Dynamics*, Springer, pp:21-58.

Henderson, L. F., 1971, The Statistics of Crowd Fluids, *Nature* 229, 381-383.

Henderson, L. F., 1974, On the Fluid Mechanics of Human Crowd Motion, *Transportation Research* 8, 509-515.

Hill, M. R., 1984, *Walking, Crossing Streets, and Choosing Pedestrian Route*, University of Nebraska Press : Lincoln, NE.

Hillier, B., & Hanson, J., 1984, *The Social Logic of Space*, Cambridge University Press : Cambridge, UK.

Hillier, B., 1998, *Describing Emergent Structure in Strongly Configurational Systems*, Requirements Engineering : Limerick.

Hillier, B., Penn, A., Hanson, J.G., & Xu, J., 1993, Natural Movement: Configuration and Attraction in Urban Pedestrian Movement, *Environment and Planning B*, Vol. 20, pp. 29-66.

Hoel, L. A., 1968, Pedestrian Travel Rates in Central Business Districts, *Traffic Engineering* 38, 10-13.

Hofstadter, D., & Dennett, D., 1981, *The Mind's I: Fantasies and Reflections on Self and Soul*, Bantam Books : New York.

Hong Kong Monthly Digest of Statistics, September Issue, 2000.

Hoogendoorn, S. P., & Bovy, P. H. L., 2000, Gas-kinetic Modelling and Simulation of Pedestrian Flows, *Transportation Research Records* 1710, 28-36.

Hoogendoorn, S. P., & Bovy, P.H. L., 2004, Pedestrian Route-Choice and Activity Scheduling Theory and Models, *Transportation Research Part B: Methodological*, vol. 38, no. 2, pp. 169-190.

Hoogendoorn, S. P., Bovy, P. H. L., & Daamen, W., 2002, Microscopic Pedestrian Wayfinding and Dynamics Modelling, in Schreckenberg, M., & Sharma, S. D. (Eds.), *Pedestrian and Evacuation Dynamics*, 123-154, Springer, Berlin.

Hughes, R.L., 2002, A Continuum Theory of Pedestrian Motion, *Transportation Research B*, 507-535.

Ibrahim, C. , 1998, *Crowds and Public Order Policing: An Analysis of Crowds and Interpretation of Their Behavior Based on Observational Studies in Turkey, England and Wales*, Gateshead : Tyne & Wear.

Jacobs, J., 1989, *The Death and Life of Great American Cities*, New York: Vintage Books.

Jahanbakhsh, B., & Patel B.G., 1977, A Method for Estimating Pedestrian Volume in a Central Business District, Pedestrian Controls, Bicycle Facilities, Driver Research, and System Safety, *Transportation Research Record* 629, Washington, DC.

Jiang, B., 1999, Simped: Simulating Pedestrian Flows in a Virtual Urban Environment, *Journal of Geographic Information and Decision Analysis*, vol. 3, no. 1, pp: 21-30.

Johnson, S., 2001, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, Simon & Schuster : New York.

Kerridge, J., Hine, J., & Wigan, M., 2001, Agent-based Modelling of Pedestrian Movements: the Questions That Need to Be Asked and Answered, *Environment and Planning B: Planning and Design* 28, pp. 327-341.

Ketchell, N., Cole, S., et. al., 1993, The EGRESS Code for Human Movement and Behaviour in Emergency Evacuations, *Engineering for Crowd Safety*, Elsevier.

Krugman, P., 1995, *Development, Geography and Economic Theory*, London : MIT press.

Kukla, R., Kerridge, J., Willis, A., & Hine, J., 2001, *PEDFLOW: Development of An Autonomous Agent Model of Pedestrian Flow*, paper presented at the 80th Annual Meeting of the Transportation Research Board, Washington, DC, January 7-11.

Kukla, R., Willis, A., & Kerridge, J., 2003, Application of Context-mediated Behavior to a Multi-agent Pedestrian Flow Model (PEDFLOW), *TRB 2003 Annual Meeting*, CD-ROM.

Kwan, M.P., & Lee, J., 2004, Geovisualization of Human Activity Patterns Using 3D GIS: A Time-Geographic Approach, in Goodchild, M.F., & Janelle, D.G.(Eds.), *Spatially Integrated Social Science*, pp.48-66, New York: Oxford University Press.

