Towards an Integrated Pedestrian Thermal Comfort Assessment System: An Agent-Based Approach

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Abstract

Pedestrians are important to sustainable cities. How to make outdoor spaces attractive to pedestrians has long been a primary concern in urban planning and design. The outdoor microclimate is found to be an important factor in affecting pedestrian's behaviors, i.e. space use. One key issue in this respect, is to evaluate the impact of the microclimate on pedestrian's thermal comfort condition. An effective tool that allows detailed investigation of pedestrian's thermal comfort and also provides implications of space use is in great need.

Effective assessment of pedestrian's thermal comfort is both a research challenge and a practical crux. Traditional bio-meteorological indicators such as PMV are only suitable for steady state subjects therefore will normally result in discrepancies when applied to transient conditions. Evaluation methodologies are also absent in the behavioral aspects: pedestrian traffic is always directed by certain activities, suggesting that their thermal comfort assessment should bear considerations of pedestrian's behaviors in order to provide pertinent planning implications.

The thesis establishes a conceptual framework for "context-sensitive" assessment on the meso-scale, and proposes to link the assessment of pedestrian's thermal comfort condition to the comprehensive urban context and therefore their activities. An integrated system is implemented with a comprehensive representation of the urban environment. A promising modeling technique, the agent-based modeling approach is taken to overcome the limitations imposed by traditional top-down models. The agent-based model simulates pedestrian's behaviors from the disaggregated scale, allowing detailed investigations of individual pedestrian's dynamic thermal comfort conditions. By examining system behavior emerged from

the interactions of different individuals, implications for planning could also be revealed on the aggregated scale. With support of geographical information system, the system could be applied in real world context with complex urban environment. A detailed case study using a downtown area in Hong Kong as an example is explored to demonstrate the advantage of the agent-based modeling approach.

Through the case study, it is found that the presented agent-based simulation system can bring dynamic and behavioral understandings in investigating pedestrian's thermal comfort, which are more relevant in outdoor space planning but is not possible using traditional thermal comfort assessment methods. This suggests that the agent-based modeling approach is a good complement to traditional static and aggregated methods.

To sum up, the thesis work has significance from conceptual, technical and practical perspectives in terms of developing a spatial decision support tool. Conceptually, the thesis identifies the need for "context-sensitive" assessment in investigating pedestrian's thermal comfort, and adopts the agent-based modeling paradigm to account for pedestrian's dynamic and individualized features. Technically, an integrated GIS-based computational system is implemented to simulate pedestrian movement and assess pedestrian's thermal comfort from both static and dynamic aspects. Practically, the system can be applied in real world context and provide implications in urban design.

摘要

行人對於城市的可持續發展至關重要。如何創造行人喜愛的室外空間一直以來都是城市規劃和設計首要關注的問題。研究表明，室外的微觀氣候是影響行人活動和空間利用的一個重要因素。與之相關的一個核心問題是如何評估微觀氣候對行人的人體熱舒適度的影響。在此形勢下，城市規劃和研究人員迫切需要一種有效的工具來細緻地研究行人的人體熱舒適度和隨之帶來的空間利用的影響。

有效地對行人的人體熱舒適度進行評估具有理論和實踐的雙重挑戰。傳統採用的生物氣象學指示因子，如*預測平均投票*（PMV）僅適用於穩定狀態，所以當應用在短暫的動態評估中通常會產生錯誤。同時，這些評估方法也沒有考慮人的行爲因素：行人流通常都是由行人活動導向的，這表示在城市規劃的意義上，行人的人體熱舒適度評估需要考慮行人活動以便給出更加中肯的規劃建議。

本論文創建了一個應用於中維尺度的“環境相關”評估的理論框架，并建議將行人的人體熱舒適度評估與其所處的全面的城市環境及其活動聯繫起來。本研究實現了一個綜合的計算機模擬系統，包括了全面的城市環境信息的表達，并採用了一個應用前景廣闊的模擬方法——多智能體模擬的方式來克服傳統的自上而下的建模方法所帶來的局限。這個多智能體模型從個體的維度對行人的活動進行模擬，從而實現了對行人動態的熱舒適度情況的詳細分析與評估。該系統也可以通過分析大量個體所形成的行爲模式，而從全局尺度上給出規劃建議。該系統支持了*地理信息系統*（GIS），所以可以應用於現實世界中複雜的城市環境。本研究以香港市區中心爲例，進行了一個詳細的個案研究，來探索多智能體模擬方法在評估行人的人體熱舒適度方面的優勢。

通過個案研究，本論文證明了多智能體模擬可以在行人的人體熱舒適度評估中引入動態和行爲的考量，因此對於城市室外空間規劃具有更相關的意義，而這

些因素是傳統的方法所不具備的。本研究顯示了多智能體模擬的方法是傳統的靜態和全局的分析方法的一個重要補充。

綜上所訴，本論文對於*空間決策支持系統*（SDSS）的開發具有理論、技術和應用等三方面的重要意義。理論上，本論文指出了“環境相關”評估的重要性，并採用了多智能體模擬的方法來考量行人的動態和個體的特性。技術上，本論文實現了一個基於地理信息系統的綜合計算機系統，來模擬行人的活動，并從靜態和動態兩方面對行人的人體熱舒適度進行評估。應用上，本系統可以應用於現實世界的城市環境中，並給出規劃建議。

Publications

Peer-reviewed journal papers

- **Chen, L.**, Ng, E. and et al. (2011) Sky view factor analysis of street canyons and its implications for intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach. *International Journal of Climatology, 31*(5), doi: 10.1002/joc.2243.
- **Chen, L.**, and Ng, E. (2011) Quantitative urban climate mapping based on a geographical database: a simulation approach using Hong Kong as a case study. *International Journal of Applied Earth Observation and Geoinformation, 13*(4), 586-594.
- **Chen, L.**, and Ng, E. Urban pedestrians, outdoor thermal comfort and outdoor activities: A review of the literature. *Cities*, under review.
- **Chen, L.** Agent-based modeling: a brief literature review. *International Journal of Simulation Modelling*, under review.

Conference papers

- **Chen, L.**, and Ng, E. (2011) PedNaTAS: An integrated multi-agent based pedestrian thermal comfort assessment system. Paper to be presented at CAAD Futures 2011, July 4 – 8, 2011, Liège, Belgium.
- **Chen, L.**, and Ng, E. (2011) Urban morphology modeling using a 3-D geo-database: simulation and implications for Hong Kong. Paper to be presented at the 18th International Seminar on Urban Form (ISUF2011), August 26 – 29, 2011, Montréal, Canada.
- **Chen, L.**, and Ng, E. (2011) Context-sensitive pedestrian thermal comfort assessment: towards an integrated multi-agent simulation system. Paper submitted to ACADIA 2011 (Association for Computer Aided Design in Architecture), Oct. 11 – 16, 2011, Calgary, Canada.
- **Chen, L.**, and Ng, E. (2011) An agent-based simulation approach to urban morphology analysis. Paper to be presented at the 28th International Symposium on Automation and Robotics in Construction (ISARC 2011), June 29 – July 2, Seoul, Korea.
- **Chen, L.**, An, X. and Ng, E. (2010) Towards the use of a 3-D geo-database in investigating nocturnal urban temperature variation in Hong Kong. Paper presented at the First International Conference on Sustainable Urbanization (ICSU 2010), December 15 – 17, 2010, Hong Kong.
- **Chen, L.** and Ng, E. (2009) Sky view factor analysis of street canyons and its

implication for urban heat island intensity: a GIS-based methodology applied in Hong Kong (**Shortlisted for best paper award**). Paper presented at the 26th Conference on Passive and Low Energy Architecture (PLEA2009), June 21 – 24, 2009, Quebec, Canada.

Table of Contents

List of figures

List of Tables

Chapter 1 Introduction

1.1 Introduction to the Research

"First we shape the cities – then they shape us."

–Jan Gehl, "Cities for People"

People make cities. Today more than half of the world's population live in cities (Population Reference Bureau, 2009), and this number is yet anticipated to reach 4.9 billion by the year of 2030, which is equivalent to 60% of the global population (UNFPA, 2007). There is no doubt that we are faced with the inevitable future of high-density urban living. Under such circumstances, how the downtown livability and vitality can be maintained and ultimately improved with a yet increasingly degrading physical environment, will continue to be a key challenge that has to be confronted and requires constant endeavors in future urban planning and design. More sustainable and lively cities, with downtowns as more desirable places to visit and live, are the ultimate goal for cities of tomorrow.

1.1.1 Urban Climate and Downtown Outdoor Thermal Comfort

A direct consequence of the dramatic urbanization is the commonly observed urban heat island (UHI) phenomenon. As illustrated in the well-known UHI profile shown in Figure 1.1, the downtown area normally has a much higher temperature than the surrounding rural area, indicating that the downtown heat stress can be quite severe. This makes downtown areas particularly vulnerable to abrupt climate changes, such as heat wave. For example, it has been found that high heat stress will increase the rate in mortality under extreme conditions (Leung, Yip, & Yeung, 2008; Martens, 1998; Smoyer, Rainham, & Hewko, 2000).

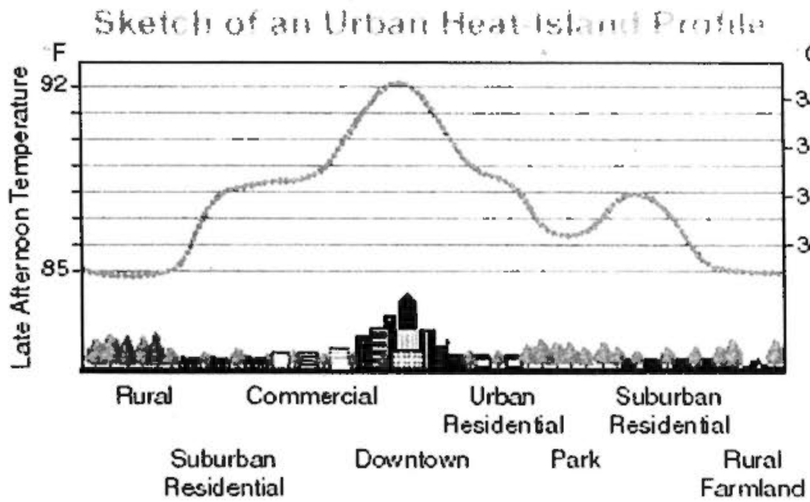


Figure 1.1 Sketch of urban heat island profile. After Heat Island Group: (http://eetd.lbl.gov/HeatIsland/).

The daily urban life is also greatly affected by the urban climate. For example, Jan Gehl, known as one of the first designers who studied the influence of microclimate on people's outdoor activities and emphasized the consideration of people's interaction with the built environment in design and planning, found that for the 8 selected streets in the city of Copenhagen, the pedestrian densities in summer were twice as high as the densities in winter; in particular, for the case of the street of Nyhavn, the difference was even 8 times (Jan Gehl & Gemzøe, 2004). This shows that, the climatic condition of outdoor urban environment will have a great impact on people's thermal comfort and therefore outdoor activity. Indeed, as stated in the report by the Committee of the American Society of Civil Engineers: "The presence or lack of direct sunlight experienced by a pedestrian can have a significant effect on thermal comfort..., The usefulness and attractiveness of outdoor areas near buildings are greatly affected by the local climate." (Task Committee on Outdoor Human Comfort of the Aerodynamics, 2004, p.35) Amongst the various factors that determine the outdoor urban climate, direct sunshine and high temperature are found to be the most significant environmental stressors (Fanger, 1982; Mayer & Höppe, 1987). Effectively, shading is considered very important in avoiding discomfort and promoting outdoor space use (Steemers, Ramos, & Sinou, 2004).

Mayer et al. (2008) has addressed the need for high spatial and temporal resolution information about human thermal comfort in city planning application. To obtain this information will require effective assessment of outdoor thermal comfort based on detailed microclimatic conditions. There are two main problems of this issue. Firstly, different aspects of the local microclimate need to be combined to evaluate human comfort due to the complicated nature of human thermoregulation. As pointed out by Thorsson et al. (2010): "Climate change is often discussed in terms of changes in air temperature, cloud, wind, etc., i.e. as trends in either averages or extremes. However, in order to evaluate its impact on people's thermal perception, health and wellbeing, it is necessary to analyze their combined effect." Secondly, people outdoor are not static and standardized subjects, but diverse individuals conducting various activities. This means that outdoor thermal comfort should be assessed with respect to people's dynamic status and also their space use in order to provide useful implications for developing outdoor space planning policies that encourage pedestrian travel. The first problem, which is static and objective, how ever difficult, will be solved or at least framed by the integration of different domain knowledge, be it meteorological, climatological or physiological. On the other hand, the second problem, which is dynamic and subjective, by far still lacks well developed or commonly accepted methodologies for assessment, and remains a key challenge in terms of both research and planning application. Commonly adapted bio-meteorological indicators for thermal comfort assessment, such as the *Predicted Mean Vote* (PMV) or the *Predicted Percentage of Dissatisfied* (PPD) (Fanger, 1982; ISO, 1994), only work for steady state subjects and don't take into account people's individual activity and subjective response, and therefore have been shown to be unsuitable for this task (Höppe, 2002; M. Nikolopoulou, Baker, & Steemers, 2001; Sofia Thorsson, Lindqvist, & Lindqvist, 2004). In such a case, a more relevant question to ask is, will the outdoor spaces with advantageous local climatic conditions be necessarily favored and utilized by pedestrians? To answer this question, the assessment of outdoor thermal comfort should be put in a "context sensitive" manner, meaning that the context of the assessment, including both the urban form and climatic condition, and also pedestrian's activity and usage of outdoor space, need all to be considered in order for the assessment to be effective.

1.1.2 Thermal Comfort Assessment in a Comprehensive Context

Alexander has captured urban design in an exemplar "five way conflicts" problem. As he put it:

> "*We cannot decide whether a misfit has occurred either by looking at the form alone, or by looking at the context alone. Misfit is a condition of the ensemble as a whole, which comes from the unsatisfactory reaction of the form and context.*" (Alexander, 1964, p.96)

Indeed urban design is essentially decision making process based on synergetic knowledge. Climatic design is no exception, i.e. the knowledge basis directing the decision making should also bear a mixture of concerns: climatological, social, economic, etc. For example, Jan Gehl has emphasized climatic concerns in outdoor space design, but he also found that the street of Strøget in Copenhagen, though only 11m wide and normally with harsh insolation in summer afternoons, turned out to be the densest street in the city in summer (Jan Gehl & Gemzøe, 2004). This implies that, the planning of pedestrian's comfort should be put in a comprehensive context beyond the mere scope of local microclimate in order to be effective. Ratti and Riches (1999) have described the spatial aspect of this comprehensiveness as "medium-scale" urban design support (different scales of the urban environment with respects to the urban climate is shown in Figure 1.2), and this view has been extensively discussed in (Ratti, 2001). In contrast, only limited concern has been addressed against the non-spatial, behavioral aspects, such as the social mobility propensities.

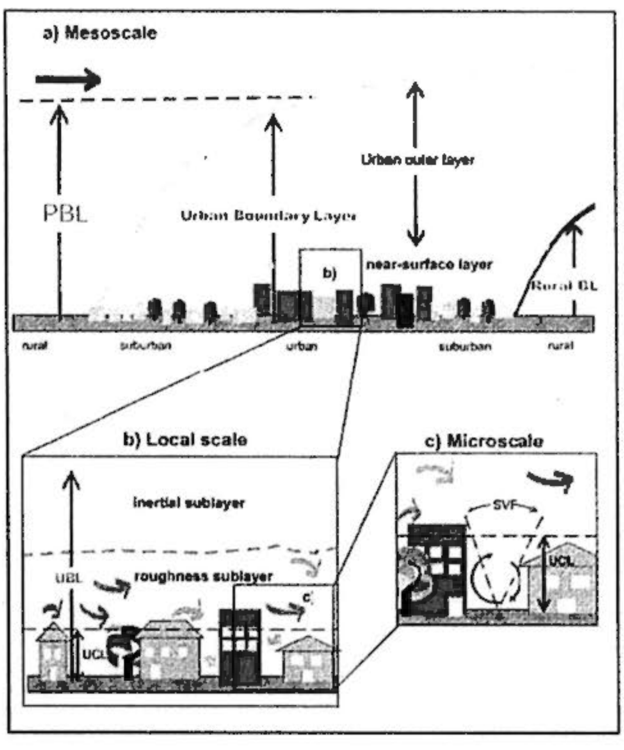


Figure 1.2 Sketch of the urban boundary layer structure indicating the various (sub)layers and their names. After (Rotach, et al., 2005), original sketch by (Oke, 1987).

For the specific issue of pedestrian thermal comfort assessment, the connection between *comfort* and *flow* is crucial, and this connection straightforwardly lends itself to the behavioral approach. As pointed out by the UK Ministry of Transport back in as early as 1961: "Vehicles do not move about the roads for mysterious reasons of their own. They move only because people want them to move in connection with activities which they (the people) are engaged in. Traffic is therefore a function of activities. This is fundamental."(Ministry of Transport, 1961) In this sense, pedestrian traffic flow is no different from vehicle traffic. Pedestrian activity will have a direct impact on their outdoor space usage pattern, and therefore should be given significant consideration with regards to pedestrian thermal comfort assessment and in climatic design process. On the other hand, methodologies and frameworks along this line are yet to be discussed in any great depth.

1.1.3 The Simulation Approach

Computer simulation is described as "a third way of doing science" in contrast to the induction and deduction approaches (Axelrod, 1997a). An illustration situating simulation among other approaches to investigating systems is shown in Figure 1.3. In the context of investigating the urban systems, by reconstructing and characterizing the urban environment in the silicon surrogate, computer simulation allows questions, always in the form of "what-if", which are difficult to be tested in the real world, if possible at all, to be asked and better yet answered (Simpson, 2001). The vast literature of applications range from primitive attempts such as the visualization of urban view, as introduced in the "Cities in Laboratory" model by (Peter Bosselmann, 1998), to sophisticated objectives such as design solution generating and urban structure reasoning, as has extensively publicized in the text books by (Batty, 2005; Kalay, 2004), etc. In particular, the constantly updated blog *Digital Urban* (http://www.digitalurban.blogspot.com/) by Dr. Andrew Hudson-Smith archives a quite up to date selection of worldwide state-of-the-art virtual city models.

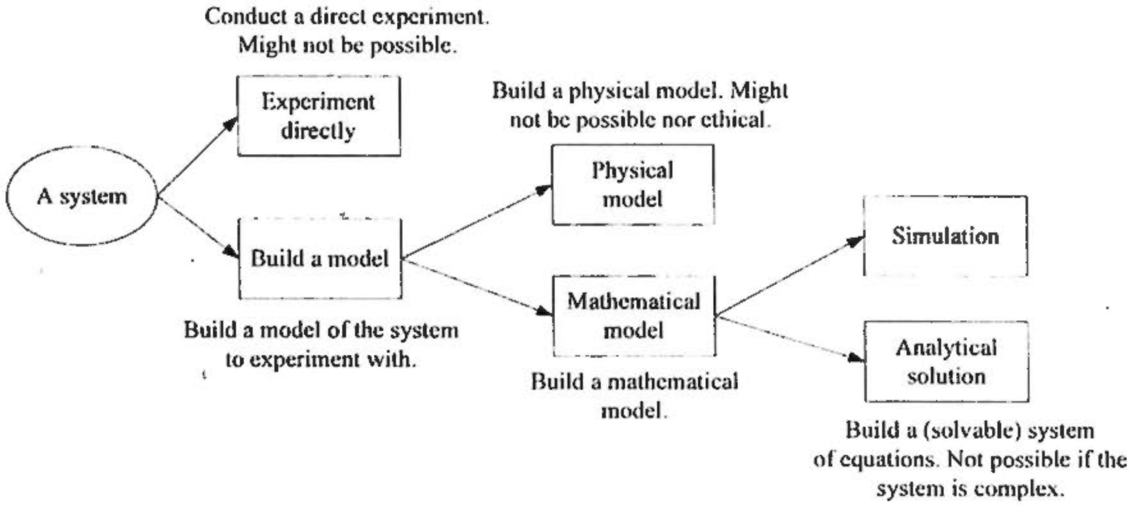


Figure 1.3 Situating the simulation approach among other approaches to investigating systems. Modified after (Law & Kelton, 2000)

Emergent Behavior and Geo-simulation

As delineated in the previous 2 sections, the accounting for pedestrians' global flow pattern based on their individual characteristics is critical in building the connection between individual thermal comfort assessment and outdoor space use. This feature could be captured by the concept of "*emergence*", which means that the global patterns that result from their interactions cannot be understood by examining the rules which govern a single unit in isolation (Darley, 1994; Mihata, 1997). In such a case, effective simulation of pedestrian behavior is a key research challenge.

Geo-simulation (Itzhak Benenson & Torrens, 2004), in this aspect, is a simulation approach that is expected to fulfill the task. This individual-based, or so called *object-based* modeling paradigm, investigates the collective dynamics of interacting objects, so is particularly suitable for characterizing spatially explicit processes or relationships (as shown in Figure 1.4). It has found its broad use in spatial analysis in urban studies (De Smith, Goodchild, & Longley, 2007; Torrens, 2006).

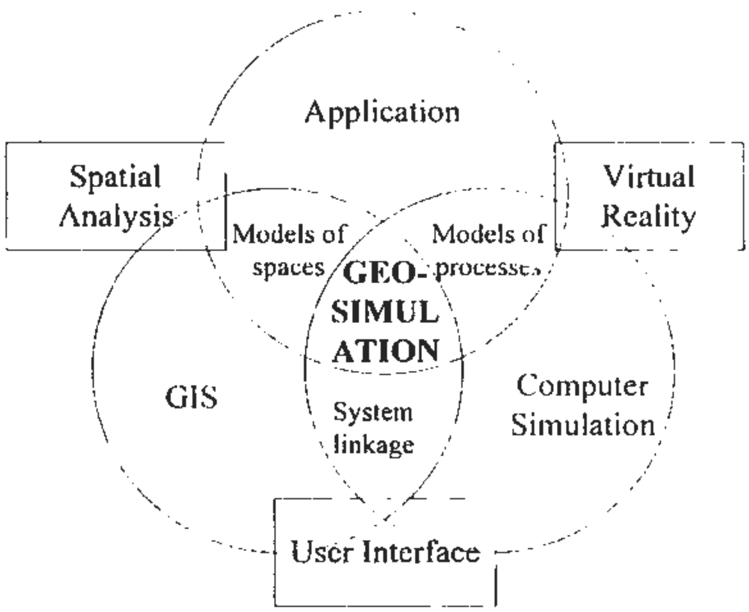


Figure 1.4 The field of Geo-simulation within an interdisciplinary context. Modified after (Mandl, 2000).

Towards a Spatial Decision Support System (SDSS)

Simon (1977) has summarized the various characteristics of spatial decision making, amongst which the 4 most relevant ones are: 1) a large number of decision alternatives; 2) spatial variables as outcome; 3) multiple-criteria evaluation; 4) both qualitative and quantitative evaluation. To address these concerns, Densham (1991) has proposed a 5-componet SDSS framework by adopting Sprague's (1980) development strategy. The architecture of the system is shown in Figure 1.5.

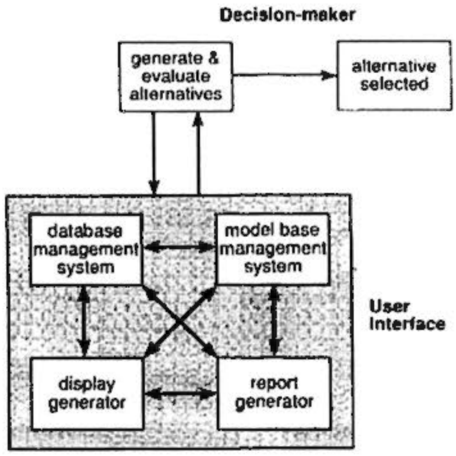


Figure 1.5 A proposed architecture for a SDSS. After (Densham, 1991). Figure original published in (Armstrong, Densham, & Rushton, 1986).

According to Densham, a typical SDSS should have 5 major components: 1) a geographical/spatial database management system; 2) a model base management system as analytical tools; 3) and 4) display and report generators as statistical and result representation tools; and 5) a user interface to provide access to the database and the other components such as display. The user carries out "what-if" scenario testing through the user interface, and evaluates different design alternatives. In this way these 5 components collaborate as a decision making support model.

In the context of investigating pedestrian thermal comfort from a behavioral aspect, very little research has actually attempted to take the simulation approach and develop a SDSS with the aforementioned framework. The BOTworld system (M.

Bruse, 2007) is to the author's knowledge by far the only computer tool developed along this line of research. Moreover, BOTworld is under continuous development so is only available for internal use (personal communication). In such a case, an integrated simulation system with a comprehensive urban context and extensive support of geographical database, is yet to be developed.

1.2 Research Objectives

This thesis presents the PedNaTAS (**Pede**strian **Na**vigation Thermal Assessment System) system. It is a prototypical SDSS for pedestrian thermal assessment in their walking activity. PedNaTAS is a GIS (geographical information system) – based integrated simulation system that takes a bottom-up modeling approach, the so called agent-based modeling approach, in characterizing pedestrians' thermal comfort condition. The main objective of this research is to develop a "context-sensitive" framework for outdoor thermal comfort assessment, which is to link the local microclimatic condition to pedestrians' behavior pattern directed by the comprehensive urban context. The system is aimed to support climatic planning decision making in the meso-scale. In order to achieve this goal, the sub-objectives of the research are formalized as:

1. Review and discuss methodologies for outdoor thermal comfort assessment from the behavioral aspects;
2. Review and discuss the agent based modeling paradigm and its applications in investigating complex systems and processes;
3. Design and implement an agent-based microscopic pedestrian simulation system;
4. Implement a comprehensive representation of the urban context in connection

with the system in 3., with extensive support of GIS database;

5. Integrate different urban climate modeling modules into the system;
6. Implement pedestrian thermal assessment model, with focus on evaluating the dynamic and transient state;
7. Apply the model to real world scenarios to test its applicability and effectiveness.

1.3 Organization of the Dissertation

The dissertation is organized as follows:

Chapter 2 conducts a broad review of related literature in the scope defined by the present research. Section 2.1 introduces the importance of pedestrians to cities and the need for planning for better downtown environment to encourage walking. Section 2.2 reviews methodologies and approaches for outdoor thermal comfort evaluation from the behavioral aspects and their implications in outdoor space planning, and identifies the need for predicting tools in climatic planning. Section 2.3 reviews the general context of agent-based modeling research, covering its applications and development platforms. Section 2.4 reviews related research work in the agent-based pedestrian simulation domain.

Chapter 3 presents the design and implementation of the PedNaTAS system. Section 3.1 and Section 3.2 describe the software framework of the system. Section 3.3, which is the most important part of this dissertation, presents the design and implementation of the agent-based pedestrian simulation system, and verification of the system. Section 3.4 presents the implementation of the pedestrian thermal comfort assessment module, which implements both steady stated and dynamic, non-steady state assessment methods. Section 3.5 presents the methodologies of how to implement this system within a GIS framework.

Chapter 4 presents how the PedNaTAS system is applied in real world context. Section 4.1 describes the study site. Section 4.2 introduces the urban environment modeling methodologies and the validation of the modeling results, and also the modeling of pedestrian attributes. Section 4.3 carries out pedestrian thermal comfort assessment using the system, with both steady and dynamic assessments conducted.

The final chapter, Chapter 5, draws concluding remarks about the research. It summarizes the significance and contribution of the research, and also discusses the drawbacks and limitations of the research. Finally, possible future work based on the present research is also recommended.

Chapter 2 Literature Review

2.1 Pedestrian's Importance for Cities

2.1.1 Pedestrians Account for a Significant Part of Urban Traffic

Pedestrians are an important component of urban traffic and also urban activities. Almost all journeys involve walking, even for automobile commuters. In the UK, nearly a quarter (23%) of all trips are made on foot and walking also accounts for 76% of all trips that are shorter than 1.6 km (Department for Transport, 2007). In the US, according to the 2001 National Household Travel Survey (NHTS), 8.7% of all trips are made on foot nationwide, and this number is up to 11% in major US cities (Pat S. Hu & Reuscher, 2001). In the centers of large cities, the overwhelming vehicular traffic has made the streets always congested, and the densely built-up constructions leave little parking space for car commuters. All of these factors have together shifted a great part of urban traffic towards public transport and, walking. Taking the city of London as an example, TfL (Transport for London) 2006 statistics shows that in a typical morning peak, around 90% of people entering central London used public transport. Walking accounts for an essential part of these trips as many people need to walk from or towards public transport connection points. Similar figures could be found for most large cities around the world (New York, Barcelona, Melbourne, etc.). For the case of Hong Kong, according to Transport Department's 2008 survey, the railway and public buses together carried a total number of 8 million passengers per day, so one can easily imagine how much walking takes place in downtown area.

2.1.2 Pedestrians Can Benefit Cities

Walking is arguably the most sustainable form of traveling and can benefit cities from various aspects. Walking has long been regarded as an efficient and powerful tool which can help people improve fitness and lead a healthy lifestyle. The impression is recently reinforced by public health research suggesting that regular physical activity can reduce the chance of obesity, prevent many chronic diseases such as cardiovascular disease and cancer, and promote people's health (Dugdill, Crone, & Murphy, 2009; Hakim, et al., 1998; Wilcox, Parra-Medina, Thompson-Robinson, & Will, 2001). Walking also has much less external environmental impacts than motorized travel. The most significant environmental benefit is that walking can replace car traffic and reduce air pollution to a great extent. In particular, studies show that short car journeys less than two kilometers contribute disproportionately higher to air pollution, since engines and catalytic converters do not work effectively while still cold (Mayor of London, 2004). Walking is an ideal substitute for car trips of this kind. Besides, it can also reduce energy use and CO_2 emission and contribute towards a better environment.

Increasingly, walking has been recognized as a critical element of social activity than just a means of travel. Pedestrian activities are expected to enhance neighborhood interaction, vitalize streets, strengthen local community and promote social inclusion (J. Jacobs, 1972; Whyte, 1988). It is also directly linked to the prosperity of commercial districts: retail and entertainment sectors are keen to locate in places where people like to visit (Hass-Klau, 1993; Whitehead, Simmonds, & Preston, 2006). For the example of London, according to TfL's survey, over 26 million visitors traveled to London in 2006 and 90% of them had used public transport or walked. These visitors spent a total amount of around £10 billion during their visits. The number reflects vividly how viable and attractive streets boost the local economy. Another social benefit of walking, as has long been advocated by crime fighters, is that encouraging more people on the street can lead to a virtuous street neighborhood where crimes such as burglary or mugging can be much reduced (J. Jacobs, 1972; Newman, 1976).

2.1.3 Declining Trend in Walking

Despite the physical, environmental, social and many other benefits associated with walking, there is an overall declining trend of walking activity. In the UK, the total distance walked per person per year fell by 22% from 392 km on average in 1985-86 to 305 km in 1999-2001 (Office for National Statistics, N/A); moreover, the average number of walking trips has fallen by nearly a quarter in the past two decades (Department for Transport, 2008). This is not an isolated example. The US Nationwide Personal Transportation Survey (NPTS) has reported that the average number of trips made on foot had dropped by 21% from 1977 to 1995 in America (Patricia S. Hu & Young, 1995); in particular, according to the report by the Center for Disease Control and Prevention (CDC), only 13% of children walk or cycle to school today (Centers for Disease Control and Prevention, N/A), which is a dramatic decline compared with 1969's statistics when this number was up to 42% (Beschen, 1972).