Lampert, R., 2002, *Agent-based Modeling as Organizational and Public Policy Simulators*, Proceedings of the National Academy of Sciences of the United States of America 99, pp: 7195-196.

LeBon, G., 1995, *The Crowd*, New Brunswick and London: Transaction Publishers.

Lee, D.B., 1994, Retrospective on Large-scale Urban Models, *Journal of the American Planning Associations*, 60, pp: 35-40.

Lin, H., & Gong, J., 2002, Distributed Virtual Environments for Managing Country Parks in Hong Kong -A Case Study of the Shing Mun Country Park, *Photogrammetric Engineering & Remote Sensing*, Vol. 68, No. 4, pp :369-377.

Lindemann, G., Moldt, D., & Paolucci, M. , 2002, Regulated Agent-based Social Systems, *First International Workshop, RASTA 2002*, Bologna, Italy, July 2002 Revised Selected and Invited Papers, Springer.

Livi, A. D., & Clifton, K. J. , 2004, Issues and Methods in Capturing Pedestrian Behaviors, Attitudes and Perceptions: Experiences with a Community-Based Walkability Survey, *TRB2004 Annual Meeting*, CD-ROM.

LONGLEY, P., 1998, Foundations, in Longley, P., Brooks, S.M., Mcdonnell, R., & Macmillan, B. (Eds.), *Geocomputation: A Primer*, New York : John Wiley & Sons.

Low, J.D., 2000, Following the Crowd, *Nature*, vol.407, pp:465-466.

MacEachren, A. M., & Cai, G., 2003a, Geocollaboration for Decision-making: Visual Mediation to Enable Human-system and Human-human Dialogue, *International Advanced Workshop on Virtual Geographic Environments and Geocollaboration*, The Chinese University of Hong Kong, December 15-16, 2003.

MacEachren, A. M., Brewer, I., Cai, G., & Chen, J., 2003b, Visually-Enabled Geocollaboration to Support Data Exploration and Decision-Making, International Cartographic Conference, Durban, South Africa, August 10-16, 2003a.

MacEachren, A.M., & Brewer, I., 2004, Developing a Conceptual Framework for Visually-Enabled Geocollaboration, *International Journal of Geographic Information Science*, vol.18, no.1, pp: 1-34.

MacEachren, A.M., & Kraak, M. J., 2001, Research Challenges in Geovisualization, *Cartography and Geographic Information Science*, 28 (1): 3-12.

MacEachren, A.M., Wachowicz, M., Edsall, R., & Haug, D., 1999, Constructing Knowledge from Multivariate Spatiotemporal Data: Integrating Geographical Visualization and Knowledge Discovery in Database Methods, *International Journal of Geographical Information Science*, 13(4): 311-334.

MacGregor, S. J., 1991, State-dependent Queueing Models in Emergency Evacuation Networks, *Transportation Research Part B: Methodological* 25: 373-389.

March, J., 1994, *A Primer on Decision Making: How Decisions Happen*, New York : Free Press.

Mark, D. (Ed.), 1999, *NSF Workshop Report -- Geographic Information Science: Critical Issues in an Emerging Cross-disciplinary Research Domain*, Washington, DC: NSF.

Mark, D. M., & Gold, M. D., 1991, Interacting with Geographic Information: A Commentary, *Photogrammetric Engineering & Remote Sensing*, 57(11) : 1427-1430.

Mayne, A. J., 1954, Some Further Results in the Theory of Pedestrian and Road Traffic, *Biometrika* 41, pp. 375-389.

McFarland, D., 1981, *The Oxford Companion to Animal Behavior*, Cambridge: Oxford University Press.

Molnar, P., 1996, Microsimulation of Pedestrian Dynamics, in Doran, J., Gilbert, N., Mueller, U., & Troitzsch, K. (Eds.), *Social Science : Microsimulation*, Berlin : Springer.

Montello, D.R., 2001, Spatial Cognition, in Smelser, N. J., & Baltes, P.B.(Eds.), *International Encyclopedia of the Social and Behavioral Science*, pp: 14771-14775, Oxford: Pergamon Press.

Moulin, B. et el, 2003, Multi-agent Geosimulation and Crowd Simulation, in *Spatial Information Theory: Foundations of Geographic Information Science, International Conference, COSIT 2003*, pp :151-168.

Muntz, R. R., Barclay, T., Dozier, J., Faloutsos, C., MacEachren, A. M., Martin, J. L., Pancake, C. M., & Satyanarayanan, M., 2003, *IT Roadmap to a Geospatial Future, Report of the Committee on Intersections Between Geospatial Information and Information Technology*, Washington, DC: National Academies Press.

Muramatsu, M., & Nagatani, T., 2000, Jamming Transition in Two-dimensional Pedestrian Traffic, *Physica A* 275, 281-291.

Navin, P. D., & Wheeler, R. J., 1969, Pedestrian Flow Characteristics, *Traffic Engineering* 39, 31-36.

Ness, M.P., Morrall, J.F., & Hutchinson, B.G., 1969, An Analysis of Central Business District Pedestrian Circulation Patterns, *Highway Research Record* 283, 1969.

O'Flaherty, C. A. and Parkinson, M. H., 1972, Movement on a City Centre Footway, *Traffic Engineering & Control* 13, 434-438.

Okazaki, S., & Matsushita, S., 1993, A Study of Simulation Model for Pedestrian. Movement with Evacuation and Queueing, in *Proceedings of the International. Conference on Engineering for Crowd Safety*, pp. 271-280.

Oviatt, S.L., Cohen, P., Vergo, J., Duncan, L., Suhn, B., Bers, J., Holzman, T., Winograd, T., Landay, J., Larson, J., and Ferro, D., 2000, Designing the User Interface for Multimodal Speech and Pen-based Gesture Applications: State-of-the-Art Systems and Future Research Directions, *Human Computer Interaction* 15,4, pp :263-322.

Paulsen, T. et el, 1995, Evaluation of Simulation Models of Evacuation from Complex Spaces, *SINTEF Report* STf75 A95020, June 1995.

Peuquet, D. J., 2002, *Representations of Space and Time*, New York : Guilford Press.

Polus, A., Schofer, J.L., & Ushpiz, A., 1983, Pedestrian Flow and Level of Service, *Journal of Transportation Engineering* 109, pp. 46–57.

Pushkarev B., & Zupan J. M., 1975, Urban Space for Pedestrians, MIT Press : Cambridge, MA.

Pushkarev, B., & Zupan, J.M., 1975, Capacity of Walkways, *Transportation Resource Record* 538, 1–15.

Quarantelli, E. L., 2001, Sociology of Panic, in *International Encyclopedia of the Social & Behavioral Sciences*, Elsevier Science.

Raper, J., & Livingstone, D., 1995, Development of a Geomorphological Spatial Model Using Object-Oriented Design, *International Journal of Geographical Information Systems* 9(4): 359-383.

Reicher, S. D., 1984, The St. Paul's Riot: an Explanation of the Limits of Crowd Action in Terms of a Social Identity Model, *European Journal of Social Psychology*, vol. 14: 1-21.

Resnick, M., 1994, *Turtles, Termites and Traffic Jams: Explorations in Massively Parallel Microworlds*, Cambridge: MIT

Reynolds, C. W., 1987, Flocks, Herds and Schools: a Distributed Behavioral Model, *Computer Graphics*, 21(4) : 25- 34.

Reynolds, C. W., 1999, *Steering Behavior for Autonomous Characters*, Paper Presented at the 1999 Game Developers Conference.

Reynolds, C. W., *Computational Models of Complex, Life-like Behavior*, http://www.red3d.com/cwr/, Access on 2006/05/06.

Roy, J. R., 1992, Queueing in Spatially Dispersed Public Facilities, presented at the *IV World Congress of the Regional Science Association Internation*, Palma de Mallorca.

Rubin, P., Vatikiotis-Bateson, E., & Benoit, C. (Eds.), 1998, Audio-visual Speech Processing, *Speech Communication* 26, 1–2.

Schelhorn, T., O'Sullivan, D., Haklay, M., & Thurstain-Goodwin, M., 1999, *STREETS: an Agent-based Pedestrian Model*, presented at Computers in Urban Planning and Urban Management, Venice, 8-10 September.

Schreckenberg, M., & Sharma, S. D. (Eds.), 2002, *Pedestrian and Evacuation Dyanmics*, Springer.

Schultz, D. (Ed.), 1964, *Panic Behavior: Discussion and Readings*, Random House : New-York.

Selim, S.Z., & Al-Rabeh, A.H., 1991, On the Modeling of Pedestrian Flow on the Jamarat Bridge, *Transportation Science* 25, 257–262.