The reasons for the decline in walking are many and various. However, one of the most important reasons is that we are living in an automobile-centered world. The dominating attitude towards urban planning and design since World War II glorified a spatial segregation of urban life and the use of automobiles as a major means of transportation to improve living quality (Le Corbusier, 1973, etc). Its application mainly in Western Europe and the US in late 20th century's urbanism has created and reformed numerous large cities where people's travel distances are significantly increased and car travel becomes a main component of urban mobility. In contrast to the effort made to accommodate more vehicle traffic, walking has long been regarded as a minor mode of transportation and gained little concern for planners and authorities. Consequently, a series of barriers raise and keep people away from the streets: poor walking environment, inconvenient access, potential danger from vehicles, etc. Again, taking the city of London as an example, according to a survey by Greater London Authority (GLA), only 33% of London residents think the City's pavement for walking is good whereas a striking 44% are not satisfied with the ease of crossing roads (Greater London Authority, 2001). As the Central London Partnership Report (2003) has put it: "Walking through the streets of London has become difficult, stressful and to many it feels dangerous. Londoners and people who come to the City everyday for work are frustrated by it, and tourists are beginning to stay away because of it."

2.1.4 Encourage Walking

In attempting to stop the declining trend in walking, many governments across the world have developed strategies, action plans and practicing guidelines to encourage walking. UK Department of the Environment Transport and the Regions (DETR) has claimed in its 2000 report: "We need to change the way that we plan, with greater emphasis on enabling access by walking." (Department of the Environment Transport and the Regions [DETR], 2000) The Mayor of London has published The Mayor's Transport Strategy and set out a strategic policy framework to promote walking and make London one of the world's most walking friendly cities by 2015. As he says: "Land use planning policies can be used to support walking journeys by encouraging developments that ensure an improved and convenient urban realm for pedestrians." (Mayor of London, 2010) In Copenhagen, the pedestrianised space has increased from 20,500 m^2 in 1968, 50,000 m^2 in 1986 to 71,000 m^2 in 1995 (J. Gehl, 2006). In Hong Kong, the Transport Department also has been implementing pedestrian schemes since 2000 in order to promote walking and to improve the pedestrian environment (Transport Department, N/A). The US Department of Transportation has started the "Bicycle & Pedestrian Program" to promote and facilitate the increased use of non-motorized transportation (Federal Highway Administration's Office, N/A). A Policy Statement on Bicycle and Pedestrian Accommodation Regulations and Recommendations has just been signed in March, 2010 to encourage walking and bicycling, with the vision that "the establishment of well-connected walking and bicycling networks is an important component for livable communities" (US Department of Transportation, 2010). Besides governmental forces, organizations such as *Walk 21*, *International Federation of Pedestrians*, *America Walks* are also committed to create walkable communities and provide strategic principles for local authorities such as *International Charter for Walking* (Walk21, 2006).

2.2 Pedestrian Comfort

2.2.1 Pedestrian Comfort and Outdoor Activities

Pedestrian comfort is a key to achieve a high level of pedestrian satisfaction; it is listed in the "5Cs criteria" of good walking network in London's walking plan (Transport for London, 2005). On the other hand, pedestrian comfort is a mixture of various concepts, ranging from socially related indicators such as high level of service (Fruin, 1987) and attractive landscape, to environmentally related indicators such as high quality pavement surface and low exposure to air pollution. One critical issue with this respect is pedestrians' thermal comfort. Different to people commuting in automobiles, pedestrians are exposed to their immediate environment: variation of sun and shade, changes in wind speed, etc., which influences their level of comfort and behaviors. For example, Rotton et al. (1990) found that elevation in heat stress will cause pedestrians to walk faster to reduce discomfort. A number of bio-meteorological indices have been developed to describe human thermal comfort level in terms of human thermal sensation: for example, Predicted Mean Vote Index (PMV) and Predicted Percentage Dissatisfied Index (PPD) (Fanger, 1982; ISO, 1994), OUT-SET* (Pickup & De Dear, 1999), Physiological Equivalent Temperature (PET) (Mayer & Höppe, 1987), etc. And the issue of outdoor thermal comfort, especially thermal comfort in urban spaces, has been extensively discussed for the last decade with investigations in various climates across the world (Ahmed, 2003; Ali-Toudert & Mayer, 2006; Cheng & Ng, 2006; Givoni, et al., 2003; Gulyas, Unger, & Matzarakis, 2006; Höppe, 2002; Marialena Nikolopoulou & Lykoudis, 2006; Spagnolo & De Dear, 2003; Stathopoulos, Wu, & Zacharias, 2004; Tseliou, Tsiros, Lykoudis, & Nikolopoulou, 2009). What is of particular interest in the context of urban planning, is that how the pedestrians' level of comfort will influence their usage of outdoor spaces.

Although there have been general discussions on the relationships between environment, human psychology and human behavior (Baker, 1968; Holahan, 1982), only recently have attempts been made to characterize the relationships between outdoor urban environment, thermal comfort and human activity from planning aspects.

In his seminal work "Life Between Buildings : Using Public Space", Jan Gehl (1971) first studied the influence of microclimate on people's social life by counting people sitting on sunny and shady benches. He showed that the microclimatic condition turned out to be of great importance in affecting people's outdoor activities. What makes Gehl's study of great value is the human condition he concerns: he proposed that people's interaction with the built environment should be considered by designers. Admittedly Gehl is an architect but not a bio-meteorologist, therefore his study took an observational approach where "microclimate" only concerned shading or sunlit areas, and "comfort" was just based on simple premise of whether people were desirable to use the space or not. Nonetheless, his pioneer work leads three decades of more specific research on the interrelationship between outdoor thermal environment and human sensation and activity. The following sections conduct an in-depth review of research in this domain.

2.2.2 Pedestrian Comfort Research

Although there have been other studies on downtown pedestrian activity (Francis, 1984; Nasar & Yurdakul, 1990; Pushkarev & Zupan, 1975; Whyte, 1980), Nagara et al. (1996) were among the first researchers who focused on the climatic and physiological aspects when they studied the subjective evaluation of pedestrians' thermal sensation in outdoor urban pedestrian spaces. They used a vote method to assess pedestrians' thermal sensation by assigning a 7-point psycho-physical scale ranging from +3 meaning very hot to -3 meaning very cold. The scale was a modification of ASHRAE standard (ASHRAE, 1989). What is of special interest is that, in the study they treated pedestrians as dynamic rather than static: they considered the changes in pedestrian's thermal sensation while moving along a route in giving the subjective evaluation. By comparing the measurement results of the thermal environment with the thermal sensation evaluation, the authors showed that pedestrians' subjective thermal sensation was generally in accordance with the physico-thermal environment, but was also influenced by their past experience, described as "history of exposure to the environment". The authors further proposed that possible modifications to urban environment could be made to achieve thermal comfort. The considerations of pedestrians' thermal comfort as subjective and dynamic as presented in the study are generally appealing, whereas the design recommendations will be made more pertinent if the pedestrians' thermal sensation could be linked with how the space is used.

Along the same track, Ahmed (2003) studied the dynamic thermal sensation of pedestrians in urban spaces, with emphasis on the transitional spaces between outdoor and indoor environment (free running buildings). The study was conducted in a warm-humid tropical city (Dhaka). A field survey method was employed where 1500 randomly selected subjects were interviewed to give comfort vote in three different urban situations with varying urban density and land use, described as *Urban Labs*. Six spatial categories were defined to represent the typical spatial characteristics of the urban spaces. The most important observations in the field survey were the dynamic comfort perceptions in both the temporal and the spatial dimension.

Temporarily, the range of voted comfort temperature from respondents following a longer stay was significantly different from that from the ones following a shorter stay, and the duration of the exposure to a particular ambience has a more pronounced effect on people who spend considerable time indoors than people who spend more time outdoors. Spatially, the respondents' comfort judgments were found to be dynamic, adapting to the conditions of the ambient condition among different urban labs, and it was also found that not all the spatial categories were preferred at the same time of day. The author derived a series of implications from the study, among which two of them are particularly worthwhile noticing with regard to pedestrian comfort. Firstly, it was suggested that to achieve outdoor comfort, a reasonable thermal range should be provided instead of an exacting thermal condition, as pedestrians' comfort perception is a dynamic process and continually adjusts to ambient environment. Secondly, it was also suggested that higher level of activities should also be concerned in urban design in relation to outdoor comfort, as pedestrians are always engaged in various form of behaviors. The author further proposed design guidelines including shading provision and reduction in radiation variation. On the other hand, as the focus of the study is on energy use and building design, no further discussion is raised from the behavioral aspect.

Thermal Transient

The issue of thermal comfort under indoor and outdoor transient conditions was reviewed by (Chun, Kwok, & Tamura, 2004; Hensen, 1990). From behavioral perspectives, the concept of "thermal transient" is further formalized and systematically measured in (Potvin, 2004), with special emphasis on pedestrians' walking through transitional urban spaces such as arcades, courtyards, and passages. In the present study, a comprehensive analysis was carried out in Cardiff, a British city. The analysis consisted of a theoretical investigation of environmental transients in terms of pedestrians' bodily adaptation assessed based on thermal equation and classified as difficult, conscious or "subliminal", and field surveys using portable sensors to record the microclimatic variations that pedestrians experienced when strolling across the transitional spaces. The theoretical investigation considered wind and solar radiation as the two main factors in affecting outdoor comfort and defined 9 theoretical climatic conditions based on combinations of wind and solar conditions. In such a case, a total number of 36 hypothetical environmental transitions were defined. The thermal transient graph was used to assess the quality of the intermediate thermal transient. Comfort zones could be identified in this graph and could provide comparison of different urban transitional configurations. In parallel, a survey method was developed to measure the instantaneous environmental stimuli the urban space put on pedestrians and assess the variation of the thermal environment experienced dynamically by pedestrians. Through this approach, field surveys were conducted in a cold sunny winter day and a hot sunny summer day. It was found that in the winter case the only place to approach comfort conditions was where the pedestrians stand in full sun with protection against the wind, while in the summer case the direction of the pedestrians' movement was a major determining factor in the sensation of comfort as solar radiation is highly relevant. In comparison, static surveys were also carried out to investigate the environmental conditions within particular spaces, i.e. thermal behavior of strolls through three arcades under seasonal conditions. All surveys were mostly limited to the period of early afternoon since it is the most active therefore critical period for cities. The study revealed that intermediate environments such as arcades can provide progressive adaptation to a new environment and therefore are important means to achieving urban diversities that are pleasurable to pedestrians. These spaces, captured by the author as *flânerie*, allow pedestrians to slow down the pace and be more aware of people and space around. They are expected to "encourage social transactions and enhance the overall experience of the city".

As opposed to the mere behavioral of walking, another line of research along this vein focuses on the more general context of microclimatic characteristics of outdoor open spaces and how people are entertained by them. They form a much broader literature.

2.2.3 Related Research on Thermal Comfort and Space Use: A General Context

The observational study by Li (1994) is one of the first investigations which concerned human response to microclimatic conditions of urban spaces. In the study, participation observations were conducted in 4 small downtown spaces in a North American city (New York City) in winter to examine their use density in cold climate. How the subjects reacted to the environmental stressor, i.e. the cold weather, and mediated the stress accordingly was recorded and analyzed qualitatively. The author described these responses as "behavioral control", as one of the three levels of personal control over environmental stressors, namely "*behavioral control*", "*cognitive control*" and "*decision control*". As opposed to the above reviewed literature, the study found that the microclimate was not the most important factor in affecting the winter use of small urban spaces. In fact, in the particular case study, only when temperature reached about 4°C did ideal microclimate conditions begin to influence peoples' behavior. In contrast, the urban context was shown to be a significant factor in influencing the usage pattern. The author then proposed a series of recommendations for urban space planning, such as to implement comprehensive pedestrian networks, and to control building height and density to guarantee solar access to urban spaces. What is particularly revealing about the study is its emphasis on the comprehensive understanding of space use: the space use issue is not related to microclimate only; a desirable urban space in winter should meet the general prerequisites of a successful urban space as well. The limitation of the study is the limited discussion from the climatic and physiological aspects: the microclimate was only captured by temperature, and no physiological measurement or assessment of thermal sensation was given to the subjects.

Zacharias et al. (2001) attempted to form a quantitative link between microclimate and usage pattern of urban open spaces. In their study, 7 corporate plazas and public squares in downtown area of a North American city (Montreal) were examined in attempt to uncover the relation between the local microclimate and use level, measured as presence levels and 3 types of activities, namely sitting, standing, and smoking. With a simple multiple regression method, the authors demonstrated that temperature and sun are preponderant factors in influencing human activity, and identified lower and upper bounds on presence as a function of temperature. While the authors concluded that public presence and activity can be predicted to a substantial degree based on microclimatic conditions and anticipated its usefulness in site planning for projects in built-up urban areas, they also noted that presence doesn't necessarily imply satisfaction, and suggested that people's perception of comfort, as complementary to levels of presence and activity type, should be taken into account if refinements on space design standards are to be achieved.

Nikolopoulou et al. (2001) investigated the thermal comfort conditions of urban open space as resting places in a British city (Cambridge). They interviewed people on their subjective evaluations of thermal sensation, given in a 5-point scale varying from too cold to too hot; on the other hand, they also took into account the objective parameters such as environmental characteristics (air temperature, solar radiation, etc.) and individual characteristics (age, sex, clothing, etc.). While the authors observed that comfort conditions generally implied more people using the spaces, by comparing the subjective and objective evaluation results, the author also showed that there was a great discrepancy between people's actual sensation and theoretical bio-meteorological indices such as PPD, as shown in Figure 2.1. The authors concluded that a physiological approach alone is not sufficient in evaluating thermal comfort condition for outdoor spaces, and suggested the importance of *thermal history* and *memory and expectation*. The idea was further formalize in the authors' later work (Marialena Nikolopoulou & Steemers, 2003) as three levels of thermal adaptation, namely physical, physiological and psychological adaptation. In the same paper, the authors demonstrated, through a quantitative approach, that only approximately 50% of the variance between objective and subjective comfort evaluations could be explained by the physical and physiological conditions. The authors speculated that the difference was due to psychological factors, such as naturalness, past experience, perceived control, time of exposure, environmental stimulation and expectations. With emphasis on people's psychological adaptation, the authors discussed design considerations in microclimatic planning to increase use of outdoor spaces, and argued that the understanding of these issues would not restrict design solutions but complement their design role. While the contention is generally tempting, as the authors admitted, because of the complexity of the interrelationship between different factors, no quantified relationship in terms of the effectiveness of a design alternative had been uncovered yet.

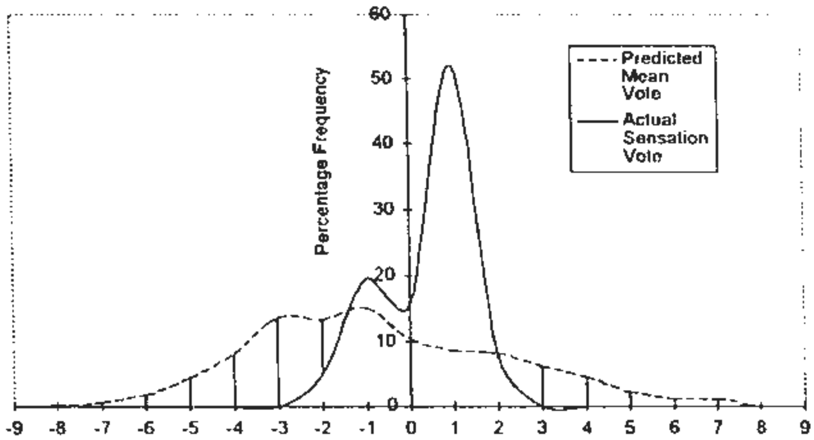


Figure 2.1 Percentage frequency distribution for Predicted Mean Vote and Actual Sensation Vote. After (M. Nikolopoulou, et al., 2001)

Thorsson et al. (2004) also studied the influence of thermal bioclimatic condition on the behavioral pattern in an urban park as a resting place, but in a Swedish city (Gothenburg). The study took a survey approach where around 280 subjects' reasons for visiting the park and their opinions on the design were collected by questionnaires. Their subjective thermal sensation, described as actual sensation vote (ASV), was also interviewed based on a 7-point psychophysical scale. The objective thermal comfort index of PMV was calculated based on mean radiant temperature, and compared against ASV. The comparison showed substantial difference between the subjective thermal sensation and objective thermal comfort level, suggesting that steady-state models such as PMV might not be appropriate for the assessment of short-term outdoor thermal comfort. Rather, the transient exposure and the thermal expectation may have more influence on the subjective assessment and satisfaction, as discovered in the study that people visiting the park voluntarily exposed themselves to sunny areas that were well outside the theoretically acceptable thermal comfort range. The authors further raised a preliminary planning recommendation, which is to create microclimate diversity to increase people's both physical and psychological adaptation and therefore the usage of outdoor spaces.

Thorsson et al. (2007) studied the subjective outdoor thermal comfort and human activity in an urban environment much more densely built-up than North American and European cases. They carried out case studies in a park and a square in a satellite city of Tokyo in Japan. The bio-meteorological index of PET was used for quantifying people's objective thermal condition, and a 9-point scale was used for evaluating people's subjective thermal sensation. Human activities in terms of attendance and behavior in relation to sunlit and shaded pattern were examined. In contrast with previous studies, the result showed that the relation between the thermal environment and the use of the sites was generally weak, which was explained by the authors in another paper to be due to cultural and climatic differences (Knez & Thorsson, 2006). However, it was also found out that the use of park was influenced more than square by microclimate, which was attributed by the authors to different functions of the sites. While the paper uncovered other interesting findings such as difference in the attitude towards sun and shading between Japanese and Swedish people, the role of urban space's social function in climate and behavior related research it revealed is more worthwhile noticing.

Nikolopoulou and Lykoudis (2007) took a step further by explicitly integrating social and environmental objectives in their investigation of the diurnal usage pattern of outdoor spaces in a Mediterranean city (Athens). In the study, a neighborhood square and a resting place near seashore with very different characteristics were examined. Social compositions of people, e.g., age, sex, professionals or pensioners etc., were also considered. Through observations and surveys, the spatial distribution of usage was derived. What is notable is that the authors took into account the socio-economic characteristics of "popular locations" in interpreting the variations of the usage. With a statistical method, the use of space was presented as a function of different meteorological parameters, among which air temperature and solar radiation were found to be the most dominant factors in affecting the use of space. The downside of the analysis is the generally low correlation (with R^2 lower than 0.1 for most cases), which is in accordance with the common wisdom of people's complex and conflicting nature of response. Nonetheless what is tempting is the distinguishable pattern of the influence of microclimate on different sites, e.g., presence in relation to sun.

The function of urban space was extended to more diverse cases in the study by Eliasson et al. (2007). Four urban public spaces in a Nordic city (Gothenburg), being square, park, courtyard, and waterfront plaza were examined. Human perception of the urban environment was categorized into functional and psychological evaluation, measured by total attendance and emotional satisfaction, respectively. Thermal comfort was surveyed based on a 9-point scale ranging from very cold to very hot in relation to participants' emotional states. Multiple regression analysis showed that clearness index, air temperature and wind speed accounted for over 50% of variance in place-related attendance, suggesting that the 3 climatic factors had a significant influence on people's behavioral assessment. Though the paper revealed different aesthetical evaluation of waterfront plaza and square in terms of feelings of beautifulness and pleasantness, their social function was not taken into account, at least explicitly, in relating to behavior assessment and usage variation. Despite that, the importance of climate-sensitive planning in urban design and planning projects was confirmed substantially in the study.

The above discussed studies are all conducted in regions with moderate climate, where warm condition and sunlight are positive factors in affecting people's use of outdoor spaces. In contrast, Lin (2009) studied the thermal perception and adaptation in relation to the use of a square in a hot and humid climate much similar to Hong Kong. Physical measurement and the bio-meteorological index of PET were used and the result was compared with the attendance of the square and people's "thermal sensation vote" indicating their levels of thermal comfort. The study showed that as opposed to findings in moderate climate environment, cool temperature and weak sunlight were desirable in hot season, and the thermal comfort range of participants was significantly higher than European cases. On this basis the author proposed design strategy such as adding trees and shelters to achieve higher level of thermal comfort and therefore higher use rate of outdoor spaces in hot and humid regions. On the other hand, the effectiveness of the general design requirements has not been uncovered in any great depth.

From the examples above, it is affirmative that microclimate has a great influence on the use of outdoor spaces in cities. Temperature, solar radiation and wind speed are shown to be the most significant. Therefore, the understanding in the relationship between building form, thermal sensation and human behavior is expected to provide guidelines and implications in urban design and planning. Actually, as early as in 1985, the city of San Francisco brought into effect legislations with design requirements to control new building's impact on the local microclimatic environment of public space, including limiting wind speed and controlling shadow casted by new construction, etc. (City and County of San Francisco, 1985) These regulations were discussed in both legal and research literature (P. Bosselmann, et al., 1988; Vettel, 1985), and were copied in many other North American cities, e.g., Montreal, New York.

Zacharias et al. (2004) had the opportunity to study a site that underwent a major design transformation to promote public use. They observed human behavior in a plaza before and after the design change. While the redesign was a standard solution intended to bring more people into the plaza by providing seating provisions, multiple regression analysis revealed that the amount of seating had a very modest impact on public attendance and could even been considered as unimportant in affecting the plaza use. In contrast, the quality and location of seating, affected by principal climatic factors of temperature and sunlight, were shown to have a preponderant effect in determining whether it was used. In this sense, the design solution failed to meet expectation since the decision was not informed by knowledge such as which factors matter, and design alternatives such as what possible outcome will be.

2.2.4 Assessment of Thermal Perception from Behavioral Aspects

From the above reviewed literature, it is clear that outdoor spaces are important in promoting living quality in cities. On the other hand, outdoor thermal comfort in urban environment is a complex issue that has multiple layers of concerns. The environmental stimulus, i.e., the local microclimatic condition, is the most important factor in affecting people's thermal sensation and comfort judgment. This judgment is found to be both dynamic and subjective: being dynamic means that the adaptation to an ambient thermal condition is progressive and the thermal sensation is largely affected by the previous experience; being subjective means that the evaluation of the thermal condition is not always consistent with the objective climatic or bio-meteorological condition. Other than the climatic aspects, people outdoors are always engaged in certain type of activities, which makes their perceptions of the urban spaces also greatly influenced by a variety of physical and social factors such as street furniture, sheltering, seating and kiosk stands. As a result, the outdoor space use is not only determined by the "*state of body*", but also by the "*state of mind*". This suggests that, to assess the outdoor thermal comfort perception from behavioral aspects, an assessment framework that works at least on four levels appears to be appropriate: *physical*, *physiological*, *psychological* and *social/behavioral*. This framework should allow the local meteorological condition to be linked with human sensation and also space use both in spatial and temporal terms. To elucidate, the static and objective aspects, i.e., the characteristics on the physical and physiological levels should be measured and modeled effectively to provide "climatic knowledge", while the dynamic and subjective aspects, i.e., the relationships on the psychological and social/behavioral levels require comprehensive field interviews and observations to provide "human knowledge".

2.2.5 The Need for a Predicting Tool

Despite the fact that people's subjective perception and response to the urban environment are various and yet not well-understood, simulation and scenario-testing tools are always of particular importance to the assessment framework in that they provide a platform where the integration of knowledge from various aspects and comparisons of different design scenarios are made possible. Givoni et al. (2003) have addressed the need of "predicting tools" in the research on how changes in design details will influence outdoor thermal comfort. As they put it: "In order to evaluate the importance of modifying the outdoor climate in a particular direction by specific design details it would be helpful if the designer would have some means for 'predicting' the effect of a particular change in a climatic element on the comfort of persons staying outdoor." The statement applies with equal force to a more general context of research issues, which is how urban design will influence the microclimate of urban environment and therefore people's outdoor thermal comfort, and how people's level of thermal comfort will in return influence their use of urban spaces. Design regulations and guidelines in this respect require comprehensive assessment before they become untested prescriptions. The town planners and decision makers, faced with the task of designing urban spaces that minimize discomfort and are desirable and therefore utilized rather than abandoned, will be better informed with a "predicting tool" which allows different design alternatives to be compared and tested under various design scenarios in terms of their attractiveness and effectiveness. To be specific, a testing tool which can provide both quantitative and qualitative understandings in characterizing the relationships between microclimatic environment, subjective thermal assessment and social behavior is in great need. Such a tool should by its virtue have the ability to process detailed environmental information depending on time and location variations and generate analytical results revealing the relationship. Environmental modeling tools such as ENVI-met (M. Bruse, 2010; M Bruse & Fleer, 1998), TownScope (Teller & Azar, 2001), Rayman (Andreas Matzarakis, 2007) and SOLWEIG (Lindberg, Holmer, & Thorsson, 2008) can provide understandings of the climatic condition, while human physiological modeling tools such as (M. Bruse, 2005; Huizenga, Zhang, & Arens, 2001) can provide assessment of human thermal comfort.

As a final remark, the predicting tool should also be able to represent the differentials of people's evaluation by taking into account individual diversities and also the dynamic aspects of the assessment. In this sense, multi-agent based simulation systems, such as BOTworld (M. Bruse, 2007, 2009), are expected to open up new avenues for achieving a better understanding of the influences of outdoor thermal environment on human activity and outdoor space use.

2.3 Review of Agent Research

2.3.1 Modeling and Simulation

Computer models in urban study have their roots dating back to the 1960s (Lowry, 1965) after the scientific concept of Urban System had been coined by emulating terminologies in the field of botany (Duncan, Scott, Lieberson, & Duncan, 1960). The simulation models, in attempting to provide both descriptive and predictive understandings of the real world by characterizing quantity and relation in a silicon surrogate of the real world, have found their increasingly wide applications in scientific research with advances in computer power. How simulation has transformed our understanding and how it has revolutionized the world of science have been extensively discussed and publicized in Casti (1997). In particular, Simpson (2001) has provided a comprehensive literature review of the application of virtual reality and simulation models in urban studies. As ambitiously as he has put it: "The combination of virtual reality, spatial modeling, and GIS, integrated into a real-time urban simulation, will allow questions to be asked that were not possible before, and better yet, answers to those questions." This is exactly what we are experiencing today (see, for example, Dr. Andrew Hudson-Smith's blog [http://www.digitalurban.blogspot.com/] for a skim of today's cutting edge technologies and applications).

2.3.2 Agent: Definition and Attributes

Agent based modeling (ABM) is an emerging approach to modeling complex processes and phenomena in research filed such as social science in recent years. Also recognized as multi-agent system (MAS), agent based simulation (ABS), or individual based modeling (IBM), its origin can be traced back to as early as the 1940s when the first prototypical "cellular automata" was invented simulating grids' interaction with their immediate neighbors by on-off state switches (Von Neumann, 1951, e.g.). Computer simulation of agents was revolutionized by Reynolds (1987) by introducing individual perception, intelligence and behavior to his Boids agents. Despite its long history, it is only until the 1990s has the agent modeling paradigm become both computationally and conceptually mature to be employed as a feasible simulation tool and sparked interest from the social science community.

Being the basic, and most essential unit of agent based models, perhaps the concept of *agent* should be defined in the first place before we embark on further review. Unfortunately, despite its common usage, there is no single universally accepted definition of what an agent is. Actually there has been a great deal of debate on this very subject (Franklin & Graesser, 1997; Müller, Wooldridge, & Jennings, 1995), and the existing definitions of agent are many and various, ranging from as primitive and loose as an individual agent is "just something that perceives and acts" (Russell & Norvig, 1995, p.7), to as elaborate and rigorous as "Autonomous agents are computational systems that inhabit some complex dynamic environment, sense and act autonomously in this environment, and by doing so realize a set of goals or tasks for which they are designed." (Maes, 1995) In attempting to avoid prescriptive arguments in the controversy, Russell and Norvig (1995, p.33) put: "The notion of an agent is meant to be a tool for analyzing systems, not an absolute characterization that divides the world into agents and non-agents." Nevertheless, a definition of agents, as *what it is* and *what it does*, will at least avoid confusion and suffice the discussion, and so is presented below.

Wooldridge and Jennings (1995) summarized the features of agents as autonomy, social ability, reactivity and pro-activeness, and in their later work formalized the definition of agent in a comprehensive as well as succinct way, stated:

> "an agent is a computer system, *situated* in some environment, that is capable of *flexible autonomous* action in order to meet its design objectives." (Jennings, Sycara, & Wooldridge, 1998)

This definition emphasizes on the two central properties of agents that have been commonly agreed on by people working in related areas: autonomy and social ability. Being autonomous means that an agent must be able to operate, carry out instructions and make decisions without direct intervention of others and have control over their actions and internal state (Castelfranchi, 1995; Hayes, 1999); being social means an agent is part of a community, being able to interact with other agents in order to complete their own problem-solving and to help others with their activities (Genesereth & Ketchpel, 1994; Hayes, 1999; Jennings, et al., 1998). These two key properties together distinguish agent based systems from related software paradigms such as object-oriented programming and distributed computation. Figure 2.2 shows an agent in its environment as depicted by this definition. A discussion of agent based system in the pure context of software engineering is beyond the scope of this thesis, and interested readers are referred to (M. Wooldridge, 1997).

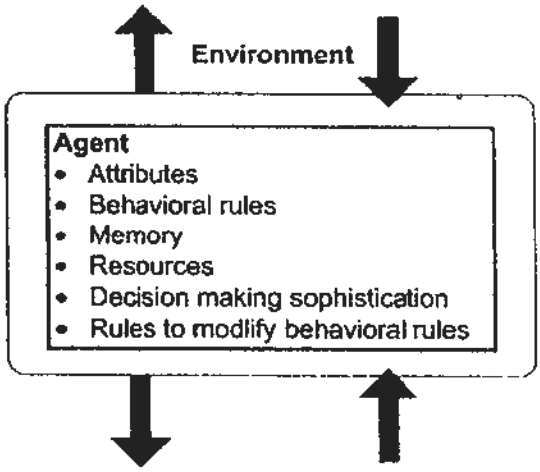


Figure 2.2 An agent in its environment. Adapted from (Macal & North, 2005)

2.3.3 ABM: Advantages and Criticisms

Advocated as a "breakthrough in computational modeling in the social sciences" (N. Gilbert & Terna, 2000), ABM has a series of advantages over conventional modeling paradigms. Bonabeau (2002) has captured the most essential ones in three statements, saying: "(i) ABM captures emergent phenomena; (ii) ABM provides a natural description of a system; and (iii) ABM is flexible". Though the expression seems a little bit crude on the surface, the elucidation is deliberate. Firstly, in contrast to traditional aggregate models, ABM frames a system from the bottom up, by studying the behaviors of its constituent units – the agents. By definition, the autonomous and social properties of agents allow complex, nonlinear interactions between them to be modeled which will lead to collective behaviors and emergent phenomena such as self-organization. Secondly, in ABM, the ontological correspondence between the computer agents in the model and real world actors makes it easy and evident to represent actors and the environment and their relationship (Nigel Gilbert, 2008, p.14). Thirdly, ABM can be defined within any given system environment with the complexity of agents tuned freely (De Smith, et al., 2007, Section 8.3); ABM can also work on different levels of abstraction. In the same paper, Bonabeau has also identified situations where ABM is suitable, paraphrased by De Smith et al. (2007, Section 8.3) as *complex interactions, heterogeneous populations, topological complexity, appropriate model framework* and *flexibility*. Apart from the three benefits of ABM as a modeling paradigm, other researchers have recognized its merits from other perspectives. For instance, Hayes (1999) has assessed ABM from a software engineering point of view and addressed that it can increase system robustness and modality and take advantage of distributed computing resources, and Kornhauser et al. (2009) has emphasized on ABM's visualization power in conveying the analytical results in the simulation course.

For the two decades since its basic landscape was developed, ABM has also raised a good deal of criticisms. The most commonly addressed issue is that the outcome of an ABM is difficult to assess. This issue is twofold. Firstly, it involves validation of the model, i.e., knowing "whether unexpected result is a reflection of a mistake in the programming, or a surprising consequence of the model itself" (Axelrod, 1997b, p.210); secondly, the heterogeneity of ABM allows it to contain a rich context of variable parameters, so "even if its output matches reality, it's not always clear if this is because of careful tuning of those parameters, or because the model succeeds in capturing realistic system dynamics" (Buchanan, 2009). Bonabeau (2002) has concerned the difficulty ABM is faced in application and argued that "The model has to be built at the right level of description, with just the right amount of detail to serve its purpose; this remains an art more than a science." Another criticism to ABM is more on the implementation level, stating that there is no institutionalized updating scheme of agent's behaviors so model comparison and result replication could be quite difficult (R. Axtell, Axelrod, Epstein, & Cohen, 1996; Cornforth, Green, & Newth, 2005; Huberman & Glance, 1993). Last but not least, ABMs lend themselves to repetitive rounds of simulation of many entities sometimes up to thousands, and so will require high computer resources when applied to large scale systems. These criticisms are all fair and sound arguments. Although some general guidelines have been suggested in response to specific critics (e.g. Axelrod, 1997b, p.211), there is definitely further work to do to address these limitations.

Nonetheless, ABM as a modeling paradigm and also a simulation approach offers great enhancement to the understanding of complex systems, which is an increasingly popular topic in science (Epstein & Axtell, 1996; Wolfram, 2002). To reiterate, by quoting Jennings et al. (1998): "The agent-based view offers a powerful repertoire of tools, techniques, and metaphors that have the potential to considerably improve the way in which people conceptualize and implement many types of software." It has found wide applications in various disciplines.

2.3.4 Application of ABM

As Wooldridge put it: "There was a time when I rather arrogantly believed I had read all the key papers in the multi-agent systems field, and had a basic working knowledge of all the main research problems and techniques. Well, if that was ever true, then it certainly isn't any more, and hasn't been for nearly two decades: the time has long since passed when any one individual could have a deep understanding of the entire multiagent systems research area." (M. Wooldridge, 2009, p.xix) Although it is formidable, if not impossible, to exhaust the broad literature of ABM's applications in different fields, developing an overall picture of how it is adopted by specialists in different domains as their conceptual paradigm as well as instrumental device will still help in terms of pushing the frontier of the research. The following section gives a brief review of ABM applications.

Geospatial and Urban Applications

ABM has found its most common use in space-related topics in geospatial and urban studies. Schelling (1971) developed the first social ABM to explain the racial segregation in American cities and has enlightened ABM's wide application in related field ever since. Along the same track, Epstein and Axtell's *Sugarscape* model (Epstein & Axtell, 1996) also paradigmatically simulated social behaviors such as aggregation and segregation. Drogoul took a more general perspective by considering emergent phenomena in cites (Drogoul & Ferber, 1994). Benenson et al. (1999) modeled the residential dynamics in a city, similar examples were also given in Kohler and Gumerman (2001). Parker et al. (2003) gave a comprehensive review of ABM's application in modeling land cover and land use change, with more up to date researches to be added (Kii & Doi, 2005; Manson, 2006; Rindfuss, et al., 2008, etc.). With the development of geographic information system (GIS), ABM has been increasingly recognized as a powerful tool for spatial modeling or so called geo-simulation (D. Brown & Xie, 2006; D. G. Brown, Riolo, Robinson, North, & Rand, 2005; Gimblett, 2002; B. Jiang & Gimblett, 2002), and understanding cities (Batty, 2005). O'Sullivan (2008) has provided a longitudinal review within this context. This field remains the most active direction of ABM's applications.

Economic Applications

In a recent journal article, Farmer and Foley (2009) argued the usefulness of ABM as a predicting tool to guide financial policies. While whether ABM will suffice as a policy tool is still an open question, there is no doubt that it has been widely applied to economic studies in the last two decades. The *Sugarscape* model by Epstein and Axtell (1996) was a prototype of a trading market. Applying the ABM paradigm to a more realistic case, Lux (1998) simulated the behaviors of speculators in a financial market by dynamically interacting agents, and studied the emergent aggregation behaviors. Axtell also simulated the emergence of companies and their growth rate distributions (R. L. Axtell, 1999). Tesfatsion first formalized the concept of Agent-based Computational Economics (ACE) and modeled more general and complex economic processes as dynamic systems (Tesfatsion, 2001, 2006). Bak et al. (1996) and Wan et al. (2002) modeled price variations within stock markets, in comparison, Kirman and Virend (2001) studied the price dispersion of a fish market, with a notable learning capacity of the agents. Parker and Filatova (2008) presented an ABM for land market. In contrast to other studies simulating markets in the real world, Marks (2006) discussed design methodology for electronic markets and gave examples. More thorough surveys of ABM's applications in economy and finance can be found in (Hommes, 2006; LeBaron, 2006).

Ecological and Environmental Applications

As discussed in previous sections, ABM is capable of depicting global consequences resulting from local constituent units, therefore is a potential tool to represent and analyze complex and dynamic processes in ecological and environmental applications.

Indeed it has been applied to a diverge range of topics ranging from biology to geographic resources management. Hogeweg and Hesper (1983) were among the first researchers who used individual-oriented model to study the forming of insect colonies, similar work includes Wolff's (1994) bird nesting colony, and simulating the growth of bacterial colonies (Kreft, Booth, & Wimpenny, 1998; Krzysztof, Dzwinel, & Yuen, 2005). ABM has been more popular in the context of environmental and ecosystem management. Lansing and Kremer (1993) first applied ABM to water resource modeling and established the basic landscape of modeling various water-related scenarios which has been influential till today (Feuillette, Bousquet, & Le Goulven, 2003). In comparison to water resources, ABM has also been applied to agriculture (Berger, 2001; D.C. Parker & Meretsky, 2004) and forestry (Hoffmann, Kelley, & Evans, 2002). Bousquet et al. (1998) took a more abstract approach and used ABM for generic resource sharing management. Hare and Deadman (2004) and Bousquet and Le Page (2004) reviewed various ABM applications in environmental and ecological modeling. Grimm et al. (2005) discussed the general strategy of designing ABM in ecosystem modeling and also provided a review.

Medical Applications

ABM has two main braches of medical applications. The first one is in the area of patient monitoring and management and health care. The GUARDIAN system by Hayes-Roth et al (1989) is credited with first hierarchically organizing patient health care into the cooperation of a collection of experts with different expertise, namely *perception/action* agents, *reasoning* agents and *control* agents. Huang et al. (1995) took a step further by presenting a system with natural representation of individuals, e.g., patient, practitioner, hospital specialist, etc. The prototypical approach established has been introduced to specific subjects (An, 2001). A recent overview of ABM application in health care simulation and modeling was given in (Paranjape & Sadanand, 2010). Another increasingly popular trend of ABM's medical application is its integration with spatial information and social network in modeling the spread of infectious diseases. With its flexible and social attributes, ABM allows to model the community's response to epidemiological events by simulating the interactions of its inhabitants in the course (Carley, et al., 2006; Stroud, et al., 2007). The validity of ABM in comparison with traditional epidemiological model was proved in (Chen, Carley, Fridsma, Kaminsky, & Yahja, 2006). Bian and Liebner (2007) presented an system modeling both spatial and temporal processes in the disease transmission. With a case study of modeling virus dispersion, Rahmandad and Sterman (2008) conveyed a constructive discussion on the comparison of ABM and differential equation models, with implications not limited to epidemiology.

Transportation System

Traffic and transportation is another area where ABM has found wide applications. Indeed the mobility and autonomy of ABM allows a straightforward representation of traffic entities, be it a pedestrian or an automobile, and makes it particularly suitable for modeling traffic dynamics. The specific topic of pedestrian modeling will be discussed in more detail in the next section, and only car-related traffic will be discussed here. One of ABM's earliest applications was to simulate the size-frequency distribution of traffic jams (Nagel & Rasmussen, 1994). Later ABM was employed in modeling transportation scheduling and management because of its geographically distributed nature (1997; Fischer, Müller, & Pischel. 1996). In reviewing the literature in this context, the monumental TRANSIMS (TRansportation ANalysis SIMulation System) cannot be circumvented. Developed by the Los Alamos National Laboratory (LANL), the ambitious TRANSIMS project is an integrated traffic simulation software package aiming to provide transportation planners with complete information on traffic impacts, congestion and pollution (Hobeika, 2005). It consists of a series of modules that create a virtual metropolitan region where individuals have complete attributes such as households, activities and route choice among activities. Traffic dynamics are created by second-by-second micro-simulation of the individuals' movements, based on which emissions are estimated. The system has been applied in real case studies in Dallas and Portland in the U.S (Travel Model Improvement Program, 1999). Other applications of ABM on large scale traffic modeling include (Balmer, Nagel, & Raney, 2004; Cetin, Nagel, Raney, & Voellmy, 2002; Raney, Cetin, Vollmy, & Nagel, 2002). Other models focusing on more specialized traffic flows include recreation movement models (Itami, et al., 2003), emergency evacuation models (Crooks, Castlea, & Batty, 2008), and parking models (Itzhak Benenson, Martens, & Birfir, 2008), etc. Davidsson et al. (2005) conducted a systematic review on the ABM approach to transportation and traffic management and supported ABM's usefulness for this domain.

Computer Games

A relatively new but boosting field, the development of computer games has found the ABM approach particularly appealing in implementing game characters. Commonly recognized as *Intelligent Agents*, ABMs naturally lend themselves to the modeling of adaptive, human-like, socialized individuals in the games. Wavish and Graham (1996) discussed some early applications of ABM in computer games. Grand and Cliff's (1998) Creature game was one of the first successful ABM games that interacting with the user in real-time. Since then, ABM application has evolved into two main streams in computer game designs. The first one focuses on the implemental level (animation, etc.) and concerns the agent's navigation in environment (C.W. Reynolds, 1999; Shao & Terzopoulos, 2007); the second trend works more on the abstract level and considers agents as embodiment of artificial life, which continue to the present day, as exemplified by successful commercial software such as Second life (http://secondlife.com/) and Civilization V (http://www.civilization5.com/), and research project such as the River City project by Harvard (http://muve.gse.harvard.edu/rivercityproject/index.html).

As mentioned at the beginning of this section, the application of ABM is so broad that it is aimless to attempt to exhaust the complete literature. So instead of rambling on another 10 pages without fulfilling the task, it makes more sense to pause here: the presented categorized review should suffice to depict a constructive picture of ABM's applications in various fields. More examples can be found in lecture books such as (Nigel Gilbert, 2008; M. Wooldridge, 2009), and The International Foundation for Autonomous Agents and Multi-agent Systems (IFAAMAS) webpage (http://www.ifaamas.org/) as for the most up to date technologies and applications.

2.3.5 ABM: Architecture and Implementation

The architecture of agent-based models is more a software engineering issue, and therefore is only briefly reviewed in this section. Discussions from computational standpoints are given in (Jennings, et al., 1998; M. Wooldridge, 2002). Owing to agents' autonomous features, ABMs generally lend themselves to the paradigm of object-oriented programming, as there is a natural analogy between the state and action of an agent in an ABM and the attribute and method of an object in a piece of object-oriented program. Along this line, the software structure of an agent is often described as a software object (R. L. Axtell, 2000), and the interactions between agents can be described as sequential or parallel thread management in multi-threaded programming. In this way, Axtell described the implementation of ABMs as *easy* as compared to other computational models. The reason for this is that all the agents share the same behavioral repertoire, so the implementation of agents' behavioral rules is a one-off thing. Effectively, the architecture could be described as "very little source code controls a much larger amount of execution code" (R. L. Axtell, 2000).

Jennings et al. (1998) discussed the distinctions between an agent and an object despite their great similarities. The first distinction is that because of their different degree of autonomy, the decision that whether or not an action is executed is different for an agent and an object: the agent which is *requested* to take the action makes the decision, while the object which *invokes* the action makes the decision, as captured vividly by the slogan "*Objects do it for free; agents do it for money*". The second distinction is that the standard object-oriented software framework has no means to integrate the *social*, *reactive* and *pro-active* behaviors, which in contrast are the key features of an agent (refer to Section 2). The third distinction is in the implementation aspect, which is that by nature each agent should have its own individual thread control, as opposed to the standard object-oriented model where there is normally a single thread control in the system. These distinctions together determine the fundamental departure of concerns on development of ABMs and object-oriented models.

Jennings et al. (1998) also discussed the issue of *development environment*, suggesting that development environments or programming languages that allow the model developers to work on higher levels of abstraction is in great need before ABMs can be more widely adapted as a modeling tool instead of a mere computation paradigm.

2.3.6 ABM: Development Platforms

In the early years of ABM research, the models were often developed using conventional programming languages (N. Gilbert & Bankes, 2002). One huge disadvantage of this approach is that model developers would have to work on the bottom level of abstraction and devote a lot of efforts to the "housekeeping" tasks such as graphical display, memory management and synchronization mechanism. Another drawback is that ABM researchers with limited or no programming skills were restricted and discouraged largely by the implementation barrier (Railsback, Lytinen, & Jackson, 2006). To address these issues, various modeling toolkits and development environments have been developed to support modelers by releasing them from the burden of housekeeping tasks they have to undergo if modeling with conventional programming languages. The most commonly adopted form of these toolkits is "libraries of frameworks" (Nigel Gilbert, 2008, p.47), which are GNU-like open source libraries that can be linked to ABM programs. The first of these to be widely employed was Swarm (http://www.swarm.org) whose design has influenced a series of succeeders including Repast (http://repast.sourceforge.net/), Mason (http://cs.gmu.edu/~eclab/projects/mason/) and so on. In parallel, the Logo family has also evolved into a number of software packages for ABM, such as StarLogo (http://education.mit.edu/starlogo/) and NetLogo (http://ccl.northwestern.edu/netlogo/). This section gives a brief review of these platforms.

Swarm

Swarm is an object-oriented platform originally developed by Santa Fe Institute (Minar, Burkhart, Langton, & Askenazi, 1996). The basic unit in it is *swarm* which is a collection of agents with a schedule of actions. It has a hierarchical structure with seven core modules managing data, scheduling, simulation and display. A prominent feature of Swarm is its *probe* facility which allows reading and setting the state of an object at runtime. It is a feature that continues to present in future generation of ABM platforms. Programming in Swarm is in object-oriented language such as Object-C and Java, and Najlis et al. (2001) has found the steep learning curve of programming in Swarm to be a significant impediment in its being chosen as a tool for developing ABMs. Though regular discussion and events such as Swarmfest are still being held, it has to be admitted that it has become superseded in the main stream of today's ABM research.

Repast

Repast (the Recursive Porous Agent Simulation Toolkit) was originally developed by the University of Chicago aiming to implement Swarm in Java but has diverged into a more comprehensive platform and now it is maintained by Argonne National Laboratory. Repast models can be implemented in three different languages: Java, Python and Microsoft's .NET. A promising feature of Repast Python libraries is that they provide a visual tool that allows a much simpler way to build models by point-and-click interactions then coding for users with less advanced programming skills. Another notable feature of Repast is its widely support of GIS, for example, Agent Analyst (Redlands Institute, N/A) is an ABM extension that allows Repast models to be integrated with ArcGIS. Now Repast Java, Python and .NET are no longer being maintained, and are superseded by Repast Simphony which is a powerful tool that provides a rich context of functionalities and continues being developed. Despite the relatively limited documentation, Repast has an active and large user community with an informative mailing list updated promptly. It is the most commonly used and promising platform in ABM research.

Mason

Mason (Multi Agent Simulation Of Neighborhood) is Swarm-like open source Java library. It was developed by the Evolutionary Computation Laboratory and the Centre for Social Complexity at George Mason University. Appealing features of Mason includes 3-D visualization and movie recording of the simulation at runtime. It also has GIS support. Though also with a mail list and some online documentation, Mason has a much smaller user group compared with Repast.

StarLogo

StarLogo is a programmable modeling environment developed by the Media Laboratory and Teacher Education Program at Massachusetts Institute of Technology. It is a specialized version of Logo programming language which is famous for its *Turtle graphics*. Similarly, agent and environment in StarLogo are represented by *turtle* and *patch*, with their interactions monitored and managed by *observer*. Programming in StarLogo is in a simple version of Java and easy for modelers with basic level of programming skills. A main difference between StarLogo and the above mentioned platforms is that it is procedurally programmed as opposed to object-oriented. Originally distributed as a software package, its open source version, the OpenStarLogo (http://education.mit.edu/openstarlogo/) was released in 2006.

NetLogo

NetLogo is another widely used ABM simulation environment. It was originally developed at the Centre for Connected Learning and Computer-Based Modeling at Northwestern University in attempting to run StarLogo on Mac OS. Its main distinction from StarLogo is its special client-sever architecture which is particular suitable for internet application (http://ccl.northwestern.edu/netlogo/hubnet.html). NetLogo also supports GIS and can record movies of simulation. Extensive documentation and demonstration examples can be found on its homepage, even with a Chinese translation of the user manual. Though not an open source distribution, the rich variety of sample models and the active user community make NetLogo a popular platform of ABM.

Comparisons of above mentioned ABM platforms have been discussed extensively (Castle & Crooks, 2006; Nigel Gilbert, 2008, p.49; N. Gilbert & Bankes, 2002). Evaluations through use case have been carried out by (Railsback, et al., 2006; Tobias & Hofmann, 2004). A summarized comparison of different ABM platforms is shown in Table 2.1.

Table 2.1 A comparison of different ABM platforms. Modified after (Nigel Gilbert, 2008, p.50; Najlis, et al., 2001)

	Swarm	Repast	Mason	StarLogo	NetLogo
Developer	Santa Fe Institute	Department of Social Science Research Computing, University of Chicago	Center for Social Complexity, George Mason University	Media Laboratory, Massachusetts Institute of Technology	Centre for Connected Learning and Computer-Based Modeling, Northwestern University
Date of Inception	1996	2000	2003	Early 1990s, java based version 2000	1999
Website	www.swarm.org	http://repast.sourceforge.net	http://cs.gmu.edu/eclab/projects/mason	http://education.mit.edu/starlogo	http://ccl.northwestern.edu/netlogo/
Email list/Forum	www.swarm.org/mailman/listinfo	http://old.nabble.com/Repast-f3965.html	http://metis3.gmu.edu/cgi-bin/wa?A0=MASON-INTEREST-L	starlogo-users@media.mit.edu	http://groups.yahoo.com/group/netlogo-users
Modeling language	Object-C, Java	Java/Python/Microsoft.NET	Java	Proprietary scripting	Proprietary scripting
Operating system	Windows, UNIX, Linux, Mac OSX	Windows, UNIX, Linux, Mac OSX	Windows, UNIX, Linux, Mac OSX	Windows, UNIX, Linux, Mac OSX	Windows, UNIX, Linux, Mac OSX
Required	Strong	Strong	Strong	Basic	Basic

programming skill					
Integrated GIS functionality	Yes	Yes	No	No	Yes
Integrated charting/graphing/statistics	Yes	Yes	No	Yes	Yes
Availability of demonstration models	Yes	Yes	Yes	Yes	Yes
Documentation	Patchy	Limited	Limited	Limited	Good
User base	Diminishing	Large	Increasing	Medium	Large
Speed of execution	Moderate	Fast	Fastest	Moderate	Moderate
Built-in ability to create movies and animations	No	Yes	Yes	No	Yes
Ease of installation	Poor	Moderate	Moderate	Very easy	Very easy

2.4 Related research on pedestrian modeling

Microscopic modeling of pedestrians' movement in the urban environment is a key issue in assessing pedestrian thermal comfort. However it is also a Gordian knot in that it involves the complexity of the effect of building forms on pedestrians' individual decisions and behaviors. There have been several main steams of approaches for modeling pedestrian movement. The first is based on solving differential equations treating pedestrians as physical flow system in continuous space, such as the social force model proposed by (Helbing, 1991). The second approach has its roots on the concept of cellular automata (CA), and represents pedestrian's movement by on/off state switches of discrete grids (Blue & Adler, 1998). There are also other studies that propose that pedestrian movement is determined by street configuration, and model the movement from this aspect, commonly known as *space syntax* (B Hillier, Penn, Hanson, Grajewski, & Xu, 1993).

ABM has advantages over other models in that it accounts for individual varieties in the local scale, and the explicit but flexible representation of pedestrians as autonomous agents makes the detailed investigation of pedestrians' characteristics much straightforward. In the context of this study, examples of ABM pedestrian simulation are reviewed. Commercial software such as Legion (http://www.legion.com/), PRARMICS (http://www.paramics-online.com/) and SimWalk (http://www.simwalk.com/index.html) are not discussed though because of the limited customized functions for special purpose.

2.4.1 STREETS

The STREETS model (Haklay, O'Sullivan, & Thurstain-Goodwin, 2001) is the first model to be discussed because in terms of simulating pedestrians' behaviors it is quite close to the objective of this study, which is to link local movement with socio-economic features of the urban environment. STREETS is a multi-agent model implemented in the Swarm environment in Object-C programming language. Its aim is to simulate downtown pedestrian movement. It comprises a GIS component representing the urban environment, and a behavioral component for simulating pedestrian movement patterns. A prominent feature of STREETS is its hierarchical structures of both data representation and control management. The GIS component contains a structured representation of the urban environment: *vector data* representing building geometries and attributes, *raster data* representing the walkability and *network data* representing street network and gate points where pedestrians enter and exit the environment. The behavioral component also consists of a list of modules operating from the low level of physical movement to the high level of route planning. A screen shot of STREETS's interface is shown in Figure 2.3. The overall structure of the system is shown in Figure 2.4.

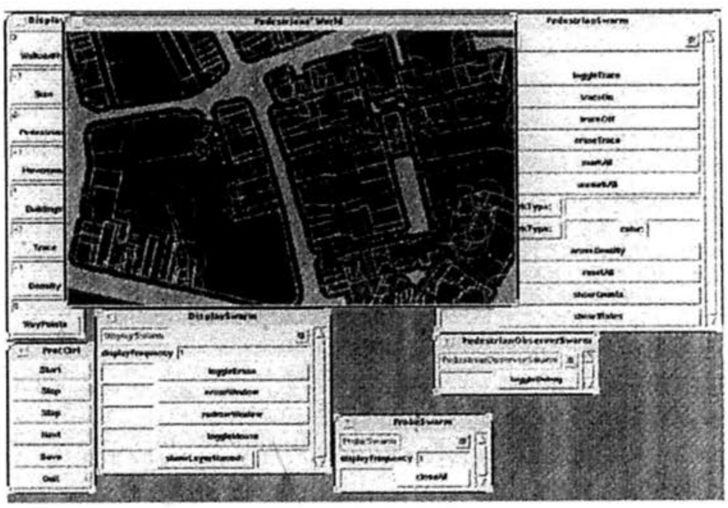


Figure 2.3 A screen shot of the interface of STREETS. After (Haklay, et al., 2001).

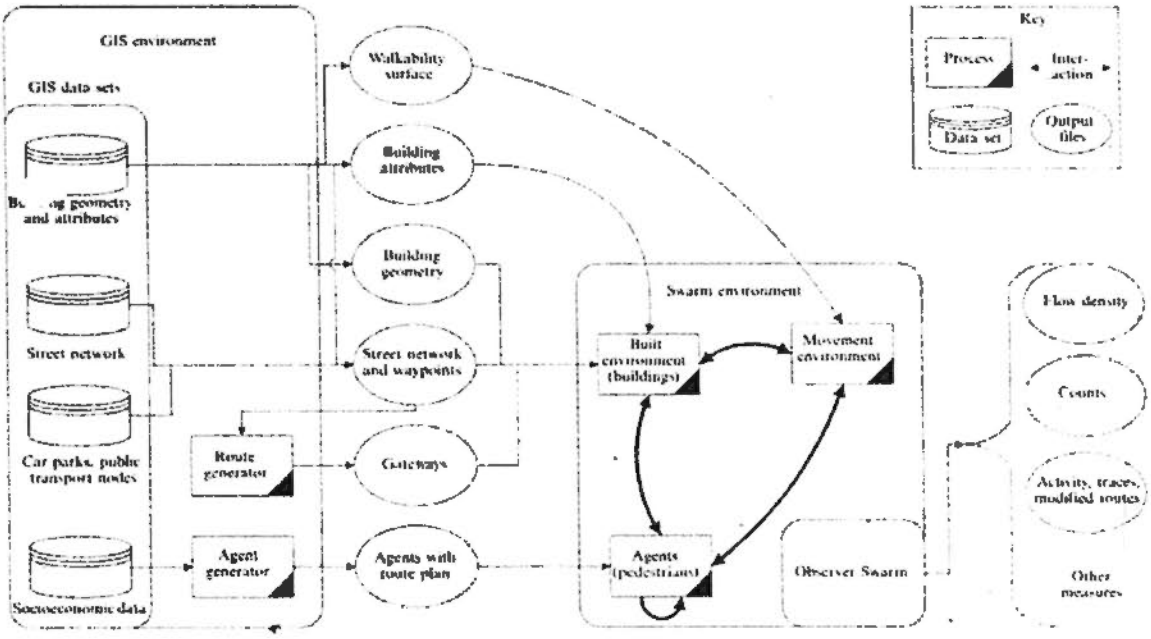


Figure 1. The overall structure of the STREETS model.

Figure 2.4 The overall structure of STREETS. After (Haklay, et al., 2001).

In aspects of implementation, STREETS uses a ~ 1m gird with a 0-255 gradient level representing the walkability of no building areas (pavement, road, etc.). A large gradient value will prevent an agent from stepping into the grid, which avoids collision. An agent looks in up to 5 directions for the next location. The updating time interval is unknown.

What is appealing about STREETS is its integration of spatial data and socio-economic data: buildings in STREETS not only have geometries but also have types such as retail, commercial and residential. Matching between building type and pedestrian type is considered in the simulation process. Socio-economic data are also used in determining the populating rate of gate points such as metro stations and bus stops. The support of GIS format files such as shape file and raster file is also a notable merit.

Though claimed to be a model integrating behaviors across different spatial scales, STREETS essentially works on the meso-scale level. Its focus is on the global walking pattern of a section of the town center but not the step-by-step process of movement. Issues such as how two agents negotiate a grid were not concerned. Besides, the routes for agents were predefined as a series of points hardcoded before inline simulation, which makes the emergent phenomena less credible. Though STREETS was developed not very long ago, sadly, through personal communication with the model developer, it is found that maintenance of the model has completely lost track.

2.4.2 PEDFLOW

The PEDFLOW model is a microscopic pedestrian simulation model with its prototypical implementation developed by (Kerridge, Hine, & Wigan, 2001; Kukla, Kerridge, Willis, & Hine, 2001) and a extended version developed by (Kukla, 2007). Different to the STRETS model, agent movement decisions in PEDFLOW were determined by a set of cause-effect rules applied to different snapshots of the urban environment. This behavior control was identified by the authors as *context mediated behavior*. Five underlying parameters were defined to control the decision making process: *static awareness*, *preferred gap size*, *desired walking speed*, *personal space measure* and *choice* for left or right. The environment in PEDFLOW was represented by a 0.75m resolution grid, with each grid being either a static entity (obstacle) or a mobile entity (pedestrian). Agents could look in up to 8 directions representing a Moore neighborhood. Time step in PEDFLOW is 0.1 second. The primary output of the model is flow pattern, whereas individuals could also be observed. As opposed to

STREETS, PEDFLOW was not implemented with a specialized ABM platform: it was originally implemented in a parallel programming language OCCAM, then in java for the modified version. The graphical interface of the model is shown in Figure 2.5, and its software structure is shown in Figure 2.6.

PEDFLOW is a substantial micro-scale complement to STREETS in that the stepwise decision making process was explicitly addressed in the model, i.e., turning left, turning right, halting, etc. Apart from the static aspects of walking such as avoidance of obstacles, the dynamic aspects were also implemented such as being companied by partner. PEDFLOW provided an analyzing tool that allowed detailed statistics of agent movement pattern to be examined. Its advantage as a decision making tool is that the behavior rules could be easily edited which means testing scenarios could be modified easily with variations of determining factors.

Developed as a prototypical model, PEDFLOW was mainly designed for simple conditions such as road crossing point. This implies that the representation of environment in PEDFLOW is rather limited; it is not clear how a complex urban environment could be input into the model. It can not be linked with GIS data. Also, the monotonous rasterized representation of environment lacks higher level information such as building shapes, street networks, which are important in determining pedestrians' movement. Also, the GUI and online visualization of the system are very limited.

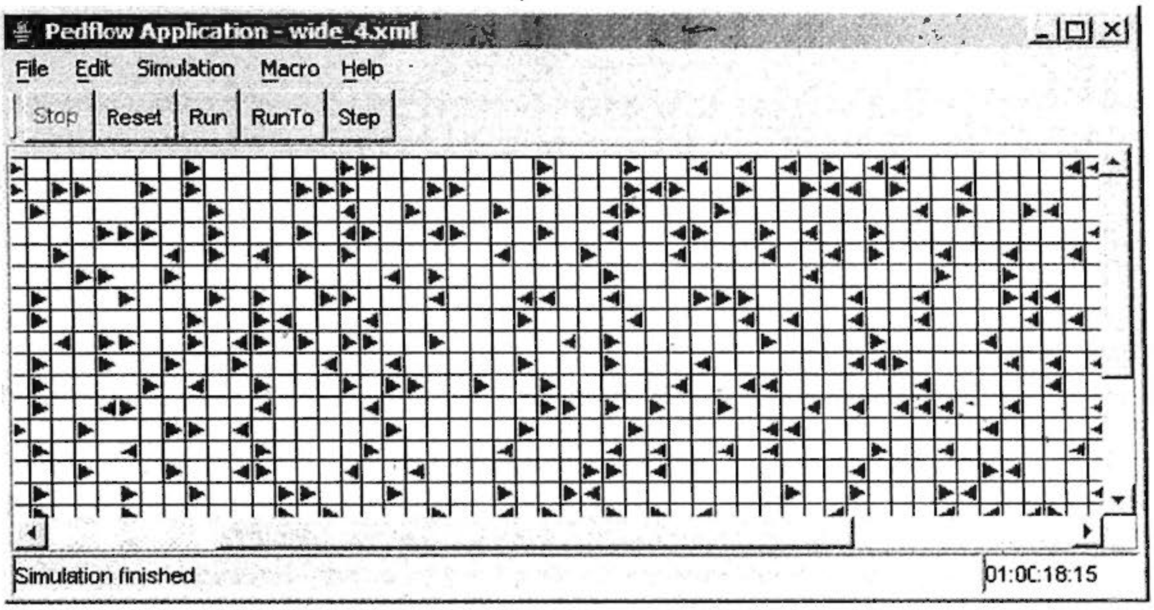


Figure 2.5 Interface of PEDFLOW. After (Kukla, 2007).

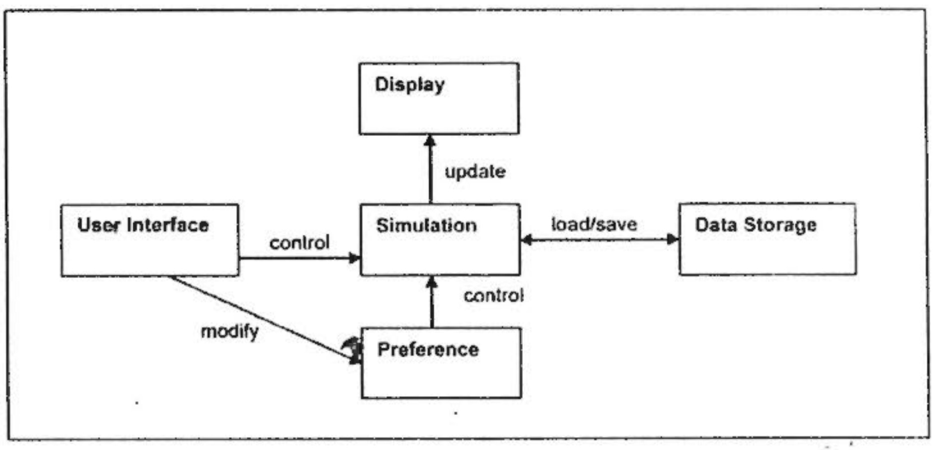


Figure 2.6 Model structure of PEDFLOW. After (Kukla, 2007).