Sheppard, S.R.J., 1999, Visualization Software Bring GIS Applications to Life, *GeoWorld* 12(3): 36-37.

Simon , H., 1987, *Giving the Soft Sciences a Hard Sell*, Boston Globe.

Smith, R.A., 1993, Volume Flow Rates of Densely Packed Crowds. In: Smith, R.A., Dickie, J.F. (Eds.), *Engineering for Crowd Safety*, pp. 313–319, Amsterdam : Elsevier.

Society of Fire Protection Engineers, 2002, *Engineering Guide to Human Behavior in Fire, Technical Report 2002*, available at http://www.sfpe.org/sfpe/pdfsanddocs/DraftHumanBehaviorGuide.pdf

Stadia & Arenas 2000, *Stadia and Arenas: Development, Design and Management*, 16-17th June 1999, London Arena, The Concrete Society.

Still, G.K., 2000, *Crowd Dynamics*, Ph.D Thesis, University of Warwick, August 2000.

Surti, V.H., & Burke, T.J., 1971, Investigation of the Capacity of the White House Sidewalk for Orderly Demonstrations, *Highway Res. Rec.* 355, 1625.

Tanaka, T., 1991, A Study for Performance Based Design of Means of Escape in Fire, in Cox, G., Langford, B. (Eds.), *Fire Safety Science – Proceedings of the 3rd International Symposium*, pp. 729–738, Amsterdam : Elsevier.

The Government of Hong Kong, 1951, *Hong Kong Annual Report 1950*, pp :19-101.

The Green Guide (Fourth Edition), 1997, *Guide to Safety at Sports Grounds*, HMSO London.

Therakomen, P., 2001, Mouse.class, *The Experiments for Exploring Dynamic Behaviors in Urban Places*, Master Thesis of Architecture, University of Washington.

Torrens, P.M., 2001, Can Geocomputation Save Urban Simulation? Throw Some Agents in the Mixture, Simmer and Wait…, *CASA Working Paper Series*, Paper 32, University College London : London.

Toshiyuki, A., 1993, Prediction System of Passenger Flow, in Smith, R.A., Dickie, J.F. (Eds.), *Engineering for Crowd Safety*, Amsterdam : Elsevier, pp. 249–258.

TRANSIMS website, http://www-transims.tsasa.lanl.gov/.

Transport Department, 1999, *Third Comprehensive Transport Study: Final Report*, Hong Kong: Transport Department, Hong Kong SAR Government.

Tufte, E.R., 1990, *Envisioning Information*, Cheshire, Connecticut: Graphics Press.

Tufte, E.R., 1997, *Visual Explanations: Images and Quantities, Evidence and Narrative*, Cheshire, Connecticut: Graphics Press.

Turner, A. et al, 2001, From Isovists to Visibility Graphs: a Methodology for the Analysis of Architectural Space, *Environment and Planning B: Planning and Design*, vol 28, pp : 103-121.

USA Department of Defence, *2003, Crowd Management Information* , USA DoD Crowd Control, via www.crowddynamics.com/main/crowd%20control.htm

Van-Driel, N., 1989, Three Dimensional Display of Geologic Data, in Raper, J., *Three Dimensional Applications in GIS*, London : Taylor & Francis.

Waldrop, M., 1992, *Complexity: The Emerging Science at the Edge of Chaos*, New York: Simon & Schuster.

Wigan, M.R., 1993, Why Should We Worry About Pedestrians? in *CAITR Paper : 15th Conference of Australian Institutes of Transport Research,* Transport Research Centre, University of Melbourne, December 10 1993.

Wood, D., 1992, *The Power of Maps*, New York : The Guildford Press.

Wooldridge, M., 2002, Intelligent Agents: The Key Concepts, *Multi-Agent Systems and Applications II*, pp :3-43.

Yu, H., & Shaw, S.L., 2004, Representing and Visualizing Travel Diary Data: A Spatio-Temporal GIS Approach, paper 1258, *ESRI User Conference 2004*.

Yuhaski, S. J. Jr., & Smith, J. M.M, 1989, Modeling Circulation Systems in Buildings Using State Dependent Queueing Models, *Queueing Systems* 4, 319-338.

Zhang, Z., & Zhang, C., 2003, *Agent-based Hybrid Intelligent Systems, An Agent-Based Framework for Complex Problem Solving*, Springer.

## APPENDIX:

Roads With Names in TST