2.4.3 SimPed (Jiang)

To be distinguished from Daamen's (2002) homonymic model which was not an ABM, the SimPed model by (Bin Jiang, 1999), with a number of similar examples (Batty, 2003; Batty, Jiang, & Thurstain-Goodwin, 1998) presents another approach of localized movement modeling. The simulation of movement processes basically uses principles grounded in the theory of space syntax (Bill Hillier & Hanson, 1988), which is that the morphology of the space and how pedestrians can see directly determine how they walk. The underlying mechanism of the movement is based on the *random walk* concept with agents following the gradient of an attraction surface and constrained by geometry but aided by their vision. Though generally a microscopic model, the model lacks a structured representation of the walking environment (e.g., actual building geometry as to building location) and an explicit classification of the objects within it (e.g., different building type), as shown in Figure 2.7. What is more crucial, the model's random navigating principle makes it difficult to be applied to real cases where purposeful routing is more realistic behavior. Besides, the model was implemented in StarLogo, meaning behavioral functionalities and control devices could be quite restricted. It is considered more as a prototypical framework than a specialized implementation.

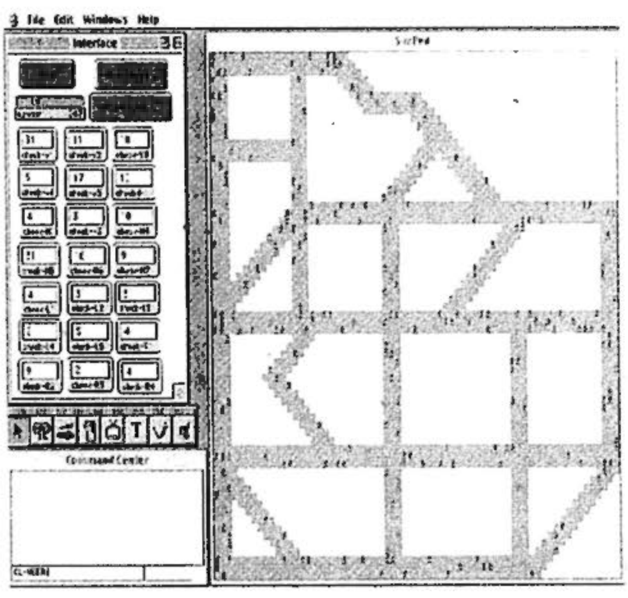


Figure 2.7 Interface of SimPed. After (Bin Jiang, 1999).

2.4.4 PedWalk

The PedWalk model is an ABM pedestrian simulation module of an integrated environment, the BOTwolrd (http://www.botworld.info/), which has inspired this study with objectives in assessing pedestrian thermal comfort through an ABM approach. Currently the documentation of PedWalk is very limited, partially due to the fact that the system is still under development (personal communication). Nevertheless, from available materials (M. Bruse, N/A), some features of PedWalk could be depicted. The environment in PedWalk is represented by a mesh of *navigation points*, which is essentially a raster grid, with resolution being either 1m or 0.5m. What is most impressive about the model is that it decomposes the decision making into 3 assessment components, namely *routing assessment*, *dynamic assessment* and *reactive assessment*. The three components are all normalized into a 0-1 scale and could be added linearly for the overall evaluation directing the movement decision. Movement details of how an agent moves from one grid to the next grid are examined with minimum time step being 0.1 second. The system is implemented in Delphi, an object-oriented programming language. The interface of the model is shown in Figure 2.8.

Though the PedWalk model has inspired the presented study from various aspects, it is also found that the model has a list of limitations in applying to this study. The first limitation is that its rasterized representation of urban environment lacks socio-economic information, such as building type and population density which definitely determines pedestrians' activities in walking in the environment. Secondly, it doesn't contain the street network information so doesn't account for it in path-finding process, which is seldom the case in reality. Also, it doesn't support GIS files so is difficult to be applied to real and complex cases. These limitations are totally acceptable given that PedWalk is mainly designed for simulating open space usage. However, in the context of this study, substantial improvement should be made if the goals are to be achieved.

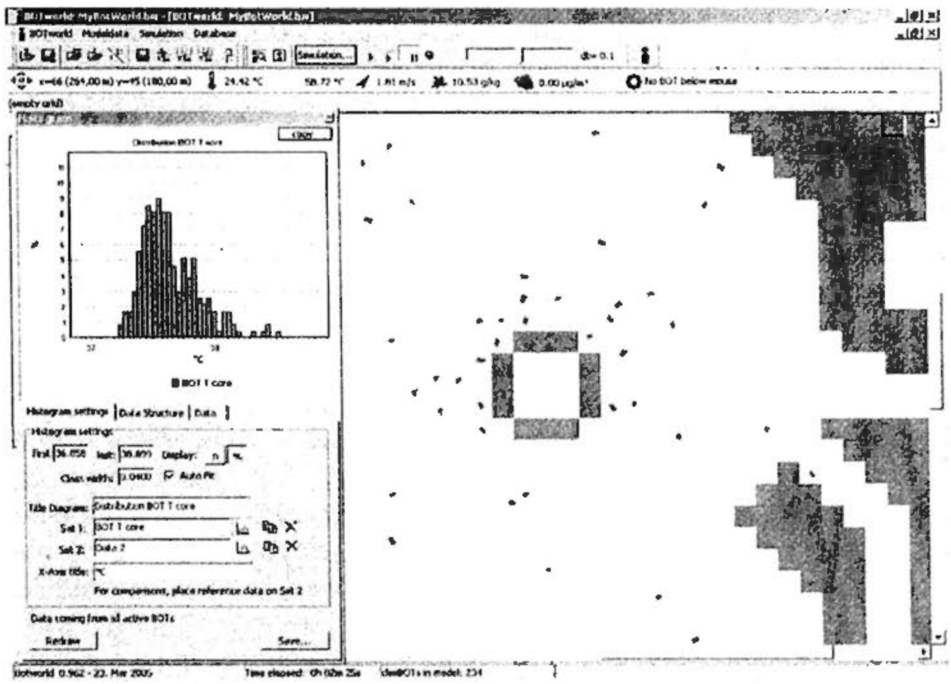


Figure 2.8 Interface of BOTworld. The interface of the PedWalk module is on the right side of the panel. After (M. Bruse, 2007)

2.5 Summary of Literature Review

Pedestrian is important to cities. Improving pedestrian comfort has drawn increasing concern for urban design and planning, especially for regions such as Hong Kong where pedestrian flow is a main force of urban dynamics. A key issue in this aspect is to investigate how the local micro-climatic conditions, being the mixture of air temperature, solar radiation, wind speed, humidity, etc., affect pedestrian's thermal sensation and influence their behaviors and therefore the use of urban space.

Unfortunately, only limited research along this line has been conducted to walking compared with general outdoor activities. Evaluation tools are also absent in the integration of meteorological assessment and usage pattern prediction. Agent based models manage to integrate the spatial, social, behavioral aspects of collective phenomena through a bottom-up approach, and so are capable of framing the underlying problem and identifying determinant factors for complex consequences. The ABM simulation allows various scenarios to be tested which makes it an effective tool to support decision making. An agent based simulation system with microscopic pedestrian modeling and thermal assessment is in need.

Chapter 3 Development of PedNaTAS, an Agent-Based Software Framework for Microclimatic Assessment

3.1 Introduction

In this chapter, a software framework PedNaTAS (Pedestrian Navigation Thermal Assessment System) is presented. The general idea of PedNaTAS is to assess outdoor local meteorological condition through individual pedestrians' thermal sensation while they walk in the urban environment. When a pedestrian is walking in an urban setting, her thermal comfort index will be calculated depending on her individual characteristics (gender, velocity, clothing, etc.) and the environmental factors (temperature, sun exposure, wind speed, etc.). This bottom-up approach has its advantage over other static thermal indices in that it takes into account pedestrians' behavior such as routing and scheduling based on the street furniture and land use, and their interactions with other pedestrians, such as overtaking and collision avoidance. In this way, frequentation of locations and usage pattern of areas can be derived with concern of pedestrians' thermal comfort. In PedNaTAS, an multi-agent system is implemented to simulate pedestrians' movement, and the popular bio-meteorological index of Physiological Equivalent Temperature (PET) (Mayer & Höppe, 1987) is used for modeling pedestrian's static state thermal sensation, and the Pierce Two-Node Model (Gagge, Stolwijk, & Nishi, 1971) is used to model pedestrian's transient state in a temporal manner. Developed as a Spatial Decision Support System (SDSS), the PedNaTAS system is developed in connection with GIS data. Figure 3.1 presents the conceptual framework of the system. It evaluates design scenarios by: 1) representing design factors by relative data; 2) simulating the scenarios through the interface; 3) visualizing the simulation process and also the result; 4) conducting both quantitative and qualitative analysis of the simulation result, and 5) providing assessment of the design scenarios.

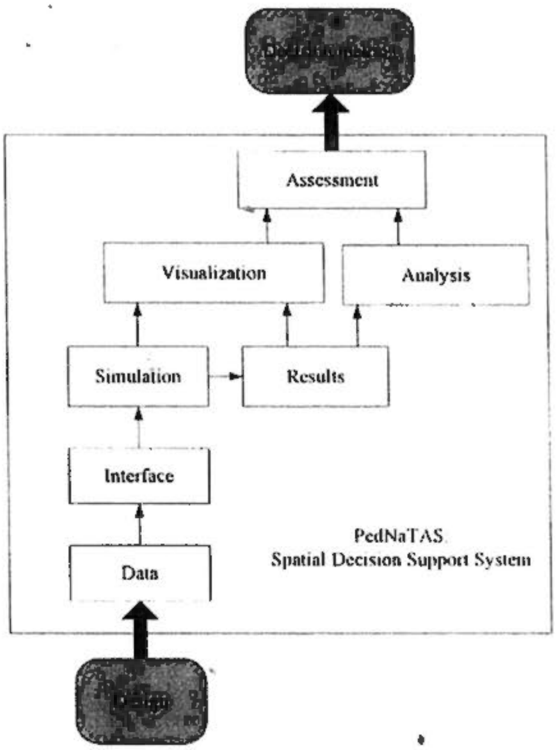


Figure 3.1 From design to decision making: the conceptual framework of PedNaTAS.

Data

The Data component is a comprehensive database storing all the information of a design scenario including spatial (urban morphology, street network, etc.), environmental (climatic condition), socioeconomic (land use, form of transportation, etc.) and behavioral information (people's activity, etc.). The information is fed into the system to generate simulations. A detailed description of the Data component is discussed in Section 3.2.

Interface

The Interface component is a graphical platform to generate scenarios and control simulation processes. Various settings are provided to investigate individual or aggregated behaviors. Through the Interface component, the simulation process can be captured by the form of snapshot or video, and the simulation result can be saved in data storage for further analysis.

Simulation

The Simulation component is the key component of the system. It implements a multi-agent system to simulate people's walking activities in urban environment. Each pedestrian is associated with a route, and the thermal sensation of the pedestrian is assessed while she walks along the route. Because of the dynamic and collective feature of pedestrians, aggregated pattern will emerge and aggregated analysis can be carried on. A detailed description of the Simulation component is discussed in Section 3.3.

Visualization

MacEachren and Kraak (2001) addressed the primary effort on the "*representation* of geospatial information, *integration* of visual with computational methods of knowledge construction, *interface design* for geovisualization environments, and *cognitive/usability* aspects of geovisualization" for decision support systems. As an SDSS, the Visualization component is also one of the most important components of the system. During the simulation process, the display is updated at each time step. Functions such as zoom-in/zoom-out and freeze display are also provided for different observation purposes. The simulation result can also be displayed graphically.

Results, Analysis and Assessment

The Results component stores the simulation output into data storage such as charts and spreadsheets, based on which spatial and statistical analyses are carried out by the Analysis component. The visualization and analysis data could be assessed to give evaluations to the tested design scenarios.

3.2 Description of Software Framework

The PedNaTAS system consists of two main modules: a pedestrian simulation module and a thermal comfort assessment module. Figure 3.2 presents the software structure of the system. The system uses an "Environmental Context + Individual Parameters + Behavioral Rules + Activities + Evaluation" schema based on Willis *et al*. (2000). The urban environment context contains both spatial and environmental information. A person possesses a list of individual parameters. She enters the urban environment associated with a route, perceives the environment, behaves accordingly and forms a walking activity. Based on the walking activity and the local environmental condition, the thermal comfort level of the person is evaluated.

The pedestrian simulation module is implemented as a multi-agent simulation system written in Java programming language with the Repast Simphony ABM library (http://repast.sourceforge.net/index.html). The thermal comfort assessment module is implemented as objects of a pedestrian based on the PET index (Mayer & Höppe, 1987) and the Two-Node Model (Gagge, et al., 1971), but re-implemented in Java programming language; the thermal comfort assessment module is also "loose-coupled" (Stevens, Myers, & Constantine, 1974) with the SOLWEIG model (Lindberg, et al., 2008) for radiation calculation. The PedNaTAS system is implemented with support of GIS data, including shape file data and ESRI format raster data. The following sections give detailed descriptions of the software framework of the system.

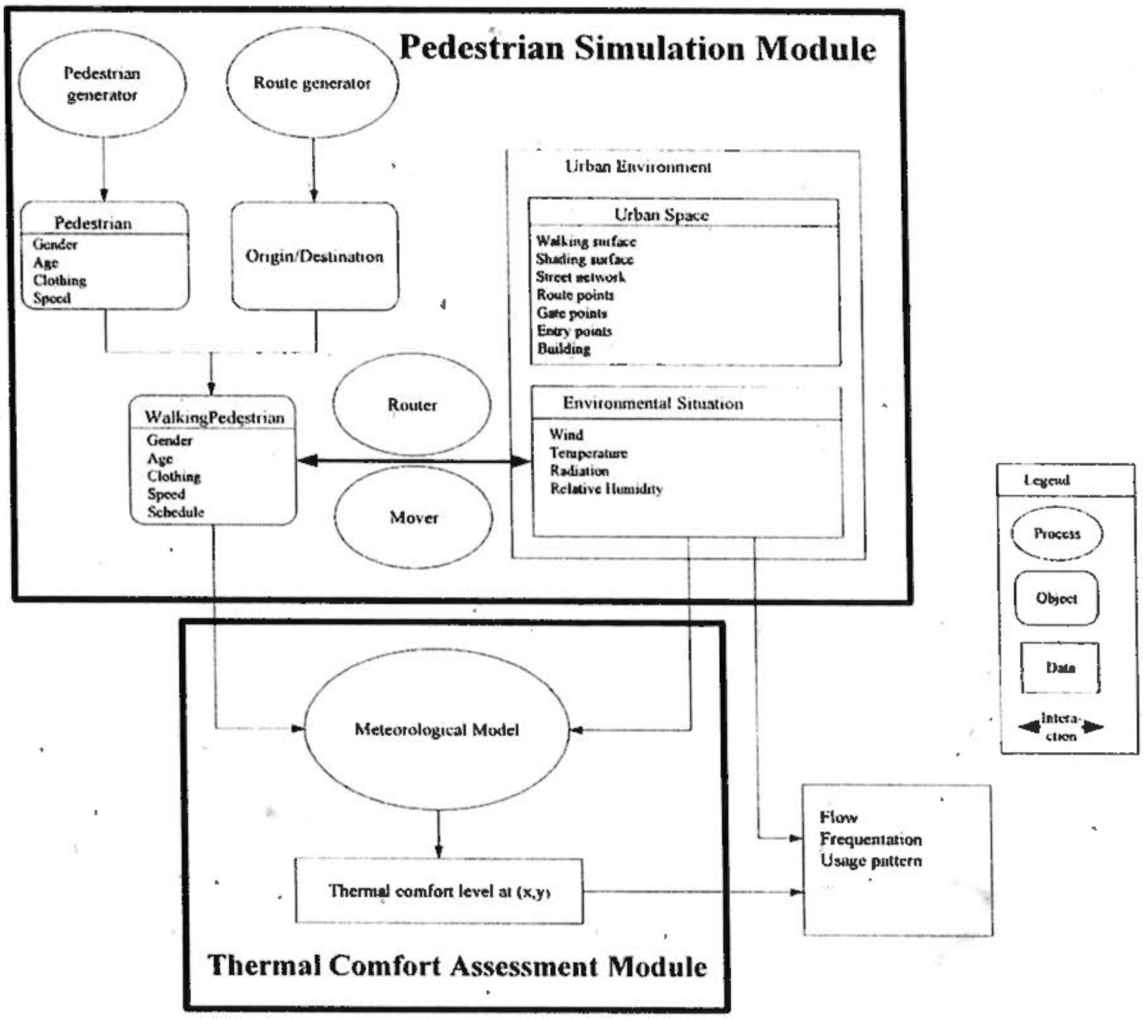


Figure 3.2 Software structure of PedNaTAS.

3.2.1 Representation of Urban Context

The urban context in PedNaTAS has a highly hierarchical structure, represented in a vector database and a raster database. Figure 3.3 shows an overview of the data structure and data flow in PedNaTAS.

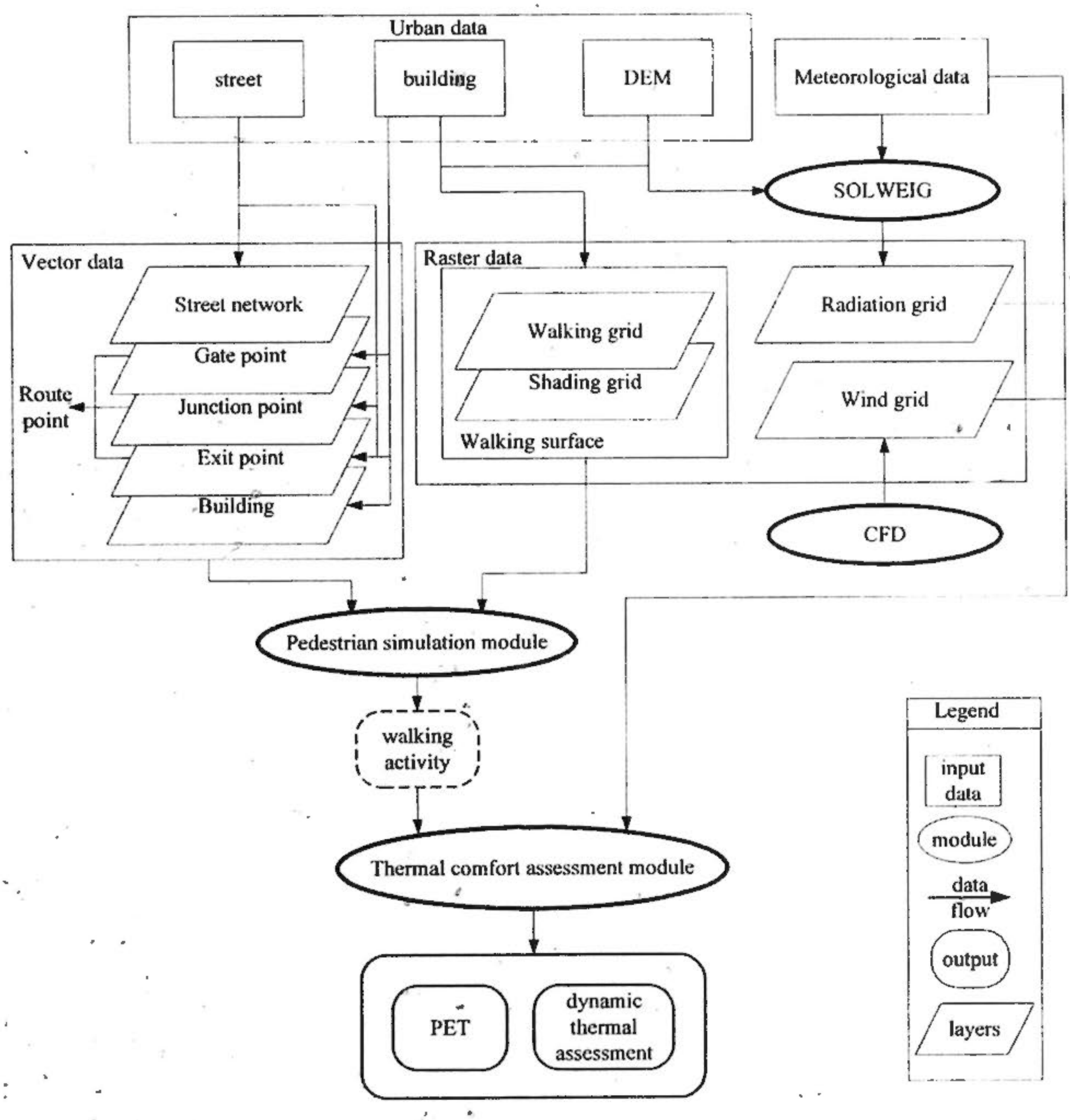


Figure 3.3 Data structure and data flow in PedNaTAS.

3.2.1.1 Vector Database

Building

The Building dataset is a GIS shape file which stores the geometries and attributes of all buildings in the domain. The attributes include both spatial attributes such as area and height of the buildings, and socioeconomic attributes such as land-use as well. This dataset is directly loaded from input data.

Gate Point

Gate points represent the locations from where the pedestrians enter the domain, such as street end points, car parks and bus stops. Each Gate point "pops" pedestrians at a certain rate according to its property. A Gate point is the origin of a pedestrian's route. This dataset is also directly loaded from input data.

Exit Point

Exit points represent the locations from where the pedestrians leave the domain, such as street end points, car parks, bus stops and most commonly building entrances. An Exit point is the destination of a pedestrian's route. This dataset is also directly loaded from input data.

Junction Point

Junction points are the end points of the streets in the domain. They are automatically constructed from input street shape file data. A Junction point has associated properties such as the total number of pedestrians around, which are used in pedestrian dynamic control (refer to Section 3.3.2.2 for a detailed discussion on the control process).

The Gate point, Exit point and Junction point together form the dataset of **Route point**. As the name implies, Route points are the points that compose a pedestrian's planned route.

Street Network

The Street network dataset is the combination of a network dataset representing the connectivity of the streets built upon Route points, and a street shape file consisting of street length information which is used in the routing process. The Street network together with the Route points controls the "*strategic*" movement of pedestrians, meaning movement from a location to another location in the urban environment. The network dataset is constructed automatically when the input street shape file is loaded.

The framework of the vector dataset of the urban context, in particular the Building, Junction and Street network representations are based on the open-source package of RepastCity by Malleson (2008). The implementation has been re-developed extensively to meet the objectives of this study. Section 3.3 presents detailed discussions of the development.

3.2.1.2 Raster Database

The PedNaTAS system has a raster database representing the **Walking surface** of the urban context. The Walking surface consists of two parts: the Walking grid representing the walkability of the urban spaces, and the Shading grid representing the shade pattern of the urban spaces. Both grids are in ESRI ASCII format. A raster reader is implemented to read in ESRI ASCII format data (refer to Section 3.5 for a detailed discussion on the raster reader). Likewise, a raster writer is also implemented to export ESRI ASCII format data for analysis purposes.

Walking Grid

The Walking grid is a raster dataset classified into 3 categories representing the walkability of different types of urban spaces: the pavement sidewalk which is always walkable, the building which is never walkable, and the car traffic road which is only walkable under restricted circumstances. The Walking grid controls the "*physical*" movement of pedestrians as opposed to the strategic movement, meaning the actual displacement of pedestrians at each time step. Weight of different types of walking spaces in route choice and the mechanism of the physical movement is discussed in Section 3.3.

Shading Grid

The Shading grid represents how the Walking surface is shaded by buildings. The shading is perceived by pedestrians while walking and can affect their route choices. The "shadow casting" algorithm (Ratti, 2001; Ratti & Richens, 1999) provides a rapid way to calculate shadow patterns based on DEM data and is applied in this study. In practice, the SOLWEIG system implements the algorithm and outputs ESRI ASCII format data so is used to generate the Shading grid for the PedNaTAS system.

3.2.2 Representation of Meteorological Environment

The meteorological environment in PedNaTAS is represented by two categories of meteorological parameters, being global parameters and spatially various parameters. The global parameters are the parameters that are considered to be constant over the domain, including air temperature (T_a), relative humidity (RH) and global radiation (radG). In contrast, the spatially various parameters are the parameters dependent on the local characteristics of the domain, including mean radiant temperature (T_{mrt}) and wind speed (v). In this sense, they are stored as raster format data and read in as grids in the raster database in the system. The T_{mrt} grid is generated by the SOLWEIG system. The wind speed grid is derived from a computational fluid dynamic study. These two grids are to be introduced in more details in Chapter 4.

With the introduced representation, the local climatic condition for a particular spot in the urban environment could be specified.

3.2.3 Representation of Person

Each person in PedNaTAS is modeled as an individual with a rich set of parameters describing her characteristics. The parameters include personal (age, gender), physiological (height, weight, clothing), spatial (location), behavioral (current speed, preferred speed, maximum speed, planned route), and thermal features of the person. The thermal parameter of a person is modeled as an object implementing the thermal comfort assessment module (refer to Figure 3.2), which updates the thermal sensation of the person along walking. A person also has a unique ID for identification which is assigned when she is populated.

A person can perceive the Street network she is on to detect changes such as congestion ahead, and re-plan her route accordingly. A person is also associated with the raster database of the urban context. In this way she can perceive the urban space while walking and acts accordingly, such as avoiding obstacles and choosing a path with more shading; on the other hand she can also perceive the local environmental conditions at her location to evaluate her current thermal comfort level. A person can also perceive other persons in the urban environment and interact with them. Details of the behavioral control of a person are discussed in Section 3.3.

3.3 Pedestrian Simulation Module

The pedestrian simulation module is the most essential component of the PedNaTAS system. The module is an agent based simulation system working at three levels from top down to model pedestrian's walking behaviors. The three levels of work (from top down) are: social behavior modeling, proactive behavior modeling, and reactive behavior modeling. The following sections give detailed discussions on each level of work.

3.3.1 Pedestrian's Social Behavior: A Simplified Activity-Based Model for Origin-Destination Assignment

The top level of a pedestrian's behavior is the social behavior, meaning the travel demand of the pedestrian represented by the origin/destination pair of a trip. However, in reality a pedestrian can take a trip from an infinite set of alternatives which makes the modeling of travel behavior both theoretically and practically intractable. To solve the problem, the origin-destination assignment of a trip needs to be formalized. In the

PedNaTAS system, an activity-based approach is taken which uses the discrete model (Ben-Akiva & Bierlaire, 2003) with the utility theory (Domencich & McFadde, 1975) to estimate the probability of a destination to be selected from a destination set. A discussion in operation management is quite relevant to the theme of this part of work. Environmental psychologists propose that individuals generally react to their environment with two opposite forms of behaviors, *approach* or *avoidance* (Mehrabian & Russell, 1974): approach behaviors include the positive behaviors that might be directed at the place such as the desire to stay, whereas avoidance is the opposite. These two behaviors could be captured by the utilities of different places.

For a finite destination set with n destination points, the probability of a destination point D_i to be selected by an origin point O_j could be derived from the logit choice model and represented by

$$P(D_i)_j = \frac{\exp(V_{i,j})}{\sum_{k=1}^{n} \exp(V_{k,j})}, \qquad \text{(Equation 3.1)}$$

where $P(D_i)_j$ is the probability for D_i to be selected by O_j, $V_{i,j}$ is the utility of D_i to O_j, and $V_{i,j}$ is given by

$$V_{i,j} = \beta_1 \times POS(i,j) + \beta_2 \times NEG(i,j) + \beta_3 \times \varepsilon, \qquad \text{(Equation 3.2)}$$

where $POS(i,j)$ and $NEG(i,j)$ are the systematic utilities representing the positive and negative utilities of V_i to O_j respectively, and ε is the random utility. To simplify the discussion as well as the implementation, the parameter of building floor area is used as a preliminary setup for the positive utility estimation, and the parameter of the distance from a destination candidate to the origin point is used as the negative utility. Although this is rather rough estimation, it agrees with the common wisdom that people are inclined to choose the destinations nearby, especially for the case when they use different exits of the subways stations, etc. The utilities of all the Exit points are calculated and a **Roulette Wheel Selection Algorithm** is implemented to select a destination point from the Exit point list. The algorithm is shown in Algorithm 3.1.

Algorithm 3.1 Roulette Wheel Selection Algorithm for selecting a destination point from the Exit point list.

```
Calculate probabilities of each destination point to be selected: {P(0), P(1)..., P(n)};
A random number r;
Sum = 0;
Do {
    Sum += P(i);
}while (Sum < r)
Destination D_i is selected.
```

3.3.2 Pedestrian's Proactive Behavior: Route Planning Methodology

The second level of a pedestrian's behavior is the proactive behavior, meaning the goal-directed navigation in a complex urban environment. The proactive behavior is one of the most important abilities of a pedestrian in that the primary task of a pedestrian is to plan a path to reach the destination in a sensible manner. As introduced earlier in Section 3.2.1.1, this level of behavior reflects pedestrian's strategic movement along a trip. In practice, this is implemented as a path-finding algorithm based on the origin/destination pair. The path is composed of a series of Route points. While moving between Route points, the pedestrian also senses the change of the Street network and uses dynamic routing to avoid congestions ahead.

3.3.2.1 Path-Finding

The basic assumption of a pedestrian's proactive behavior is that she tends to reach the destination with minimum cost, being the combination of distance, convenience and comfort. These factors can be projected to the weights associated with the Street network, and a shortest path in terms of the cost can be calculated.

The framework of the path-finding method is based on the routing method of the open-source package of RepastCity (Malleson, 2008). The basic steps for a pedestrian p at origin O to reach her destination D are (as illustrated by Figure 3.4):

1) p travels from O to the nearest street $\overline{AA'}$;
2) p travels along the Street network, taking a shortest path to the street $\overline{BB'}$ which is closest to D;
3) p travels from the street to D.

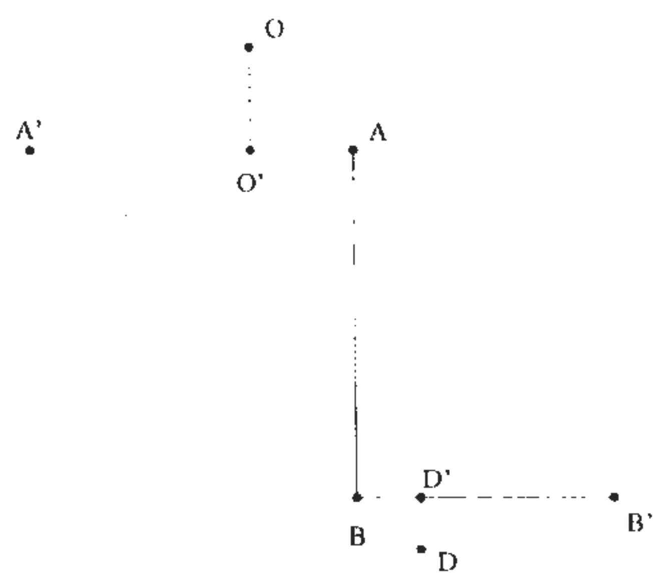


Figure 3.4 Illustration of the path-finding steps from origin O to destination D.

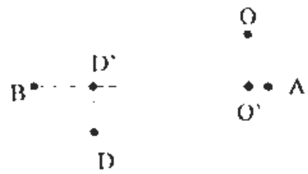
In implementation, the steps to calculate the path from O to D are reversed:

1) find the nearest street point to O: O';
2) find the nearest street to O: the first street $\overline{AA'}$;
3) find $\overline{AA'}$'s nearest Junction point to O: the first Junction A;
4) find the nearest street point to D: D';
5) find the nearest street to D: the last street $\overline{BB'}$;
6) find $\overline{BB'}$'s nearest Junction point to D: the last Junction B;
7) find a shortest path between A and B: [AB];
8) the path from O to D is given by {O, O', [AB], D', D}.

The shortest path between two Junctions points in a Street network, in this case A and B, is calculated by *Dijkstra's* algorithm (Cormen, Leiserson, Rivest, & Stein, 2001), which is provided as a class method by the Repast Simphony package. However, there are still a few more steps to be added before the above mentioned method can produce correct paths with no redundant routing. These issues are not addressed in (Malleson, 2008) and are discussed here. The basic idea is that, after finding the two Junction points A and B, the method needs to check and ensure that the calculated path doesn't go repetitively between Junction points when calculating the shortest path. The checking algorithm is presented by Algorithm 3.2, with illustrations of different cases (in the same notation with Figure 3.4).

Algorithm 3.2 Algorithm for finding a path between O and D by constructing a route consisting of a list of route points.

1) Add O to route.
2) If A and B are different:
   This means that there is a path between the first Junction and the last Junction.
   a. Find path [AB];
   b. If $\overline{AA'}$ and $\overline{BB'}$ are the same:
      This means that O' and D' are within the span of the same street:



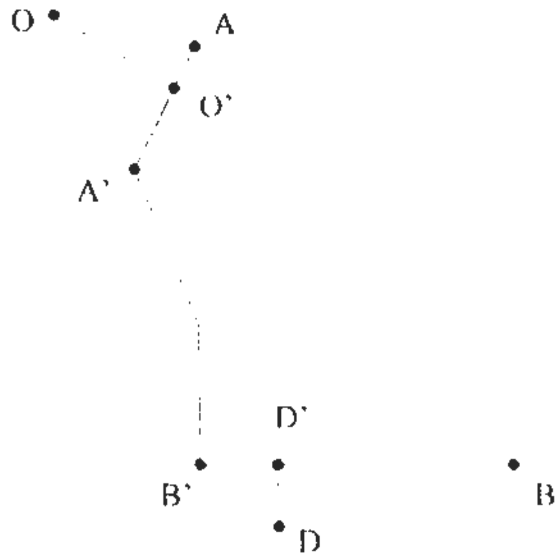
i. Add [O'D'] to route;

ii. Add D to route.

iii. End.

c. If $\overline{AA'}$ and $\overline{BB'}$ are different:

This means that there are more than one edge in the path between O' and D':



i. If O' is on the first edge $\overline{AA'}$ of path [AB]:

1. Delete A;
2. Set A' as the first Junction.

ii. If D' is on the last edge $\overline{BB'}$ of path [AB]:

1. Delete B;
2. Set B' as the Last junction.

iii. Find path [first Junction, last Junction];

iv. Add [O', first Junction] to route;

v. Add [first Junction, last Junction] to route;

vi. Add [Last junction, D'] to route;

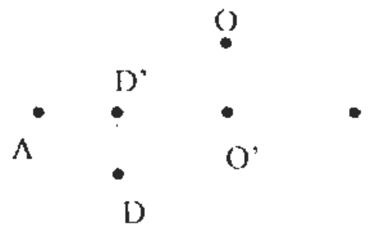
vii. Add D to route;

viii. End.

3) If A and B are the same:

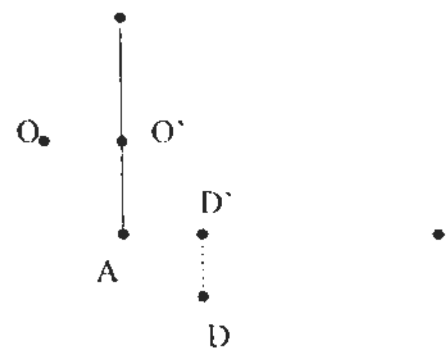
This means that A and B are the same Junction, so O' and D' are connected by one Junction A.

a. If ∠O'A is equal to ∠D'A (∠O'A means the angle formed by the vector $\overrightarrow{O'A}$ and the +X axis):



i. Add [O'D'] to route;
ii. Add D to route;
iii. End.

b. If ∠O'A is not equal to ∠D'A:



i. Add [O'A] to route;
ii. Add [AD'] to route;
iii. Add D to route;
iv. End.

The path-finding process reflects the "*static*" aspect of pedestrian's proactive behavior: given a setting of the Street network, a pedestrian plans for a route that connects the origin and the destination by a list of Route points at the beginning of the trip. In this way the trip is divided into a series of sub-trips which ensure the pedestrian could always reach her destination. The movement control between Route points is discussed in Section 3.3.3.

3.3.2.2 Dynamic Routing

As discussed in the previous section, the path-finding method pre-plans a route for a pedestrian before a trip. However while the pedestrian is in the middle of her trip, the urban environment could also be changed: some streets may get congested, which makes them less attractive in the path selection; some Junction points may even get jammed, which completely denies the pedestrian's access. The dynamic routing method is implemented to allow the pedestrian to sense the change of the urban environment, in particular congestions in the Street network, and reroute accordingly to avoid them. This section first defines the congestion setting in the system, and then introduces the dynamic routing method.

Congestion Definition

In the system, the congestion condition for a Junction point j is described by the number of pedestrians nearby, denoted as $PedCount(j)$. In implementation it is calculated by counting the number of pedestrians within a 2.5m radius circle centered at j. This parameter is compared with the commonly used Level-Of-Service (LOS) (Fruin, 1987) index to derive threshold values to define congestion occurrence. The LOS index is one of the most important indicators to describe the density of traffic flow, especially pedestrian flow. Different categories of LOS for pedestrian traffic and their corresponding characteristics are listed in Table 3.1. Figure 3.5 presents an illustration of different LOS categories.

Table 3.1 Different categories of Level-Of-Service (LOS) for pedestrian traffic and characteristics. Modified after Fruin (1987) and Transportation Research Board (2000).

LOS	Density (P/m^2)	Description	Traffic characteristics
A	0.00 – 0.10	Open	No restriction
B	0.10 – 0.30	Impeded	Free movement
C	0.30 – 0.45	Constrained	Occasional obstruction
D	0.45 – 0.60	Crowded	Partially restricted

E	0.60 – 0.75	Crowded	Significant obstruction
F	0.75 – 1.00	Congested	Dense traffic
G – I	> 1.00	Jammed	Moving queue

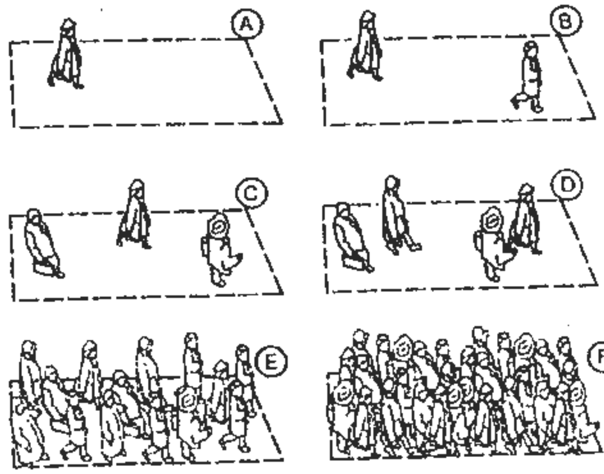


Figure 3.5 Illustration of LOS A-F (Transportation Research Board, 2000).

It can be seen from Table 3.1 that LOS D and F are two significant thresholds in describing the congestion condition of a point: LOS D indicates the point is becoming crowded so less attractive for an upcoming pedestrian therefore the associated cost to taking this path should be increased, and LOS F indicates that the point is jammed so the pedestrian should take alternative paths if there is one. These two conditions are described by the lower threshold and the upper threshold of pedestrian count, denoted as $Threshold_{low}$ and $Threshold_{up}$, respectively. In practice, $Threshold_{low}$ is rounded to 10 and $Threshold_{up}$ is rounded to 25 to simplify the calculation. Then the congestion factor $C(j)$ for Junction point j is given by:

$$C(j)=\begin{cases}1, & \text{if}\,(PedCount(j)\le Threshold_{low})\\ \dfrac{Threshold_{up}-Threshold_{low}}{Threshold_{up}-PedCount(j)}, & \text{if}(Threshold_{low}<PedCount(j)<Threshold_{up})\\ infinity, & \text{if}\,(PedCount(j)\ge Threshold_{up})\end{cases},$$

(Equation 3.3)

Figure 3.6 shows an illustration of the curve $C(j)$. The "virtual length" of a street with Junction points A and B is given by:

$$length(\overline{AB})_{virtual}=\sqrt{C(A)\times C(B)}\times length(\overline{AB})_{physical},\qquad \text{(Equation 3.4)}$$

where $C(A)$ and $C(B)$ are the congestion factors for Junction A and B respectively, and $length(\overline{AB})_{physical}$ is the physical length of the street $\overline{AB}$. The virtual length of a street is used in the shortest path algorithm. In this way, congested Junction points are "pushed" far from the origin, making them less likely to be selected in the path-finding process. An extreme case would be a street with jammed Junction points will be considered as infinitely far from the origin and consequently never selected as a path, which is consistent with the facts in real life that jammed spots will always be avoided in traveling.

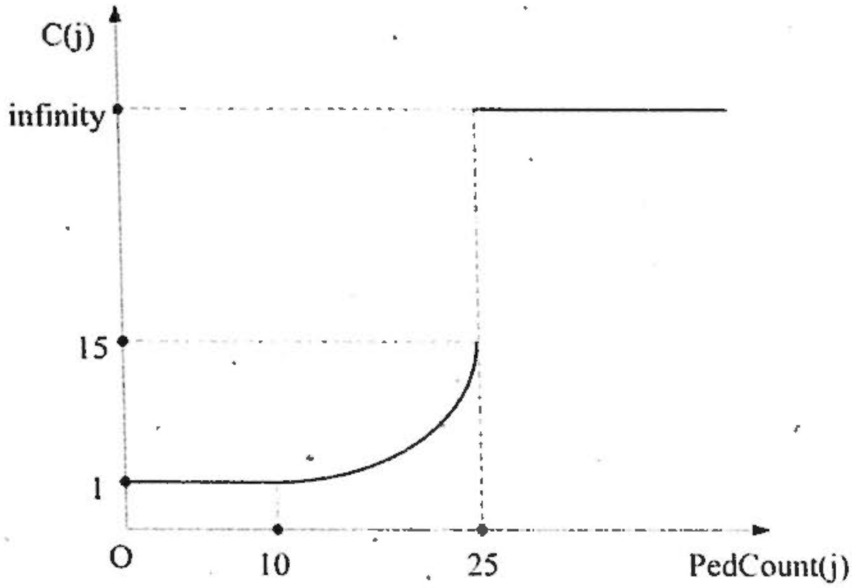


Figure 3.6 Illustration of *C(j)* curve.

Dynamic Routing Method

As introduced at the beginning of this section, the main function of the dynamic routing method is to allow pedestrians to look for congestion ahead and re-plan the path dynamically to avoid it. The control mechanism is quite straightforward after the congestion setting is defined. The basic idea is, when a pedestrian arrives at a Junction point, she re-calculates the shortest path based on the updated virtual length of the Street network; traveling from a Junction point to another, she constantly checks if she is close to the current target Route point and whether congestion occurs around it. If so, she neglects the current target Route point and moves to the next Route point in the route. In this way, a pedestrian can avoid congestion both nearby and far away. The control flow of the dynamic routing method is presented in Figure 3.7.

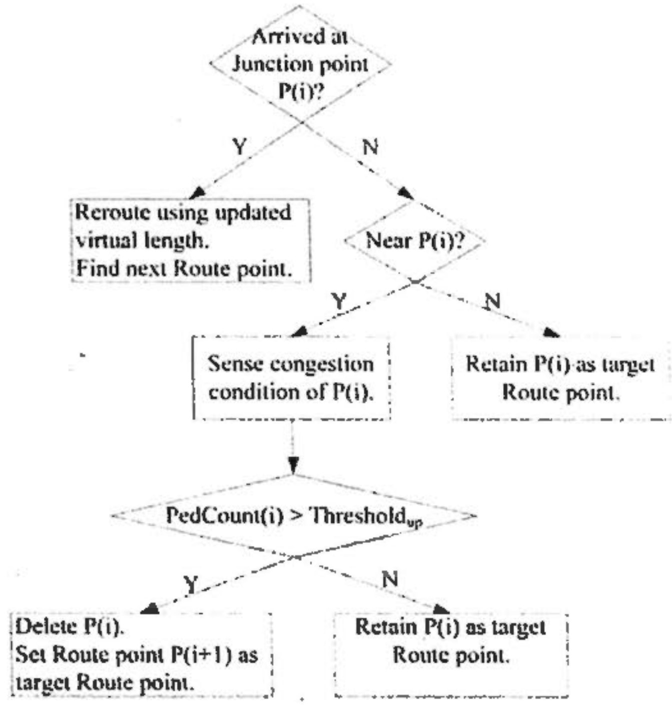


Figure 3.7 Control flow for dynamic routing method.

The dynamic routing process reflects the "*adaptive*" aspect of a pedestrian's proactive behavior: she perceives changes in the urban environment and adjusts the route planning behavior instantly to deal with the changes. This adaptive behavior is working on the level of strategic movement. How pedestrians adapt to the environment on the level of *physical* movement, such as collision detection and avoidance, is further discussed in Section 3.3.3.

3.3.3 Pedestrian's Reactive Behavior: Microscopic Movement Control

The proactive behavior works on the level of route planning and allows pedestrians to navigate through Route points along the Street network to reach their destinations. However, another level of behavior needs to be implemented to control the *physical* movement of pedestrians between Route points. The situations dealt with here include pedestrians' timely displacement, how they avoid static obstacles such as building, how they detect potential collision with other pedestrians and avoid it, and how they occupy space on sidewalks and car traffic roads, etc. The reactive behavior is designed in this purpose to model pedestrians' microscopic movement behavior. Since the objective of this research is to assess the local microclimatic condition of the urban environment, modeling pedestrians' microscopic movement is the key part of the simulation course.

3.3.3.1 Grid Layout Definition

The walking domain of the system is organized as a two-dimensional grid of size $W \times H$ (cells), with each cell representing the space occupied by a pedestrian. Early studies have suggested that the minimum area covered by a moving pedestrian is 0.9m×0.9m (Fruin, 1987; Pushkarev & Zupan, 1975; Transportation Research Board, 2000), and in simulation implementation, the settings of 0.5m×0.5m, 0.75m×0.75m and 1m×1m have been used (M. Bruse, N/A; Kerridge, et al., 2001). Considering the high-density feature of the normal urban situation in Hong Kong, the cell size of 0.5m×0.5m is selected for this system. The cell size is denoted by ΔD, where ΔD = 0.5. The **Moore** neighborhood is used to describe the eight cells surrounding a pedestrian. An illustration of the representation of grid cell is shown in Figure 3.8. The movement of the pedestrian at a grid cell P(i, j) is discretized into the movement to her neighborhood cells, as represented by the heading indexed from 0 to 7 ordered anti-clockwisely.

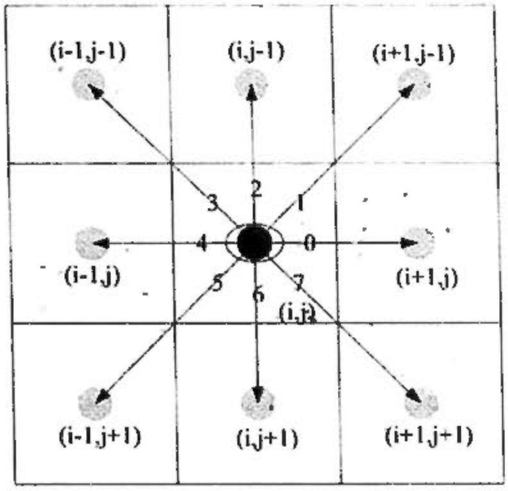


Figure 3.8 Representation of grid cell. A person at cell P(i, j) has 8 neighborhood cells. The headings to eight neighborhood cells are represented by 0, 1, ..., 7 ordered anti-clockwisely. One thing to be noticed is that the +J axis is pointing down (south) because of the matrix implementation in Repast Simphony. Details of coordinate orientation are discussed in Section 3.5.

It can be drawn from Figure 3.8 that the travel distance between two neighborhood grid cells Pa and Pb, denoted by Δ(Pa, Pb) can be given by:

$$\Delta(Pa,Pb)_{non-diagonal} = \Delta D, \text{ for non-diagonal cases,} \qquad \text{(Equation 3.5)}$$

and

$$\Delta(Pa,Pb)_{diagonal} = \sqrt{2}\Delta D, \text{ for diagonal cases.} \qquad \text{(Equation 3.6)}$$

In the domain, each grid cell is associated with 1 person only. This is realized by defining an **Occupied matrix** O of size $W \times H$ storing the occupancy status of each grid cell of the walking domain. When a person P steps onto a cell grid P(i, j), then O(i, j) is set to the ID of the person, which prevents other persons from stepping onto the cell grid until P leaves the grid. Otherwise O(i, j) is set to -1 which means the cell grid is vacant and could be occupied by any person.

3.3.3.2 Microscopic Movement Between Grids

The grid cell representation of space has been adapted by many pedestrian simulation models, including both ABM and cellular automata (CA) approaches (Blue & Adler, 2000; Haklay, et al., 2001; Kerridge, et al., 2001). However how pedestrians move from one grid cell to another, in another way their microscopic movement has not drawn enough attention. A conventional way is to have pedestrians "hopping" from cell to cell in a CA manner. This approach will cause issues when dealing with pedestrians with different walking speed and also the interaction of pedestrians. So far to the author's knowledge, only the PedWalk model by Bruse (N/A) has addressed this issue explicitly. The present work is largely inspired by PedWalk.

The microscopic movement control method uses a "**discrete space + continuous movement**" schema, meaning the associated cell gird of a pedestrian is discrete, while the displacement of a pedestrian is continuous. An illustration is presented in Figure 3.9. As shown in the illustration, a pedestrian p associated with the grid cell Pa is moving to a neighborhood grid cell Pb. The distance between Pa and Pb is denoted by $\Delta(Pa, Pb)$. The distance p has traveled since leaving the center of Pa is denoted by $\Delta_{traveled}$, and the distance p needs to travel before reaching the center of Pb is denoted by $\Delta_{to\_be\_traveled}$. Then the associated grid cell of p needs to be changed to Pb if

$$\Delta_{traveled} > \frac{1}{2}\Delta(Pa,Pb), \qquad \text{(Equation 3.7)}$$

which is indicated as the "*" sign in the illustration.

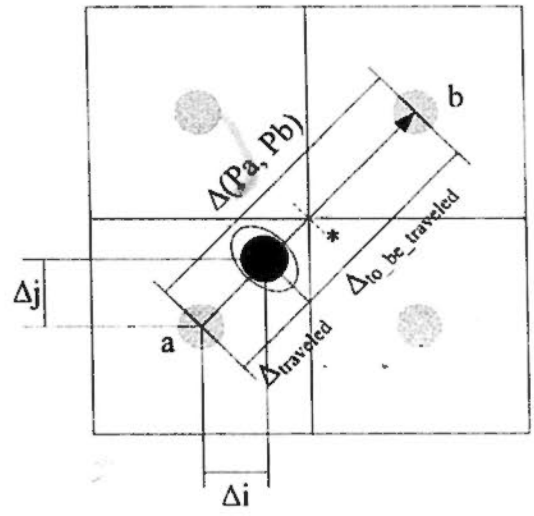


Figure 3.9 Illustration of the control of pedestrian's movement between grid cells. Modified after (M. Bruse, N/A). The sign "*" indicates the place where the associated grid cell of the pedestrian is changed.

In implementation, the updating schedule is set to have a very small time interval, which is in the order of 0.1 second. And when a pedestrian is within a small distance from a grid cell center (5cm in the current implementation), she is set to the grid cell center automatically. This approach might be a little bit different from the natural movement process of pedestrians, but it seems to be the only way to simulate pedestrian's microscopic movement in a grid environment in a sensible manner without making the model endlessly complex.

3.3.3.3 Decision Making in Target Grid Cell Choice

The decision to select a target grid cell to move to is the most important process in pedestrian's microscopic movement in that it forms a consecutive movement from cell to cell to reach the current target Route point. The decision making is mainly directed by the goal to move towards the target Route point, on the other hand it is also affected by situational factors such as in case all other neighborhood grid cells are occupied, the pedestrian has to move to the only vacant one, and subjective factors such as the preference to move to grid cells with shade. This section discusses the decision making control in target grid cell selection.

Lewin (1951) has suggested to describe the space perceived by a pedestrian as an ellipse, which is adapted in this study. The basic assumption is that a pedestrian is unlikely to move backwards when the goal is to move forwards (Kerridge, et al., 2001). So given a target Route point T, a pedestrian looks up to 5 directions aligning with the direction to T to evaluate the 5 neighborhood grid cells. An illustration is presented in Figure 3.10.

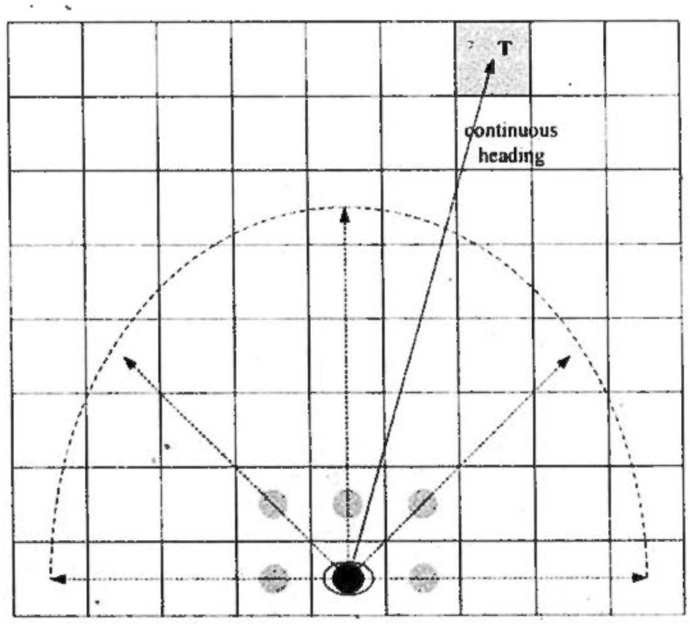


Figure 3.10 Illustration of a pedestrian's perception ellipse in deciding the next grid cell to move to. T is the current target Route point. The grey dots are possible target grid cells. The pedestrian looks up to 5 directions towards T. Figure is drawn as indicative.

In implementation, a pedestrian looks ahead up to 5m (10 grid cells) towards T to evaluate each neighborhood grid cell. The evaluation function at this stage is defined as:

$$\Pi(i) = V(i) \times \cos(Heading_{continuous} - Heading(i)), \qquad \text{(Equation 3.8)}$$

where i is the neighborhood grid cell, $V(i)$ is the visible length along direction i, $Heading_{continuous}$ is the continuous heading to T and $Heading(i)$ is the discrete heading to i. $V(i)$ is defined as the length of the visible grid cells along direction i, including both sidewalk and car road but not building. The evaluation function reflects how much the importance and attractiveness of a neighborhood grid cell is projected along the direction to the target Route point.

The neighborhood grid cell could either be building, sidewalk or car road (refer to Section 3.2.1.2). In case it is building which is not walkable, the pedestrian deletes the grid cell from the possible target grid cell list. In other cases, the selection of a sidewalk cell or a car road cell needs to be controlled properly. Theoretically, pedestrians are only allowed to walk on sidewalks, however in real life a pedestrian might also want to walk on car road if she has to. To distinguish the different priorities of sidewalk and car road grid cells in being selected, the concept of **weight ratio**, denoted by w is introduced. It means that the evaluation value of a car road grid cell must be greater than w times of the evaluation value of a sidewalk grid cell in order to be selected. One thing to be noted is that $\Pi(i)$ could also be negative, so the evaluation value for a car road grid cell, denoted by $\Pi(i)_R$ is defined as:

$$\Pi(i)_R = \begin{cases} \Pi(i)/w, & \text{if}(\Pi(i) > 0) \\ \Pi(i) \times w, & \text{if}(\Pi(i) \le 0) \end{cases}. \qquad \text{(Equation 3.9)}$$

A pedestrian calculates the evaluation values for all the neighborhood grid cells and sort their values into a descending list $\{\Pi(i)\}_d$. The grid cells sorted in the front of $\{\Pi(i)\}_d$ are the grid cells with larger evaluation values meaning they have higher priorities to be selected. An illustration of the sorted list is presented in Figure 3.11. This definition of Π for car road grid cells ensures that the car road grid cells are always selected after the sidewalk grid cells with the same +/- sign of Π, and a car road grid cell with positive Π is selected before a sidewalk grid cell with negative Π. The pedestrian p selects the first grid cell in $\{\Pi(i)\}_d$ and tries to move to it. In case the move fails, i.e., the grid cell is occupied by another pedestrian, p deletes the grid cell from the list and repeats the selection operation. If the list has been exhausted but the pedestrian still doesn't have a target grid cell, it means that currently there is no possibility for the pedestrian to move towards the target Route point, in which case the pedestrian pauses for this time step. How a pedestrian negotiates grid cell with other pedestrians nearby is discussed in next section.

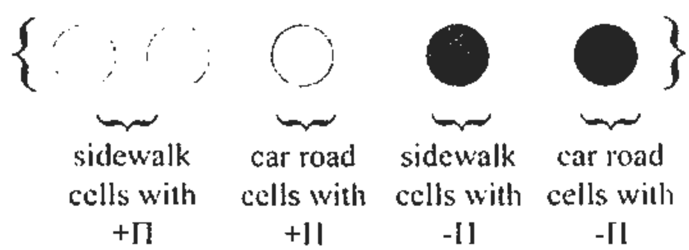


Figure 3.11 Illustration of a sorted list of neighborhood grid cells $\{\Pi(i)\}_d$.

The evaluation function Π and the weight ratio w could be easily modified based on other domain knowledge since they are not intrinsic to the structure of the model. At this stage, Π is defined as the visible length and w is set to 10.

3.3.3.4 Interaction with Other Pedestrians: Collision Detection and Avoidance

Pedestrian interaction includes a large set of activities such as grouping, queue forming, or even pausing and talking to each other. For the objective of this study, a simplified approach could suffice which only deals with collision detection and avoidance in pedestrian's grid cell choice. As discussed in previous sections, the Occupied matrix *O* serves as the basic method to prevent a pedestrian from stepping into a cell grid already occupied by another pedestrian. However, more checking algorithms need to be implemented to detect and avoid potential collision when a pedestrian tries to move into an unoccupied grid cell. An illustration of the checking method is presented in Figure 3.12.

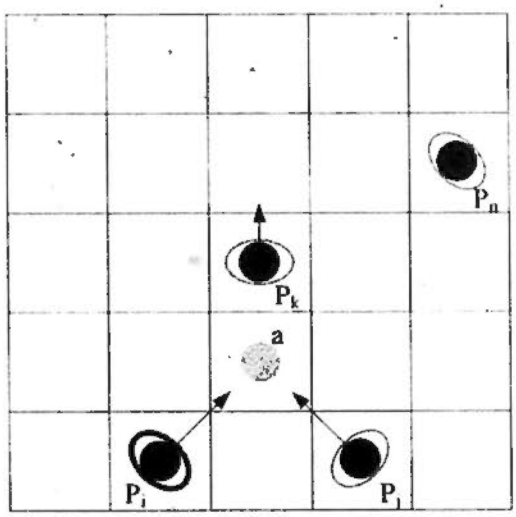


Figure 3.12 Illustration of collision detection and avoidance method. p_i is the pedestrian being examined, *a* is the grid cell p_i tries to move into. The grey cells are the Moore neighborhood cells of a, and p_j, p_k and p_n are nearby pedestrians. The arrows indicate the headings of the pedestrians.

In this method, a pedestrian perceives the movement of nearby pedestrians to negotiate grid cells with them. As shown in Figure 3.12, when a pedestrian p_i tries to move to an unoccupied grid cell a, she checks the neighborhood of a to see if there are other pedestrians nearby. Because of the small time interval used in the model. only the pedestrians at the neighborhood grid cells of a have the potential to cause collision with p_i, in this case p_j and p_k but not p_n. After finding nearby pedestrians, p_i checks their headings to see if they are moving to a. In case there is one, as represented by p_j, p_i checks the pedestrian's walking speed to decide whether to set a as the target grid cell. If speed(p_i) > speed(p_j), which means that based on the current situation p_i will arrive at a earlier than p_j if she makes the move, she selects a as target grid cell, otherwise she gives up a and tries to move to the next grid cell in the sorted list. A random allocation is used for pedestrians with same speed. A **Reserved matrix** R of size $W \times H$ is defined to store which pedestrian a grid cell is reserved for as target grid cell. Similar to the Occupied matrix, if a pedestrian has selected a grid cell P(i, j) as the target grid cell, then R(i, j) is set to the pedestrian's ID until she reaches P(i, j), otherwise R(i, j) is set to -1. A pedestrian can not move to a grid cell which is already reserved for another pedestrian.

3.3.3.5 Microscopic Movement Control Summary

The previous sections discuss the control methods of a pedestrian's microscopic movement. These methods are like the "building blocks" of the model which need to be assembled properly to make the model to work. Figure 3.13 presents the control flow of the implementation of these methods. This control flow constructs the backbone of the simulation system.

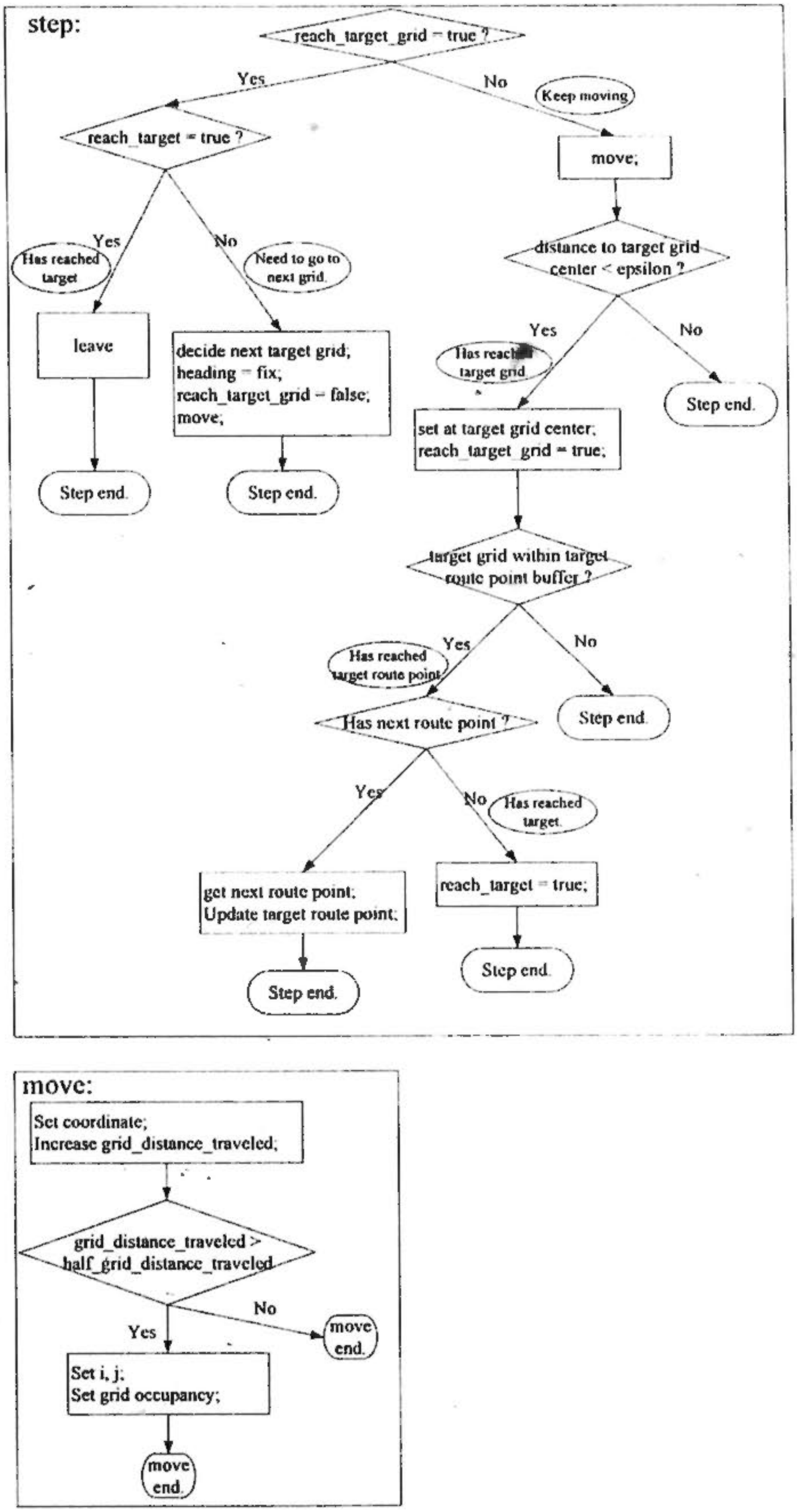


Figure 3.13 Control flow of microscopic movement. The "step" block is the routine performed at each time step, and the "move" block is a sub-routine of "step".

3.3.4 Verification of the Pedestrian Simulation Module

Being the kernel of the PedNaTAS system, the pedestrian simulation module needs to be verified properly, i.e., to ensure that it is programmed correctly and check that it behaves as expected (De Smith, et al., 2007). This is refereed to as "inner validity" by (Axelrod, 1997a; D. Brown, 2006). Theoretically, the most comprehensive way of verifying an ABM is to re-implement the model using a different programming language or a different ABM toolkit. This re-implementation process is referred to as "docking" or "alignment" of ABM (R. Axtell, et al., 1996). However, the model in the present research is highly complicated and comprehensive, working on various layers and consisting of more than 10 000 lines of Java code. In such a case, a re-implementing verification method is hardly feasible. Instead, a systematic testing of the model to check its error-freeness and sensitivity will also suffice as model verification. Admittedly this is not the most thorough way of verifying the model *per se*. Nevertheless, the model's hierarchical representation of the environment and modular structure of different components allow errors to be identified easily and also its plausibility to be tested in commonsense terms. In this attempt, two parametric cases are tested, one being a street canyon case, another one being a crossroads case. Typical traffic situations are simulated. The model results are analyzed qualitatively and also compared with data obtained from empirical studies to prove that the model has been implemented correctly. The testing routines and case settings are based on the test cases suggested by (M. Bruse, N/A).

3.3.4.1 The Street Canyon Test Case

The first parametric model is a simple street canyon case as shown in Figure 3.14. The street canyon has a length of L = 100m and a width of W = 10m. It has 5 Gate points distributed uniformly at each end from where the pedestrians enter the model, as represented by the red stars in Figure 3.14. Plus, it has 5 Exit points, also distributed uniformly at each end from where the pedestrians leave the model, as represented by the green dots in Figure 3.14. To analyze the traffic data, i.e., pedestrian speed and density etc. in details, a "survey area" is selected in the middle of the street canyon, with the size of 10m by 10m, as represented by the grey square in Figure 3.14. Pedestrians entering this area are examined carefully. As introduced in the previous sections, a grid resolution of 0.5m is selected. Both unidirectional and bidirectional pedestrian movement scenarios are simulated. The simulations are run over a total time period of 15 min.

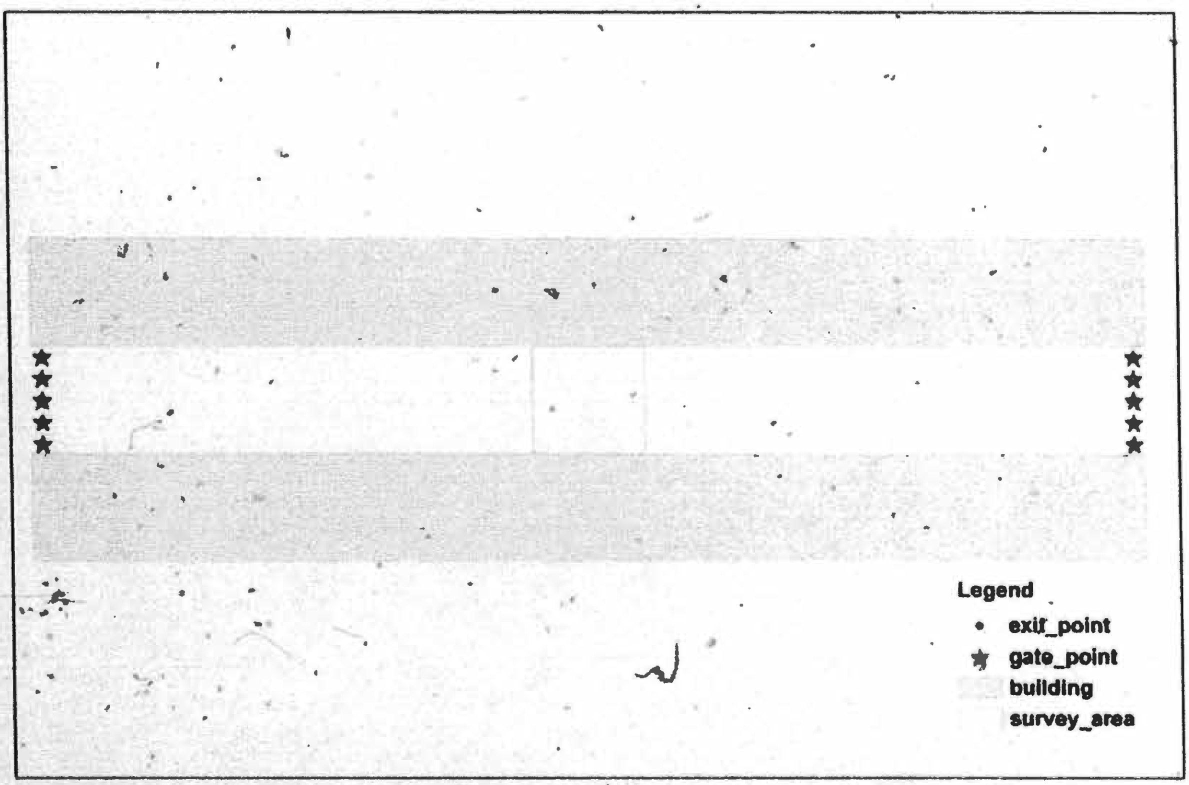


Figure 3.14 Illustration of the street canyon test case, showing the layout of building, exit point, gate point and survey area.

Pedestrian Traffic Generation

Various pedestrian generation rates are used, ranging from 60 persons per minute to 600 persons per minute (implemented as population rate of Gate points, refer to Section 3.2.1.1). The pedestrian generating settings are summarized in Table 3.2. In the unidirectional scenarios, pedestrians are only generated from the gate points on the left end of the street canyon; while in the bidirectional scenarios, pedestrians are generated from gate points on both ends of the street canyon. In the bidirectional cases, to avoid immediate congestions around the gate points and exit points, only half of the pedestrian generation rates used in the correspondent unidirectional cases are used, as described in Table 3.2. This setting also allows the total frequentation of pedestrian traffic to be the same for both unidirectional and bidirectional cases. Also, all gate points are set to have the same population rate, and all exit points are set to be equal, i.e., having the same weight in being selected as a destination (compare with the Roulette method in Section 3.3.1).

Table 3.2 Pedestrian generation rate assigned to the gate points. In the unidirectional scenarios, only gate points on the left side generate pedestrians, while in the bidirectional scenarios, gate points on both sides generate pedestrians.

Persons per minute		Scenario description
Unidirectional movement (left/right)	Bidirectional movement (left/right)	
60/0	30/30	Sparse
150/0	75/75	Light
300/0	150/150	Semi-dense
600/0	300/300	Dense

Model Settings

Pedestrians' speed is set to follow a *Normal distribution* $N(\mu, \sigma^2)$ where μ is 1.2 and σ is 0.3. Detailed discussion of the distribution of pedestrian speed is introduced in Chapter 4. Other Person attributes, such as gender, age, height and body weight, do not have impacts on the simulation in this part, so is not considered. The survey area is set to have an updating rate of 1 second recording pedestrians' speed and density. A *File Writer* method is implemented to output the data into .csv format file for analysis.

Simulation Results

Density Distribution

Figure 3.15 and Figure 3.16 show the traffic density of the survey area for unidirectional and bidirectional scenarios respectively. The density is also compared with the LOS indicator (level of service, refer to Table 3.1 and Figure 3.5). The "dense traffic" scenario is designed to generate traffic flows described by LOS of D level, while the "light traffic" scenario is designed to generate traffic flows associated with LOS of B level. It is seen from the illustrations the simulation produces stable pedestrian traffic data for both unidirectional and bidirectional cases. A notable feature is that the bidirectional case will produce the pedestrian traffic data that is slightly denser than the unidirectional case for dense traffic scenarios. This is as expected, as in the bidirectional case pedestrians will engage a lot in the avoidance of oncoming pedestrians by moving diagonally, etc., which will increase the density of the survey area within a certain time period.

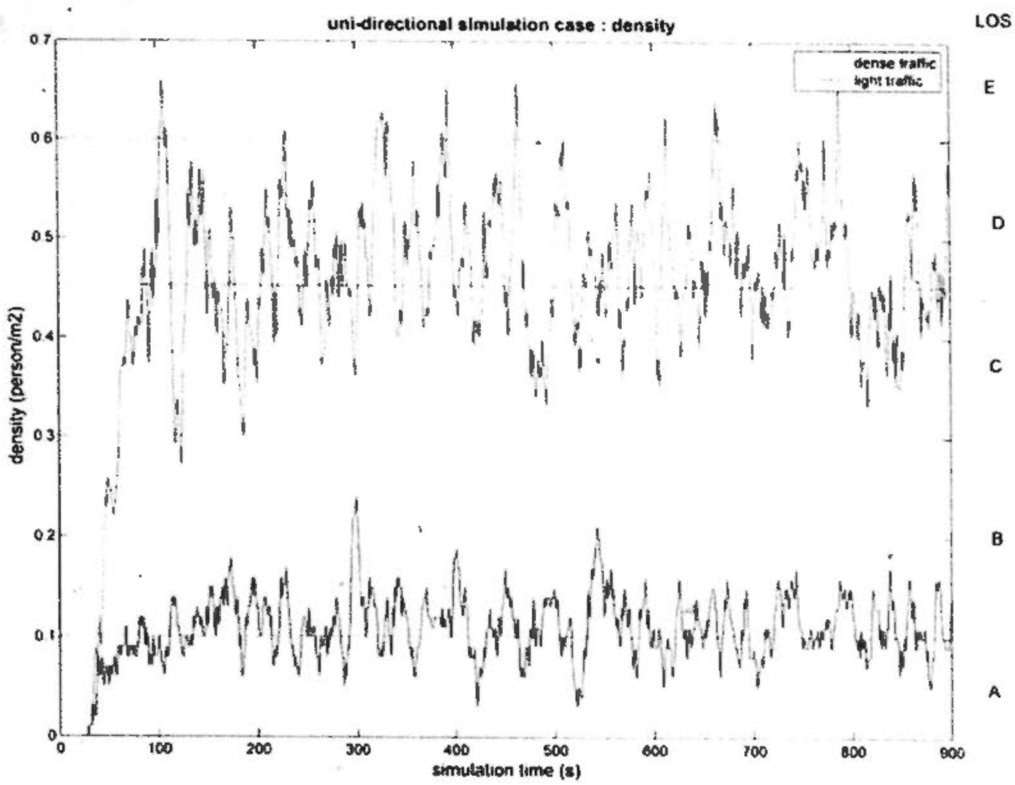


Figure 3.15 Traffic density of the survey area during the 15 min of simulation period for unidirectional scenarios. Both light and dense traffic scenarios are shown.

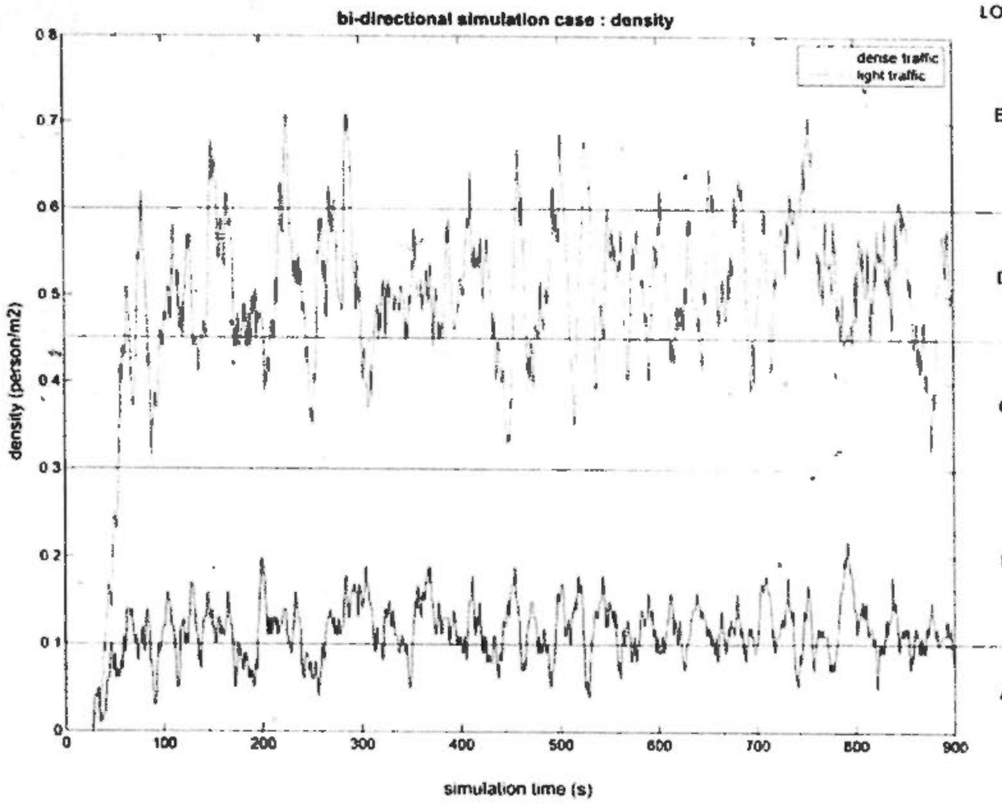


Figure 3.16 Traffic density of the survey area during the 15 min of simulation period for bidirectional scenarios. Both light and dense traffic scenarios are shown

Speed-Density Relation

Buchmueller and Weidmann (2006) have suggested the so called *Kladek formula* to approximate the relationship between pedestrian density and walking speed, which is:

$$v = 1.34\{1 - \exp[-1.93(\frac{1}{u} - \frac{1}{u_M})]\},\qquad \text{(Equation 3.10)}$$

where v is the pedestrian's speed, u is pedestrian density, and u_M is a constant which is 5.4 persons/m^2 for density cases. In this sense, the speed-density relationship of pedestrians passing the survey area is recorded and analyzed, and compared with the Kladek formula. More than 4 000 pedestrians are recorded for the simulation time period. Figures 3.17 and 3.18 show the comparison results for the unidirectional and bidirectional cases respectively.

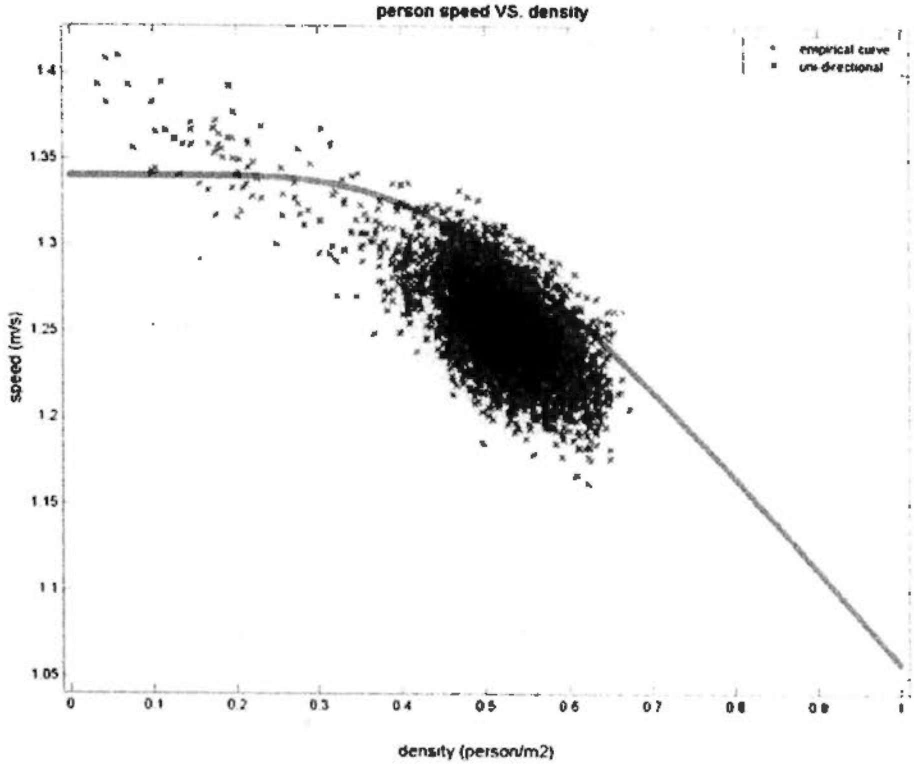


Figure 3.17 Speed-density relationship for the unidirectional case and its comparison with the empirical curve from the Kladek formula.

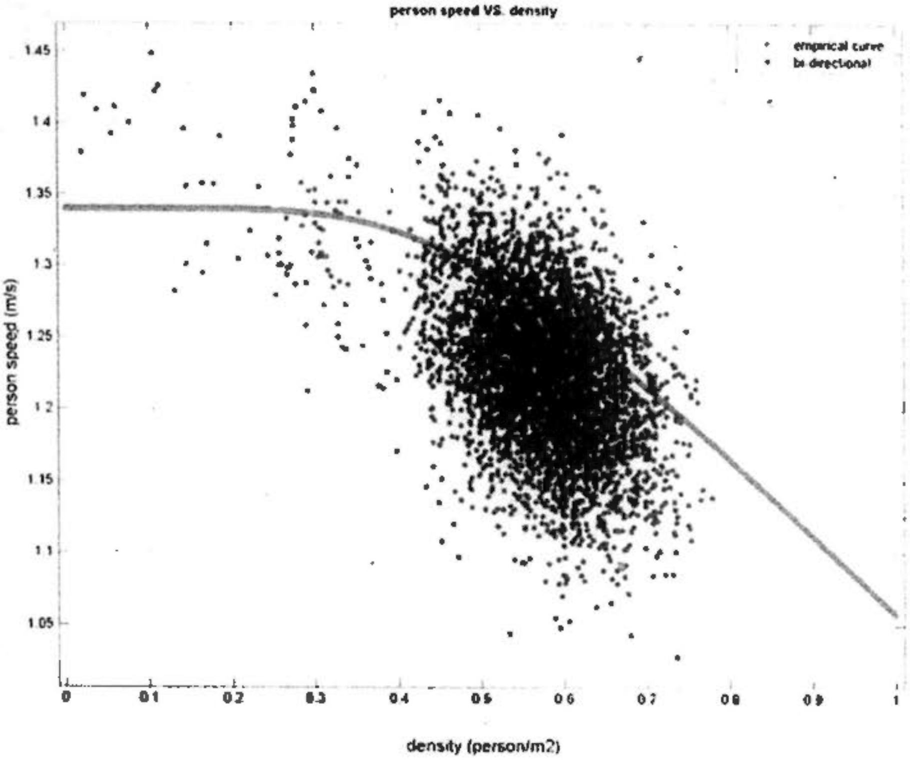


Figure 3.18 Speed-density relationship for the bidirectional case and its comparison with the empirical curve from the Kladek formula.

It is seen from Figure 3.17, that in the unidirectional simulation case, pedestrian speed and density follow the empirical relationship reasonably well. However, for the bidirectional case, there is a substantial deviation, as shown in Figure 3.18. Nevertheless, this is acceptable, given that in the bidirectional case a lot of stochastic variables come to play in the collision avoidance method. At the very least, the distribution shows that pedestrian speed has a generally reverse-proportional relationship as pedestrian density increases, which is as expected.

3.3.4.2 The Crossroads Test Case

The second parametric model is a symmetric crossroad scenario aiming to test the simulation model's stability under more complicated situation. The parametric model is shown in Figure 3.19. Each street segment has a length L = 100m and a width W = 20m, with two sidewalks with 6m in width and a car road with 8m in width. The gate points are located at the street ends, one on each sidewalk. Different from the street canyon test case, a total number of 39 exit points are distributed randomly along the streets, allowing a diverse movement pattern to be created. The aim of this parametric model is to test the stability and fluency of the simulation model, and to check if collisions or stuck pedestrians occur.

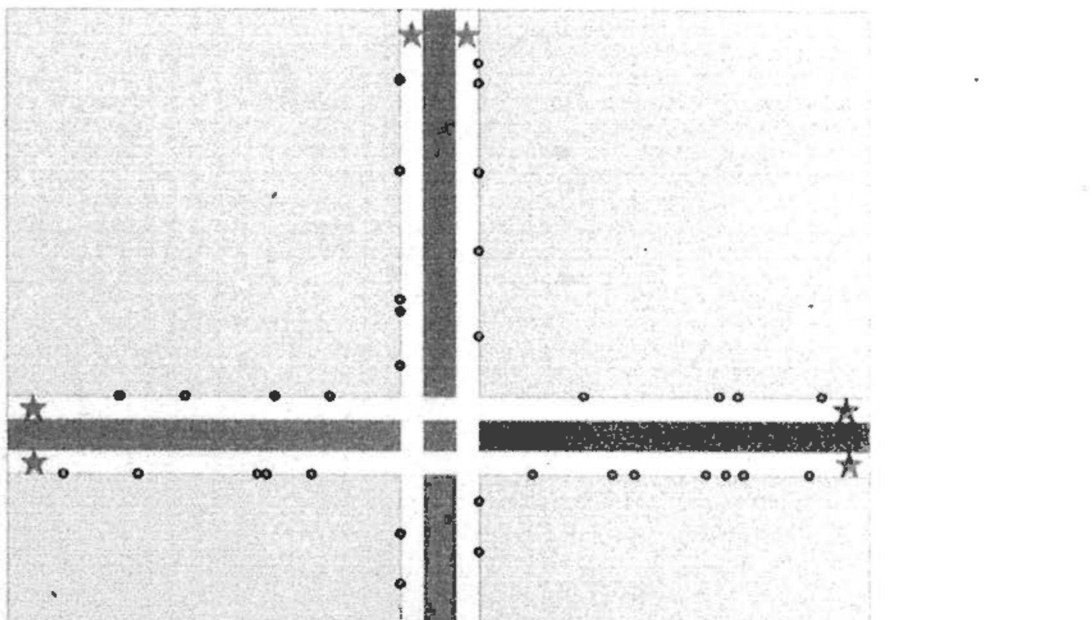


Figure 3.19 Illustration of the crossroads test case, showing the layout of building, exit point, gate point, car road and sidewalk.

Each gate point is set to have a populating rate of 60 persons per minute. According to the street canyon test case, this will generate pretty dense pedestrian traffic flow. The simulation is run over 15 minutes. A total number of 7 200 pedestrians are generated. By the end time of the simulation, there are around 1 200 active pedestrians walking in the domain, with around 6 000 pedestrians that have reached their destinations and left the domain. By visually examining the simulation course, no "stuck" or "ghost" pedestrians (meaning pedestrians that will never reach their destinations) are observed. No collisions are found either. The "video capture" function provided by the modeling toolkit used, i.e., Repast Simphony, allows thorough examination of the emergent pattern or incident in the simulation process.

Figure 3.20 shows the pedestrian traffic distribution map of the crossroads test case. It shows that 1) pedestrians primarily choose to walk on the sidewalks, with preferences to walk on the center of the sidewalks; 2) occasionally pedestrians also choose to walk on car road, this happens when there are too many pedestrians or even congestions found on the sidewalks, however pedestrians never walk on the car road center; 3) the crossing points have the highest frequentation, proving that these are the spots that most frequently used by pedestrians. All these findings are logical and agree with common knowledge and daily observations.

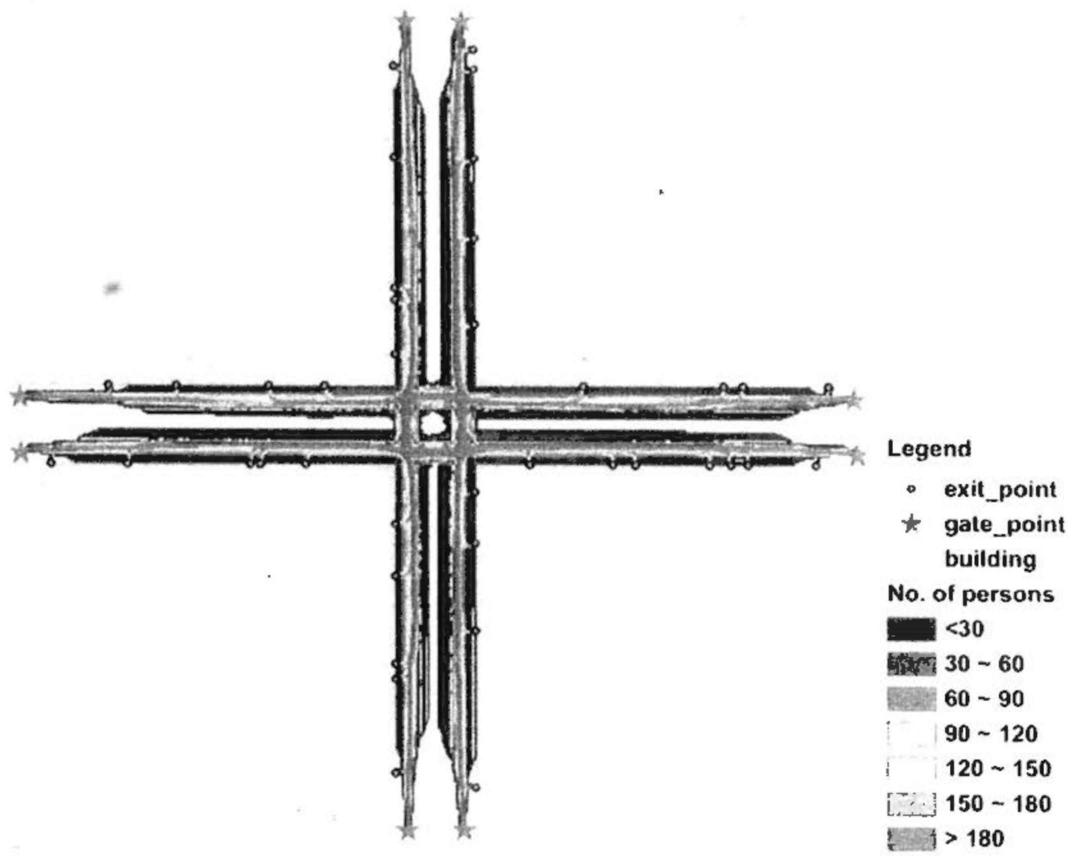


Figure 3.20 Illustration of pedestrian traffic distribution in the crossroads test case during the simulation period.

The two test cases prove that the simulation module produces reasonable and stable pedestrian traffic data. The algorithm and the structure of the simulation module are therefore verified.

3.4 Thermal Comfort Assessment Module

The thermal comfort assessment module evaluates pedestrians' thermal sensation while they walk in the urban environment. Pedestrians' thermal sensation is determined by the local climatic condition of their ambient environment, including air temperature, sun exposure, humidity, wind speed etc., and their individual characteristics such as body weight and walking speed. In the PedNaTAS system, two types of thermal assessment modules are implemented, one steady state module and one dynamic module. The steady state module adapts the bio-meteorological index of the Physiological Equivalent Temperature (PET) to quantitatively evaluate pedestrians' steady state thermal sensation. It calculates the standard PET index of a particular person and generates the spatial variation of PET as reference for analysis. The dynamic assessment uses the *Pierce Two-Node Model* which has been commonly adapted in thermal comfort studies to monitor the temporal course of a pedestrian's thermal condition, including skin temperature, core temperature, etc. along walking. Because of the individual based approach of the system, detailed conditions of any pedestrian could be investigated, visualized and analyzed. These individual thermal conditions could be linked with the global emerging pattern of the walking activity, and provide implications for space use.

This section first gives a brief introduction of PET and how it is calculated, and then discusses the implementation of the PET model and its integration into the system. Same course is conducted to the dynamic assessment module in the second part of this section.

3.4.1 Steady State Assessment

3.4.1.1 Introduction to PET

The thermal index of PET (Mayer & Höppe, 1987) is a bio-meteorological index developed in attempting to map human thermal sensation onto a scale which is comprehensive to people without sufficient meteorological domain knowledge. PET is defined as the air temperature in a typical indoor setting at which the human energy budget is maintained by the same skin temperature and sweat rate as those under the conditions to be assessed (Höppe, 1999). By definition, PET uses a unit of degree Celsius (°C) so has advantages over other thermal indices such as PMV (Fanger, 1982; ISO, 1994) and OUT-SET* (Pickup & De Dear, 1999) in that the evaluation result is familiar to people's common wisdom so can be easily interpreted.

PET is based on the Munich Energy-balance Model for Individuals (MEMI) (Höppe, 1984). Details of how PET is calculated based on the model have been discussed in (Höppe, 1999; Andreas Matzarakis & Amelung, 2008). The calculation process is briefly introduced here. The model requires the following meteorological parameters:

- Air temperature: T_a (in °C)
- Mean radiant temperature: T_{mrt} (in °C)
- Relative humidity: RH (often represented by vapor presser VP in hPa).
- Wind velocity: v (in m/s)

and physiological parameters:

- Heat resistance of clothing: (in clo units, detailed specifications are referred to (ISO, 2007))
- Human activity: (in W, e.g., 80W for light activity such as walking)

to model human body energy balance. The model first calculates the thermal condition based on these parameters, then solves the energy balance equation for T_a by replacing the meteorological parameters with indoor settings ($T_a = T_{mrt}$, $v = 0.1$m/s and VP = 12hPa). The calculated T_a is considered as the air temperature physiologically equivalent to a human, i.e., the PET value.

The PET index has been widely applied in areas with various climatic conditions (Ali-Toudert & Mayer, 2006; Höppe, 1999; Lin, 2009; Andreas Matzarakis, Mayer, & Iziomon, 1999). It has also been adapted in Hong Kong as the standard thermal comfort index and shows substantial explanatory power (Ng, Chan, & Cheng, 2007; Ng, Kwok, Sun, Yau, & Katzschner, 2008). Therefore, it is applied in PedNaTAS as the steady state thermal comfort assessment index.

3.4.1.2 Implementing PET as a Steady State Thermal Comfort Assessment Module

Currently the publicly accessible procedure to calculate PET is the FORTRAN program developed by Höppe (1996). There are several limitations of the program that need to be dealt with before it can be applied in the present system. Firstly, the FORTRAN programming language is becoming increasingly superseded by much more advanced programming languages such as Java and C++, which makes the program difficult to be integrated with more up to date applications. Secondly, the meteorological and physiological parameters (refer to Section 3.4.1) are either hard coded or read-in from manual command line input, so are not compatible with the software framework of ABM where there can be thousands of distinct sets of parameters. Thirdly, the program was not written in a user friendly style so debugging and maintenance of the program could be rather intractable. With these concerns, the PET program is re-implemented in Java in an object-oriented scheme and tight-coupled with the PedNaTAS system, which is discussed below.

A PET index is implemented as an object of a person (refer to Section 3.2.3). The attributes of a PET object is presented in Table 3.3. The personal parameters can be directly retrieved from the person the PET object is associated with, and the meteorological parameters can be retrieved through the person's perception of the urban environment (refer to Section 3.2.2 and Section 3.2.3). Dynamic parameters, including temporally various parameters such as the person's walking speed and spatially various parameters such as local T_{mrt} are updated along the walking process. When called, the PET object calculates the current PET value and reports to the associated person. In this way, the calculation of PET for different persons can be carried out in an individually independent manner.

Table 3.3 Attributes of a PET object.

Personal parameters		Meteorological parameters	
static	dynamic	static	dynamic
age	speed	T_a	T_{mrt}
gender		VP	v
body weight			
height			
clothing index			

The implemented PET module is verified by comparison with the results generated by the original FORTRAN computer program. In practice, 100 PET values are calculated by the two computer programs based on randomly selected input values. The comparison shows that the results are exactly the same, proving that the PET method has been re-programmed correctly in Java.

One thing to be noticed here is the T_{mrt} parameter. The estimation of T_{mrt} based on other meteorological parameters is a complicated issue and different approaches have been taken (ASHRAE, 2001; Lindberg, et al., 2008; Andreas Matzarakis, 2007; Sofia

Thorsson, et al., 2007). The SOLWEIG model (Lindberg, et al., 2008) has been shown to be an effective software application which can model the T_{mrt} for an entire urban environment and generate satisfactory results. The model is adapted to produce T_{mrt} parameter for the system. In implementation, SOLWEIG is integrated into the system through loose-coupling, meaning that it interacts with the system through input/output files, i.e., the T_{mrt} grid (refer to Section 3.2.2). Specifications of the parameter settings of SOLWEIG are discussed in Section 4.2.2. The wind speed grid is derived from a dataset obtained in an earlier CFD study, and is also discussed in detail in Section 4.2.2.

3.4.2 Dynamic Assessment of Non-Steady and Transient State

The PET index, along with many other bio-meteorological indices such as PMV or PPD, is based on steady state models, which means that the resulting value indicate the thermal comfort condition in an energy balance mode. During the walking course this pre-assumption is hardly the case, as walking involves transient process and dynamic and temporal adaptation. In such cases, the use of steady state indices will normally cause great discrepancies from pedestrians' "actual" thermal sensation, as has already been revealed by the broad literature in Chapter 2. In deed Höppe (2002) has explicitly shown the difference between a pedestrian's dynamic thermal adaptation and the steady state condition using a simple "sunny street segment" case, as is shown in Figure 3.21. Similar analysis has also been conducted by (M. Bruse, 2005), etc. These facts suggest that steady state models are not suitable for outdoor thermal assessment considering pedestrian behaviors.

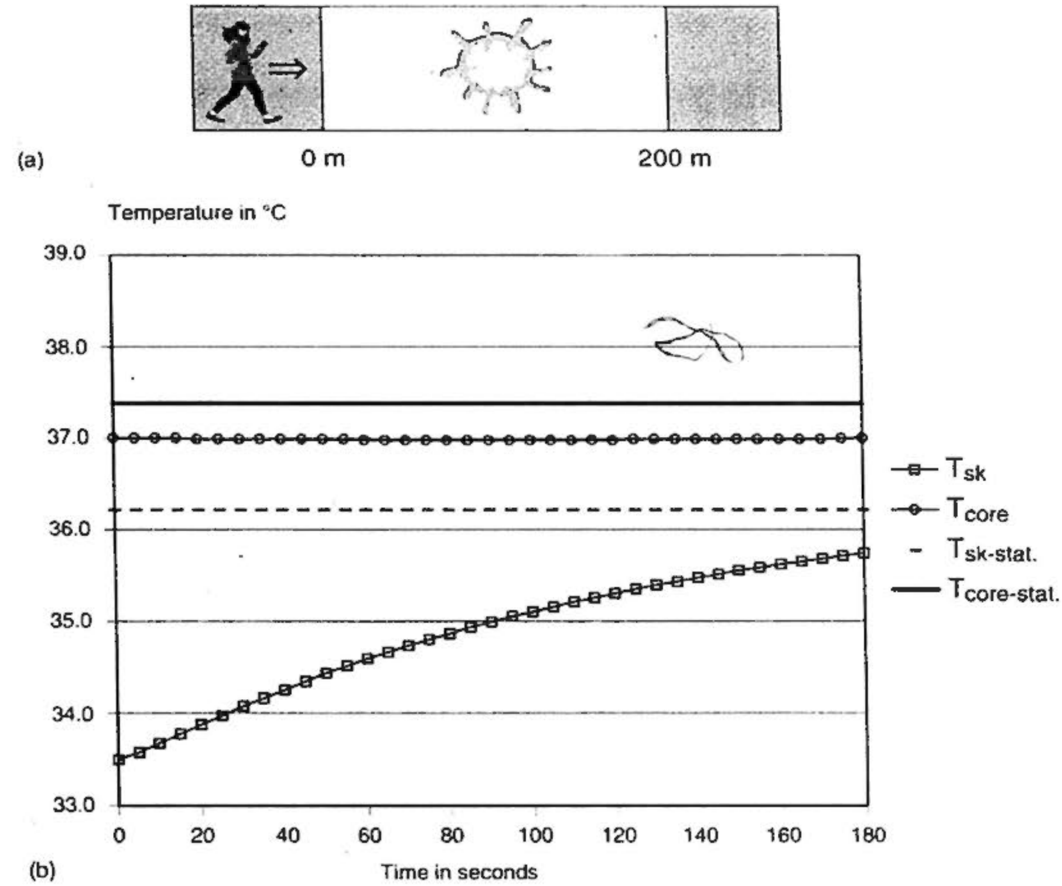


Figure 3.21 An illustration showing the difference between a pedestrian's dynamic thermal adaptation and the steady state condition: (a) scenario "sunny street segment"; (b) temporal variation of pedestrian's physiological conditions, described by skin temperature (T_{skin}) and core temperature (T_{core}). $T_{skin\text{-}stat}$ and $T_{core\text{-}stat}$ are steady state skin temperature and core temperature, respectively. After (Höppe, 2002)

As opposed to the various indicators developed to assess human steady state thermal comfort, the methodologies for dynamic assessment are quite sparse. As Höppe stated it in as early as 2002: "The problem we face today is that there are no internationally accepted non-steady state indices for the solution of this problem." (Höppe, 2002) The picture remains unchanged today. It was first expected that the ambitious Universal Thermal Climate Index (UTCI) (http://www.utci.org/) would address this issue. However from its early documentation (Jendritzky, Maarouf, &

Staiger, 2001) and a later update (Jendritzky, Maarouf, Fiala, & Staiger, 2002), and most importantly its online computer program for calculation (Bröde, 2009), we have to conclude, although very disappointedly, that the development of dynamic models has lost track in UTCI.

As a state-of-the-art, currently there are two mainstream models that work along the line of dynamic thermal assessment: the Pierce Two-Node model and the Instationary Munich Energy-balance Model (IMEM) by Höppe (1984). The IMEM model was once recommended by the VDI-guideline 3787 (Part 2, Section 1) to assess unsteady thermal states (VDI 3787, 1996). However, the model is still under development and is for internal use only (personal communication with Matzarakis), therefore documentations on its technical details as well as applications are quite limited (Höppe, 1989, 2002). In contrast, the Pierce Two-Node Model has been constantly developed and applied in thermal comfort studies. Therefore it is adapted in this study.

3.4.2.1 Introduction to the Pierce Two-Node Model (TNM)

First a bit history on TNM. It was initially developed by (Gagge, et al., 1971) at the John B. Pierce Laboratory (http://www.jbpierce.org/) affiliated with Yale University. As the name implies, TNM treated the human body as two isothermal parts: the skin and the core, based on which the thermoregulation, i.e., heat exchange equations were constructed for passive state. Effectively, the core temperature, skin temperature and mean body temperature could all be derived by their deviation from the set points. Other thermoregulatory indicators such as sweating rate and skin blood flow could also be evidently defined. Notably today's commonly used TNMs are based on a substantial update of the initial model (Gagge, Fobelets, & Berglund, 1986). Different computer implementations of TNM was reviewed in (Fountain & Huizenga, 1995), including computer programs written in programming languages such as FORTRAN, Basic and C++. The model has been continually expanded, such as considering the impact of the wind environment (Parsons, Havenith, Holmér, Nilsson, & Malchaire, 1999), implementation of 3-D representation of human body to respond to complex urban environment (Huizenga, et al., 2001), introducing additional parameters of individual properties such as body composition or acclimatization status (Havenith, 2001), and expanding the two-node model to multi-node models representing different body parts (Foda & Sirén, 2010; Tanabe, Kobayashi, Nakando, Ozeki, & Konishi, 2002).

3.4.2.2 Implementing TNM as a Dynamic Thermal Comfort Assessment Module

The computer program written in C++ programming language published in (Fountain & Huizenga, 1995) is used in this study. Same as the PET implementation introduced in Section 3.4.1.2, the program is rewritten in Java programming language and implemented as an object of a person agent. The model is modified to account for the wind environment. It is to be noted that the biggest change made to the original program is that a "temporal" characteristic is added: the model is integrated with the movement control of a person agent, allowing the temporal update along with the agent's spatial variation. In practice, a 1 second updating rate is selected.

Parameter Setting

Apart from the common parameters TNM shares with PET, as listed in Table 3.3, there are a few other parameters of TNM that need to be selected properly. The first is the initial neutral state of human body, described as set point in TNM (refer to Section 3.4.2.1). In PedNaTAS, a person agent is set to have a skin temperature (T_{skin}) of 33.7°C and a core temperature (T_{core}) of 36.8°C, as the neutral state of human body. Similar setting is also selected by (Höppe, 2002). The second parameter is the Body Surface Area (BSA), which is needed for modeling the skin thermoregulation. In practice, the commonly applied *Mosteller's formula* (Mosteller, 1987) is adapted, which is

$$BSA(\mathrm{m}^2) = ([height(\mathrm{cm}) \times weight(\mathrm{kg})]/3600)^{1/2} \qquad \text{(Equation 3.11)}$$

where *height* and *weight* are a person's height and weight parameters respectively. The last one is the person's metabolic rate, measured in the unit of MET (the Metabolic Equivalent of Task). According to (Ainsworth, et al., 2000), when a pedestrian is walking on a level firm surface, his (her) metabolic rate can be estimated by the following relations:

2 METs: *walking at 2 miles per hour (0.9m/s)*

5 METs: *walking at 5 miles per hour (2.2m/s)*

In the PedNaTAS system, pedestrian's walking speed is normally between 1m/s to 1.5m/s (for person attributes modeling, please refer to Section 4.2.3.2), in such a case, an estimated metabolic rate of 3 METs is selected.

Verification

Because of the newly added timely updating function, the implementation of TNM in PedNaTAS needs to be verified properly to ensure that the model has been re-programmed correctly. Therefore, the model is cross-tested with *The WWW Thermal Comfort Index Calculator* by (de Dear, N/A). The air temperature T_a is set to be 30°C, and the mean radiation temperature T_{mrt} is set to be 42°C, and the relative humidity is set to be 50%, which is a simplification of the real urban environment (refer to Section 4.2.2). The default setting for the subject used by the WWW Calculator is selected, which is 70.0kg weight, 0.6 clo clothing insulation, and 58.2W/m^2 metabolic rate. A temporal course of 60 minute exposure time is calculated. The option of *Transient Values* is selected, meaning that the subject's thermal condition for each minute is calculated.

In parallel, same values are calculated using the TNM model implemented in the PedNaTAS system. In practice, this is easily done by assigning a "virtual walk" for a person agent. The walk is set to have a length of 60 steps, with each step representing 1 minute's course. The person agent's thermal condition is therefore updated for each step. Values calculated include *skin temperature* (T_{skin}), *core temperature* (T_{core}), *respiratory evaporative heat loss* (E_{res}), *respiratory sensible heat loss* (C_{res}), *dry heat loss from skin surface* (DRY), *total evaporative heat loss at skin surface* (ESK), and *skin blood flow* (SKBF). Of course there are other values that are possible to be calculated, nevertheless they can all be derived based on the above mentioned parameters, so for the purpose of the verification, these 7 values should be enough for comparison with the WWW Calculator. For E_{res} and C_{res}, both methods give the same results, being two constant values during the temporal course: 3.76 (W/m^2) and 0.326 (W/m^2) respectively. The comparisons of the other 5 values are shown in Figures 3.22 ~ 3.26.

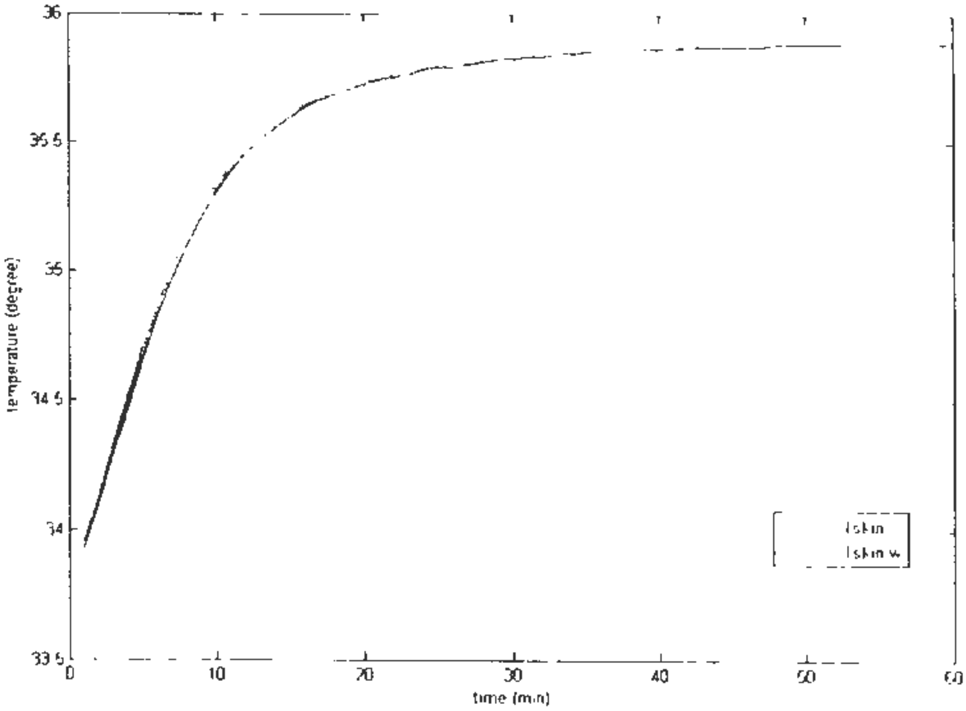


Figure 3.22 Comparison between PedNaTAS and WWW Calculator: skin temperature (T_{skin}). The value calculated by PedNaTAS is denoted as T_{skin} and the value calculated by the WWW Calculator is denoted as $T_{skin\text{-}w}$.

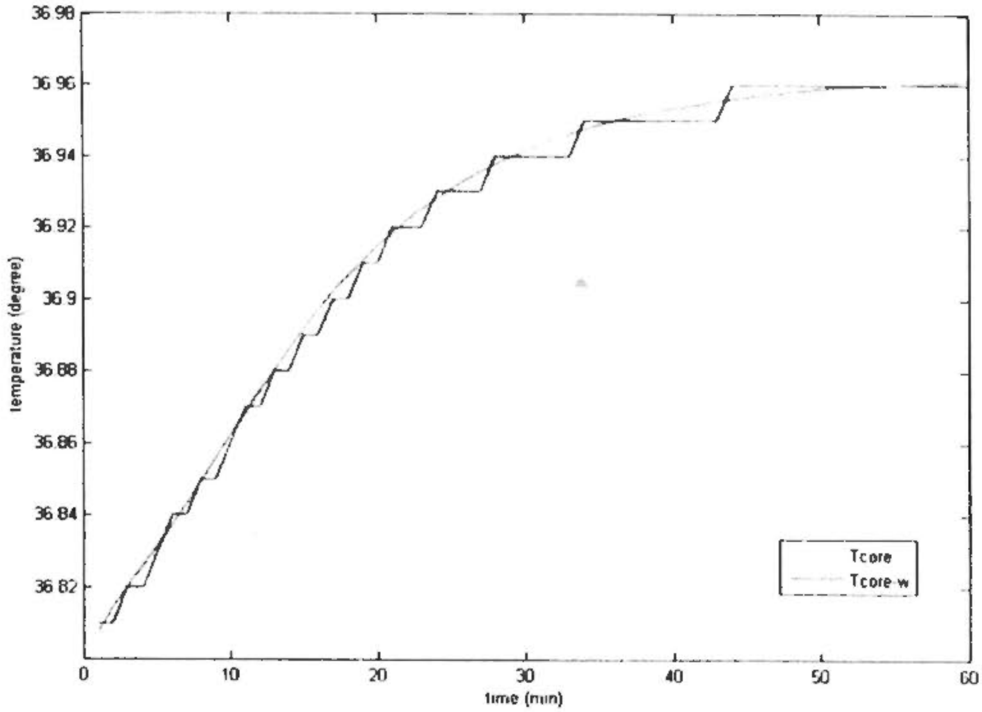


Figure 3.23 Comparison between PedNaTAS and WWW Calculator: core temperature (T_{core}). The value calculated by PedNaTAS is denoted as T_{core}, and the value calculated by the WWW Calculator is denoted as $T_{core\text{-}w}$.

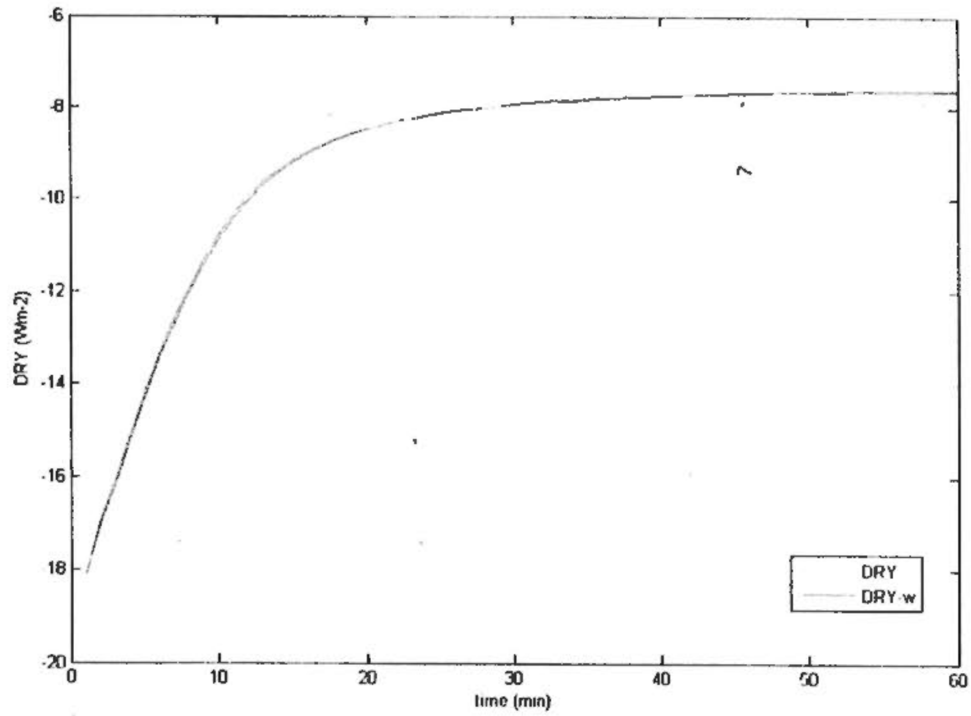


Figure 3.24 Comparison between PedNaTAS and WWW Calculator: dry heat loss from skin surface (DRY). The value calculated by PedNaTAS is denoted as DRY, and the value calculated by the WWW Calculator is denoted as DRY-w.

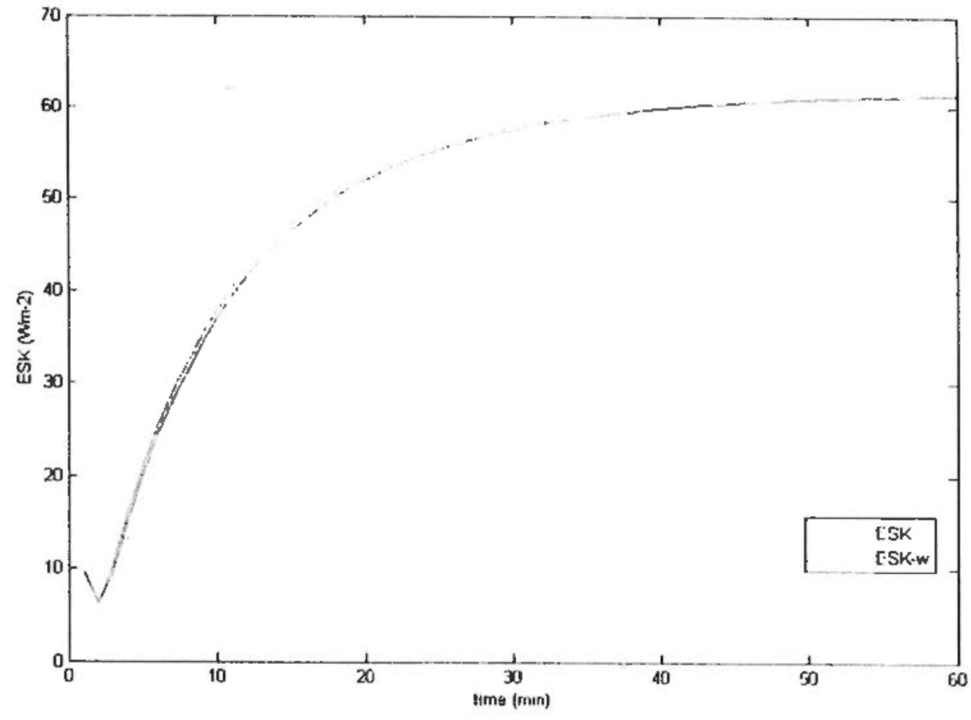


Figure 3.25 Comparison between PedNaTAS and WWW Calculator: total evaporative heat loss at skin surface (ESK). The value calculated by PedNaTAS is denoted as ESK, and the value calculated by the WWW Calculator is denoted as ESK-w.

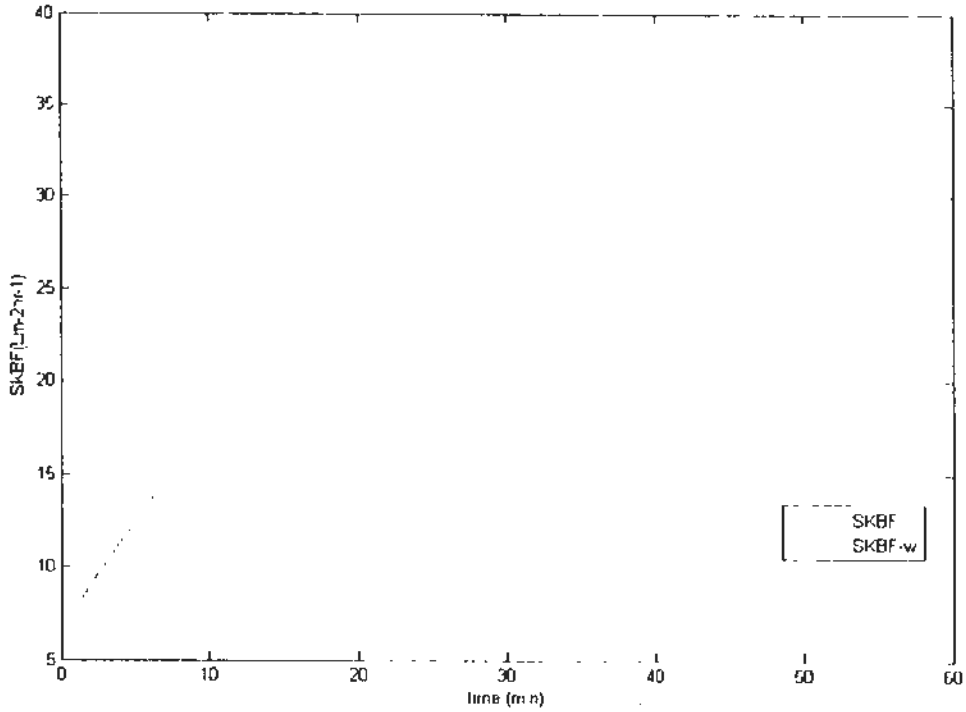


Figure 3.26 Comparison between PedNaTAS and WWW Calculator: skin blood flow (SKBF). The value calculated by PedNaTAS is denoted as SKBF, and the value calculated by the WWW Calculator is denoted as SKBF-w.

It can be seen from the figures, that the results calculated by the two methods agree with each other very well. Therefore, the correctness of the TNM implementation in PedNaTAS is verified.

As introduced above, based on the above mentioned parameter setting, TNM is successfully modeled as an object associated with a person agent. The agent based approach of PedNaTAS makes it quite straightforward to "probe" the detail information of a person's thermal condition along walking activity, including skin temperature, core temperature, clothing temperature, skin blood flow, sweating rate, net heat production etc. These functions will be explored in details through a case study in Chapter 4.

3.5 GIS-Based Modeling

Gimblett (2002) has noted that the integration of GIS with ABM could be a powerful tool for decision makers. Brown *et al.* (2005) have discussed the importance of the integration of ABM and GIS for spatial decision systems, with special focus on the support of real geographic data in the spatial modeling process. In this context, a lot of efforts have been made to link ABM and GIS (Itzhak Benenson & Torrens, 2004; Gimblett, 2002). The Repast Simphony package provides the users with a rich set of functions managing GIS data, such as loading and displaying shape files, so is a powerful platform for GIS-based modeling.

As discussed in Section 3.2, the PedNaTAS system manages two categories of datasets at the same time: a vector dataset represented in shape file format, and a raster dataset represented in ESRI ASCII grid format. Since the Repast Simphony package doesn't support raster data directly, an algorithm is implemented to read in ESRI ASCII format files. Table 3.4 gives an example of an ESRI ASCII grid file. The descriptions of flag tokens in the file are listed below:

- ncols: the number of columns of the grid
- nrows: the number of rows of the grid
- xllcorner: the geographic "x" coordinate of the lower left corner of the grid
- yllcorner: the geographic "y" coordinate of the lower left corner of the grid
- cellsize: the size of a grid cell
- NODATA_value: the value representing no data

Table 3.4 An example of an ESRI ASCII grid.

ncols	1000
nrows	1000
xllcorner	835789.00006104
yllcorner	817516.00006104
cellsize	0.5
NODATA_value	-9999
0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0	
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	
1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0	

The vector dataset in PedNaTAS, including Building, Street, Gate point, etc. use the standard geographic projection of Hong Kong 1980 grid (Survey & Mapping Office, 1995). This is also the projection used by pedestrian agents, which means when a pedestrian moves along the Street network, her spatial location is presented by the coordinate (latitude, longitude). On the other hand, the pedestrian's location in the associated Walking surface, such as the Walking grid and the Shading grid, and in the movement control matrices such as the Occupied matrix and the Reserved matrix, and also in the associated environmental dataset, such as the T_{mrt} grid and the Wind speed grid are all represented by the coordinate (i, j) as an entry in the $W \times H$ grid. This indicates that a coordinate system transformation is needed to link the geographic projection with the grid projection. An illustration of the transformation is presented in Figure 3.27. The transformation needs to work in both ways in that:

1) When a pedestrian is walking, she needs to retrieve the grid index she is on, so the transformation needs to convert (latitude, longitude) coordinate to (x, y) i.e., (i, j) coordinate;

2) Due to the microscopic movement control, a pedestrian will be set to a grid center from time to time (refer to Section 3.3.3.2), so the transformation needs to convert a grid coordinate (i, j) to (latitude, longitude) and update it for the pedestrian in order for it to be placed under the geographic projection.

In the system, two transformation algorithms are implemented based on (Survey & Mapping Office, 1995). And the spatial correspondence of different coordinate systems is presented in Figure 3.28. During the movement process, a pedestrian's grid coordinate (latitude, longitude) and geographic coordinate (i, j) are updated simultaneously.

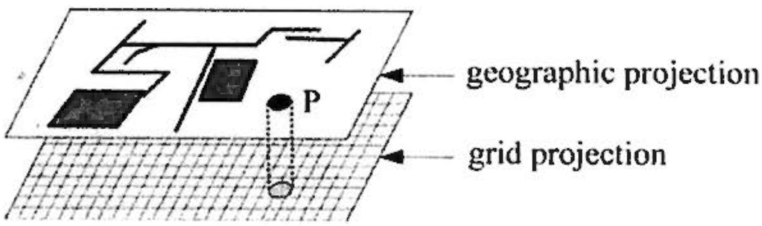


Figure 3.27 Illustration of spatial reference transformation of PedNaTAS. The transformation is between geographic projection and grid projection. P is a pedestrian. Figure is drawn as indicative.

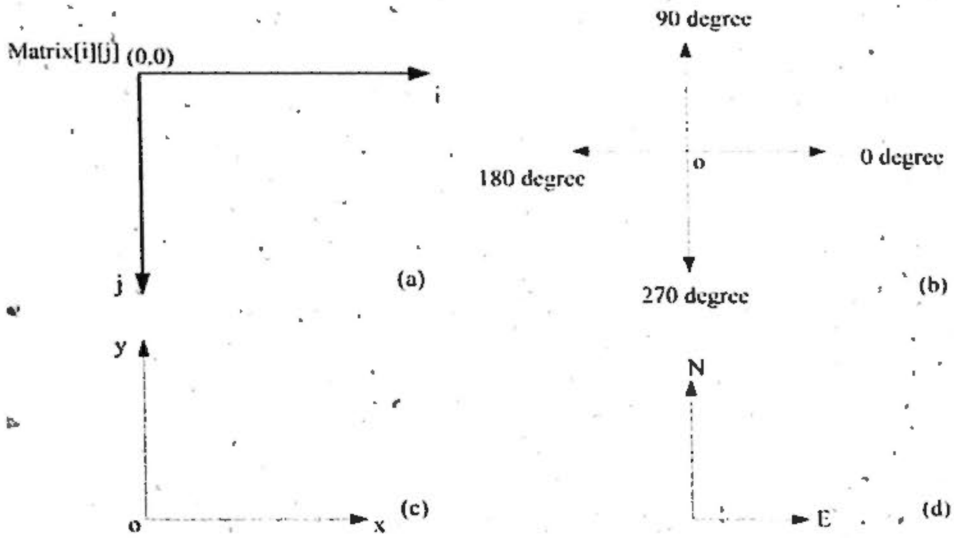


Figure 3.28 Spatial correspondence of different coordinate systems in PedNaTAS: a) grid representation; b) polar representation; c) X-Y representation and d) geographic representation.

3.6 Chapter Summary

This chapter presents both the conceptual and implementation framework of the PedNaTAS system. The system manages to integrate ABM, GIS, visualization and data analysis to serve as a spatial decision support system for outdoor urban micro-climatic assessment. With emphasis on simulating pedestrians' microscopic movement behavior, the system also takes into account people's social activities which are directed by socioeconomic properties of the urban environment. So far this is the first attempt to link thermal assessment with human behavior in a GIS-based simulation scheme. The highly hierarchical structure of the system makes it easy to be refined and expanded, and also be integrated with other applications. The system is expected to be capable to characterize the micro-climate of urban environment through a bottom-up approach.

Chapter 4 Case Study

This chapter presents a case study to demonstrate how source data, modeled results and simulation can be integrated within a GIS framework in the PedNaTAS system to provide analysis and assessment of pedestrian's thermal comfort in the urban environment. It provides a spatial decision support system for climatic-centered urban environment evaluation in the planning process.

4.1 Study Site Description

4.1.1 Urban Form Description

The Tsim Sha Tsiu East (TST) area, which is in the east end of the Kowloon peninsula, Hong Kong (22°15'N, 114°10' E), is selected as the case study site. TST is one of Hong Kong's most densely built-up areas. It has a coastal flat terrain and little vegetation (Figure 4.1). The selected site has the size of 500m × 500m. Differences in building height and density are commonly found in domain (Figure 4.2). There are in all over 500 buildings and the average building height is 36.3m with a deviation of 23.9m. The detailed map of TST is shown in Figure 4.3. As shown in the map, there are two main automobile traffic roads: the Chatham Road South and the Nathan Road, which traverse the domain from the north to the south. The major public transportation connection point is the Tsim Sha Tsui MTR station, together with some car parking lots. Walking is the major travel mode between MTR exits and building entrances and street ends.

Figure 4.1 Google Map for Kowloon peninsula. The study site, TST, is indicated by the white rectangle.

(Source: http://maps.google.com)

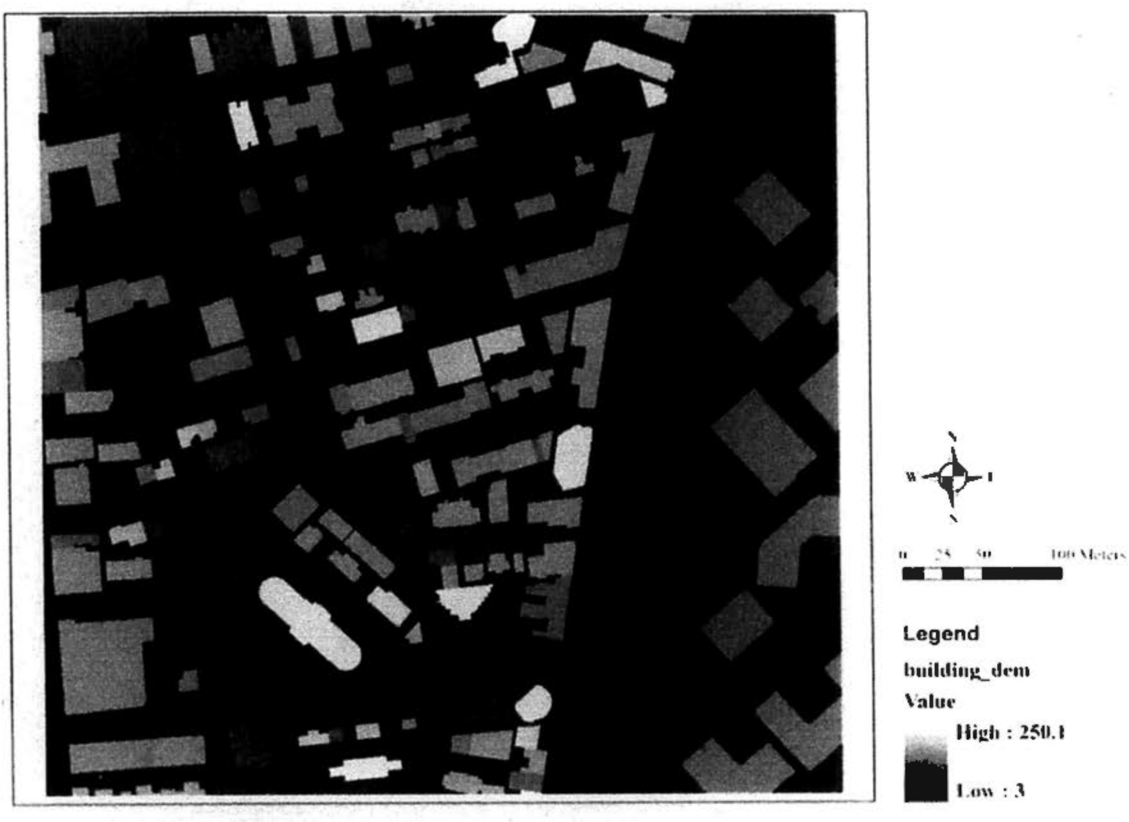


Figure 4.2 Building DEM map for TST. The map is in 2m resolution.

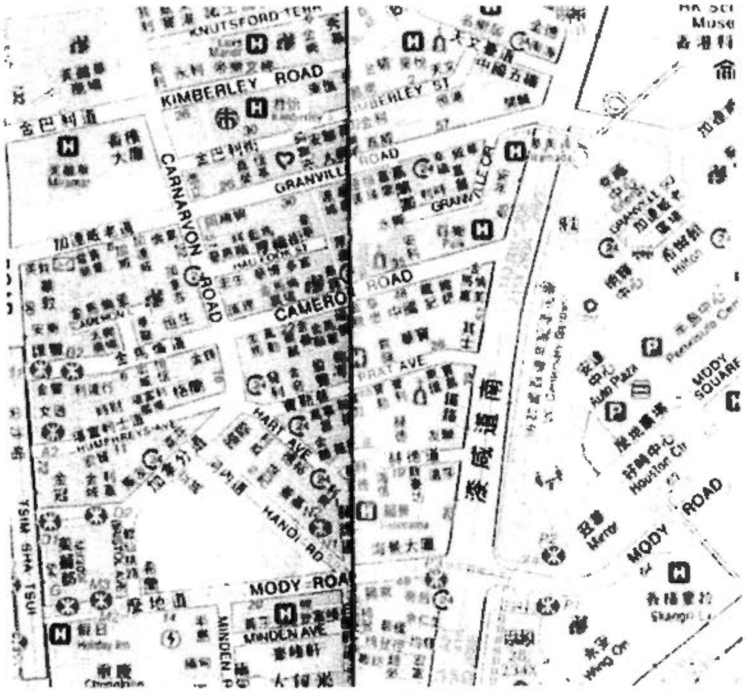


Figure 4.3 Tsim Sha Tsui map. (Source: (Survey and Mapping Office, 2010))

One thing to be noted is that Hong Kong Observatory (HKO) is next to the domain, which is to the north of the Kimberly Road. The major meteorological station located in HKO keeps detailed climatic information records of the local environment, including air temperature, radiation, humidity, wind speed and direction, sun hour, etc. These records provide detailed information for the PedNaTAS system to make assessment of microclimatic condition in the domain.

4.1.2 Climatic Information Description

The climatic characteristics of the domain are briefly introduced in this section. In general, Hong Kong has a typical subtropical climate, with hot, humid and long summer months lasting from May to September. The summer average temperature is normally around 28.5°C, the relative humidity is normally up to 80%, and the average sun hour is around 6 hour/day (Hong Kong Observatory, N/A). This type of climate already has some impact on urban thermal comfort. What aggravates the situation is the high-dense and high-rise urban structure: tall buildings of more than 30 storey high lining narrow streets of 15 to 25 meters have been the norm (Figure 4.4). The high thermal load of the concrete constructions result in extremely high urban surface temperature, and the surface urban heat island (SUHI) has been observed (Figure 4.5). On the wind environment side, HKO station records that the prevailing wind in summer for the study site is east wind. The wind rose is shown in Figure 4.6.

Figure 4.4 Aerial photo of Kowloon. (Source: http://www.globalphotos.org)

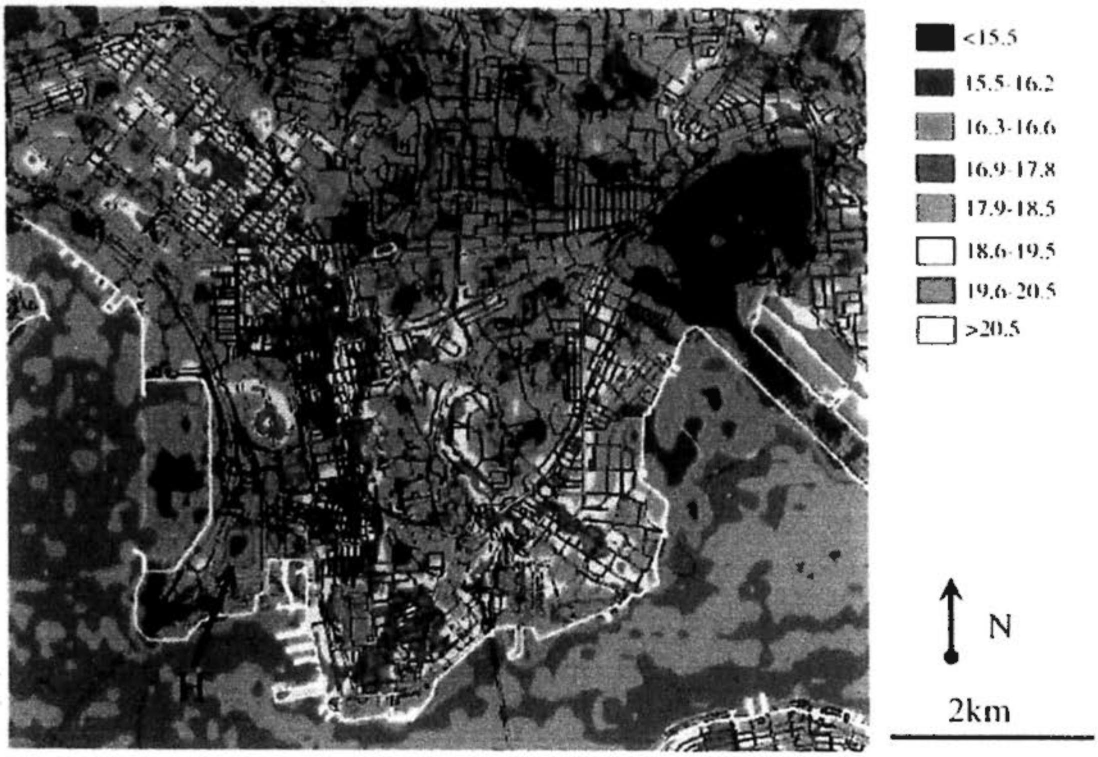


Figure 4.5 General distribution of the SUHI over Kowloon Peninsula, showing a north south alignment of the heat island core along Nathan Road, the main commercial and shopping district. After (Nichol, Fung, Lam, & Wong, 2009)

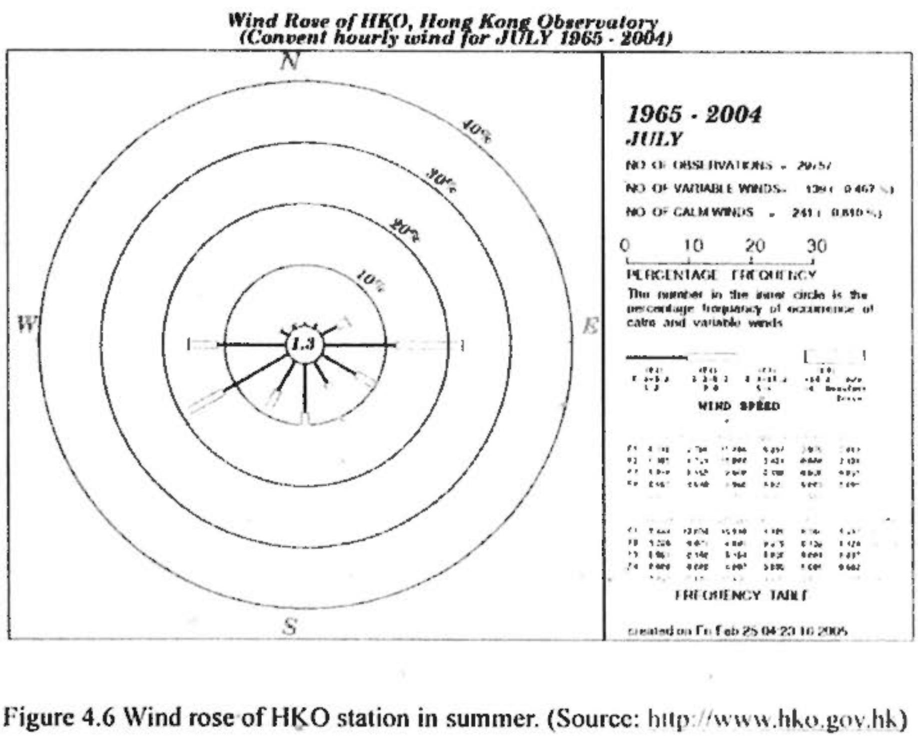


Figure 4.6 Wind rose of HKO station in summer. (Source: http://www.hko.gov.hk)

4.2 Urban Environment Modeling

This section introduces how the urban environment of the study site, including both the urban form and the environmental characteristics, is modeled in the PedNaTAS system. All the modeling processes are put in a GIS-based framework. The readers are referred to Chapter 3 for the software structure and implementation methodologies of the modeling.

4.2.1 Urban Form Modeling

The urban form modeling corresponds to the "urban context" representation as introduced in Section 3.2.1. It is mainly based on a vector-based 3-D building database. A car road map is also used. Figure 4.7 shows an illustration of the employed database. The modeling is carried out in the Repast Simphony package. The socially-related components, including street end points and bus stops etc., are digitized according to the map as shown in Figure 4.3, and the shape files are edited in the ArcGIS system.

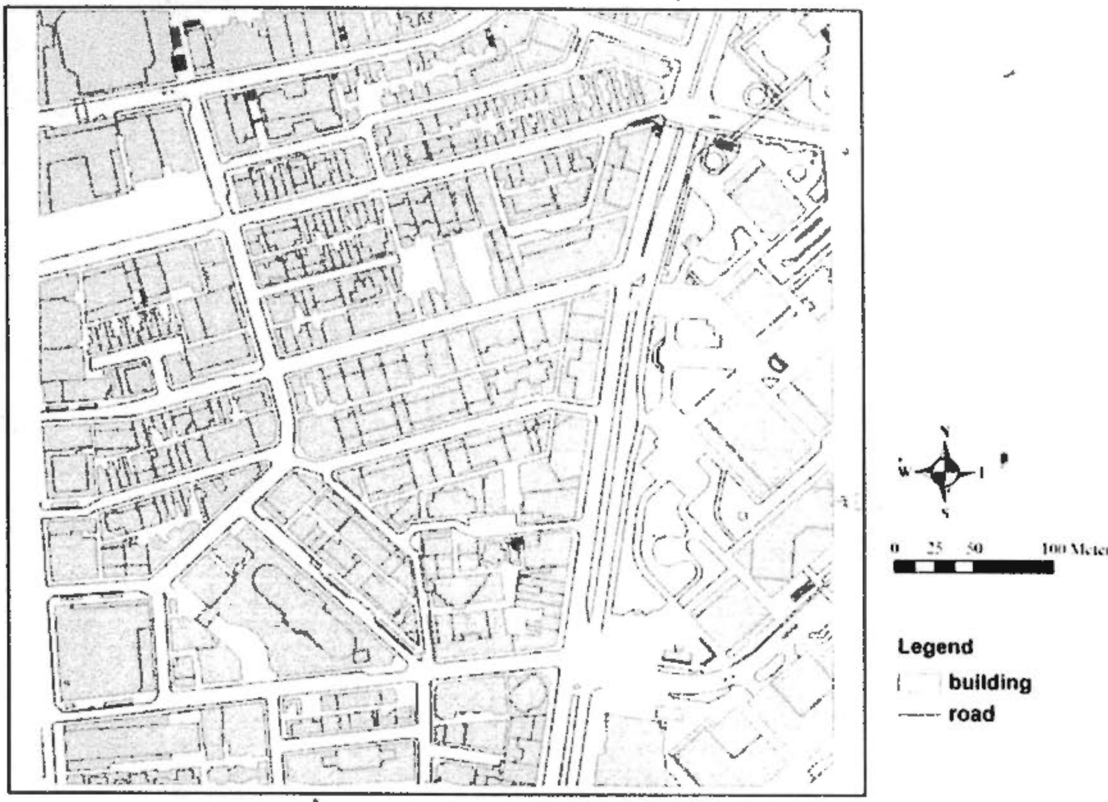


Figure 4.7 Illustration of the employed vector database for urban form modeling. The database includes a 3-D building data, and a car road map.

Building: Polygon Shape File

The building shape file is directly loaded into the PedNaTAS system using the *ShapefileLoader* class provided by Repast Simphony. All attributes of the shape file are also loaded simultaneously, including building height and area. Each building has a unique system-assigned ID.

Gate Point: Point Shape File

As introduced in Section 3.2.1.1, the Gate points are the locations where the pedestrians enter the domain. By examining the map (Figure 4.3), these points are created in the ArcGIS system, including 12 MTR exits, with Exit IDs being A2, B1, B2, D1, D2, M2, M3, N1, N2, P1, P2 and P3, and 16 street end points, and 2 parking lots. This created point shape file is loaded into the PedNaTAS system using the *ShapefileLoader* class.

Exit Point: Point Shape File

The Exit point shape file is also created in the ArcGIS system. Building entrances are manually drawn according to the map. The ArcGIS-embedded function, "Join based on spatial location", is used to spatially join a building entrance with its associated building. In this way the "building area" attributes are assigned to Exit points. There are 270 Exit points in all, with "building area" attributes ranging from 90 to 326 m^2. To avoid too large value in the utility calculation (refer to Section 3.3.1), this attribute is divided by 1000. The point shape file with the newly assigned attributes is loaded into the PedNaTAS system using the *ShapefileLoader* class.

Street Network: Poly-Line Shape File

The Street network shape file is created in the ArcGIS system. As introduced in Section 3.2.1.1, the PedNaTAS system automatically constructs the street network when the street shape file is loaded, so the edit job at this stage is only to manually draw the poly-line shape file based on the car road map. There are two issues that are worthwhile noticing: firstly, the line segments created here are the streets that pedestrians walk along, as opposed to the employed car road map; secondly, after a line segment is created, it is assigned a unique ID, which is to be used in the street network construction when the shape file is loaded. The poly-line shape file is also loaded using the *ShapefileLoader* class.

Walking Grid: Raster

The walking grid is in 0.5m resolution so is a 1000 × 1000 matrix. It is used to control the physical movement of pedestrians and works in the background but not for display purpose (compare next section *Side walk*). In practice, the building shape file and the car road map shape file are used to derive this grid. The edit is carried out in the ArcGIS system: 1) the building polygon shape file are converted to raster file representing built-up space and non-built-up space; 2) the car road map poly-line shape file is used to create a polygon shape file defining the boundary of the car road and the shape file is further converted to raster file representing car road and otherwise; 3) the resulting 2 raster files are combined and reclassified to define 3 types of walking spaces: 0 as pavement, 1 as car road, and 2 as built-up area. The Walking grid is exported from the ArcGIS system to an ESRI ASCII format text file, and loaded into the PedNaTAS system using the self-implemented class *ASCIIReader*.

Sidewalk: Polygon Shape File

The Sidewalk shape file is for interface display purpose only. It is converted from the Walking grid and represents the pavement space where pedestrians prefer to walk on. The polygon shape file is loaded into the PedNaTAS system using the

ShapefileLoader class.

Shading Grid: Raster

The Shading grid is also in 0.5m resolution. As it is generated by the "shadow casting" algorithm implemented in the SOLWEIG system, it is introduced in the T_{mrt} section in Section 4.2.2 Environmental modeling. The resulting ESRI ASCII format text file is loaded using the *ASCIIReader* class.

Shade: Polygon Shape File

The Shade shape file is for interface display purpose only. It is converted from the Shading grid and represents the shade pattern of the domain. The polygon shape file is loaded into the PedNaTAS system using the *ShapefileLoader* class.

So far, the urban form of the study site, including both the data structure and the graphical interface, has been successfully modeled in the PedNaTAS system. Both vector-based data and raster-based data have been created and imported into the system. The highly hierarchical modeling process defines a comprehensive urban space based on which the pedestrian movement simulation is further carried out. The modeling process is well put in a GIS framework, allowing the simulation and analysis to be easily incorporated with any commonly used GIS platforms. With the help of the Repast Simphony package, various layers of data have been visualized through the user interface. Figure 4.8 shows an illustration of the interface of the PedNaTAS system. The display sequence of the layers of shape files, from top down, is: Gate point, Exit point, Street, Shade, Building, Sidewalk, and the domain frame.

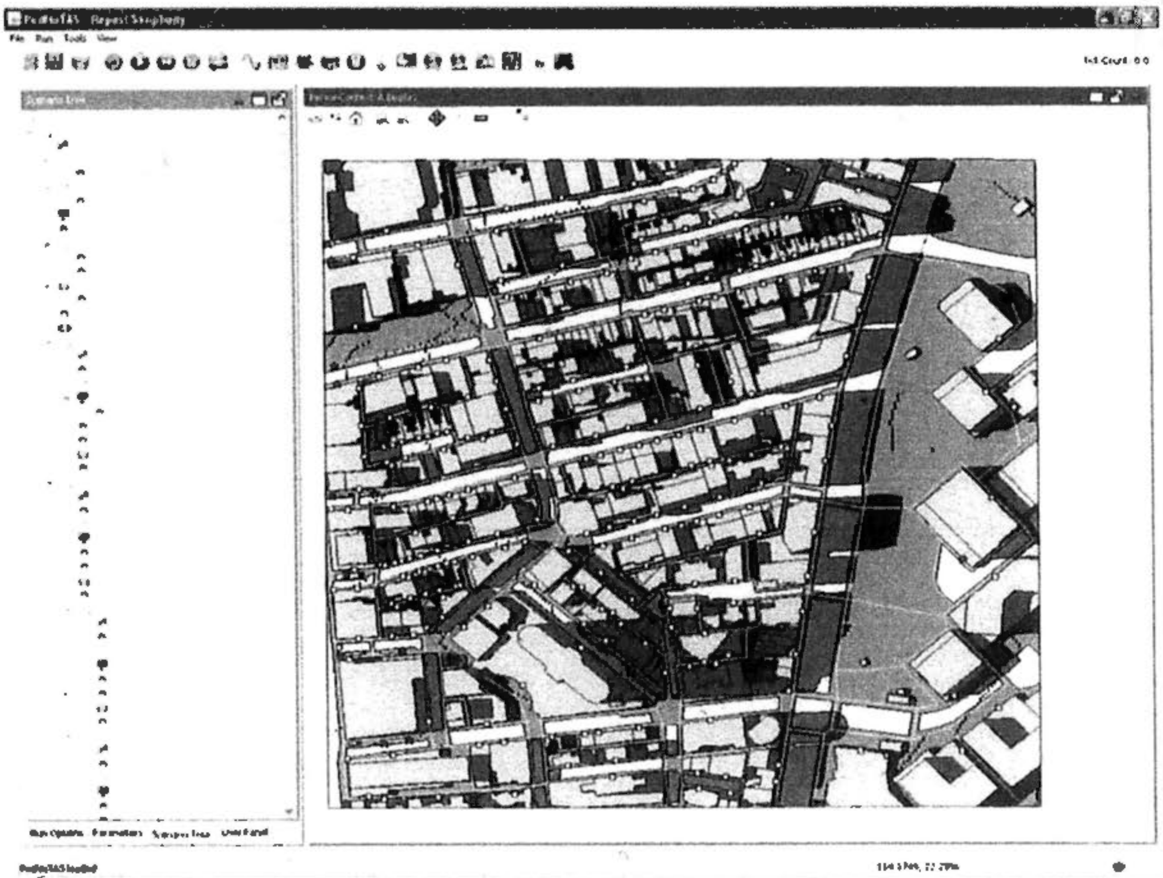


Figure 4.8 Interface of the PedNaTAS system. The control panel is on the left, and the graphical interface is on the right. Buildings are represented by blue polygons; Gate points are represented by red stars; Exit points are represented by light green dots; Streets are represented by light pink lines; Shade is represented by dark grey polygons and Sidewalk is represented by light grey polygons.

4.2.2 Environmental Modeling

The environmental modeling process models the micro-scale climatic condition of the study site on a clear summer afternoon. In practice, the date of 9 May, 2008 is selected because the detailed on-site meteorological observation on that day provided sufficient data to validate and test the modeling result, and the modeling period is selected to be 14:00 to 15:00 (refer to the following T_{mrt} section for detailed discussion). As introduced in Section 3.2.2, the meteorological condition of the urban environment is defined by two types of parameters: the spatially constant parameters such as air temperature and relative humidity, and the spatially variant parameters such as T_{mrt} and wind speed. The spatially constant parameters are directly obtained from HKO's meteorological records, as summarized in Table 4.1.

Table 4.1 Summary of climatic conditions of the modeled period, including air temperature (T), global solar radiation (Radiation), relative humidity (RH), and duration of sunshine (Sunshine). The data were recorded by Hong Kong Observatory at a station next to the study area.

Date	Modeling period	T (°C)	Radiation (W/m^2)	RH (%)	Sunshine (hour)
9, May, 2008	14:00-15:00	30	500	65	10.5

The spatially variant parameters, in particular, the T_{mrt} and wind speed are of great importance in modeling the local climatic condition. In the PedNaTAS system, these two parameters are modeled by collaborating with other modeling software, being the SOLWEIG system and the CFD model, respectively. The modeling results are in high-resolution ESRI ASCII raster format, being 0.5m resolution. These two raster files only work in the background of the PedNaTAS system but are not for interface display purposes, as to display multiple raster files will normally requires different transparencies of the layers, which will get messy really easily. The display of the raster files are carried out in the ArcGIS system. The following sections present detailed discussions on the modeling process.

4.2.2.1 Radiation Modeling: T_{mrt}

Estimation of T_{mrt} in outdoor urban environment is a complex issue and the determination methodology is far from being evident. Thorsson *et al.* (2007) have summarized different methods for estimating T_{mrt} and preliminarily compared them. As for computer tools for modeling T_{mrt}, currently there are several publicly accessible models, including the ENVI-met model (http://www.envi-met.com/), the Rayman model (http://www.urbanclimate.net/rayman/), and the SOLWEIG model (http://www.gvc2.gu.se/ngeo/urban/Activities/solweig.htm). These models have been shown to give good estimation of outdoor T_{mrt} in outdoor urban environment and have been widely applied in urban climatology studies (M Bruse & Fleer, 1998; Lindberg, et al., 2008; Andreas Matzarakis, 2007; Andreas Matzarakis, Rutz, & Mayer, 2010).

Why the SOLWEIG Model Is Used

The SOLWEIG model particularly fits for the scheme of the present study in that it can deal with real and complex urban settings and give good estimation of the spatial variation of T_{mrt}. The output is in ESRI ASCII format which can be directly loaded to the PedNaTAS system. With these concerns the SOLWEIG model is adapted in the study. The following section presents the methodologies of determining T_{mrt} for Hong Kong's urban environment using SOLWEIG.

A sample site is selected to test the applicability of SOLWEIG in Hong Kong's urban environment. The site is in Tsuen Wan (TW) which is one of Hong Kong's most densely built-up areas. The site has coastal flat terrains of similar land use category (mostly commercial and residential development) with little vegetation. Differences in building height and density are commonly found in the site. The site is 1km by 1km in size. Spatial variations of the urban geometry of TW are represented by a high-resolution digital elevation model (DEM) as shown in Figure 4.9.

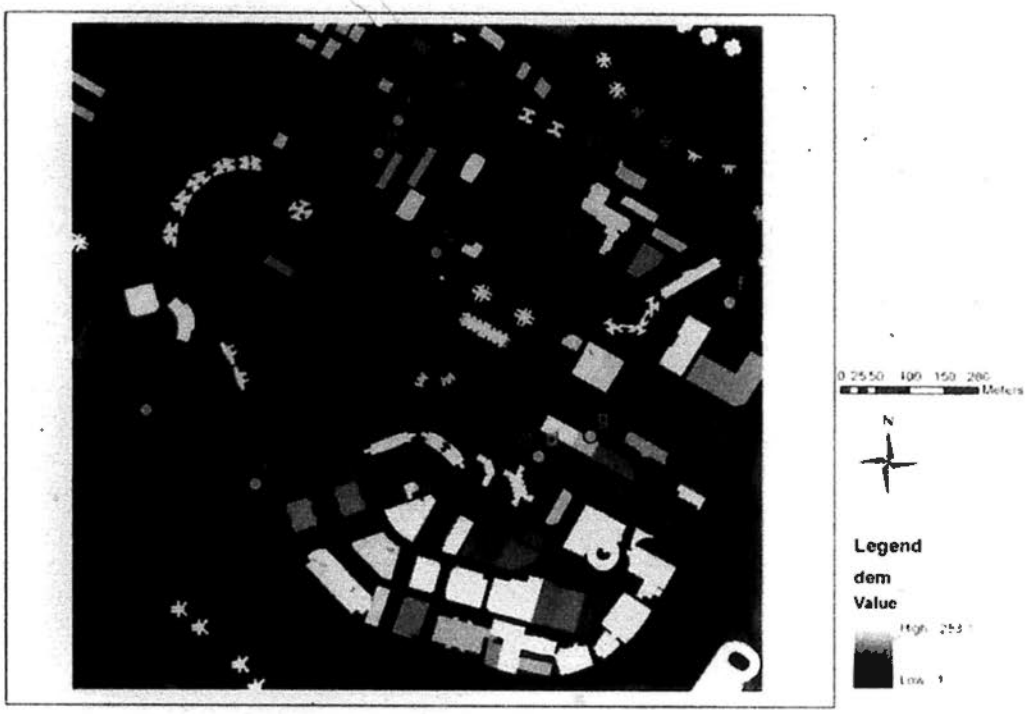


Figure 4.9 A high-resolution (1m) DEM of the TW site. The labeled points are the locations where field measurements were conducted to test the SOLWEIG model.

Estimation of T_{mrt} Based on Field Measurement

A dataset obtained in field measurements carried out in the summer of 2008 is used to investigate T_{mrt} of the site: one measurement on 21 June and another on 4 July. Both measurements were carried out in clear afternoons from 14:30 to 15:30. Climatic conditions of the measurements are given in Table 4.2. A mobile meteorological station fixed at 2m above ground level was employed in the measurement (Figure 4.10). Measurement equipments include a globe thermometer for radiation measurement, a 3-function sensor probe from TESTO 400 for air temperature, relative humidity and wind speed measurement, and TESTO 400 data logger for instant processing of measured data. The data logger was set to have a sampling rate of 5 seconds and an averaging time of 10 minutes. Detailed methodologies and specifications of the measurements are given in Ng *et al.* (2008).

Table 4.2. Summary of climatic conditions of field measurement in TW, including air temperature (T), global solar radiation (Radiation), relative humidity (RH), wind speed (V) and duration of sunshine (Sunshine). The data were recorded by Hong Kong Observatory at a station next to the study area.

Date	Measurement period	T (°C)	Radiation (W/m^2)	RH (%)	V (m/s)	Sunshine (hour)
2008/06/21	14:30~15:30	≈31.5	560~720	≈65	0.6~2	10.9
2008/07/04	14:30~15:30	30.5~32.0	460~690	≈70	0.7~4	10.2

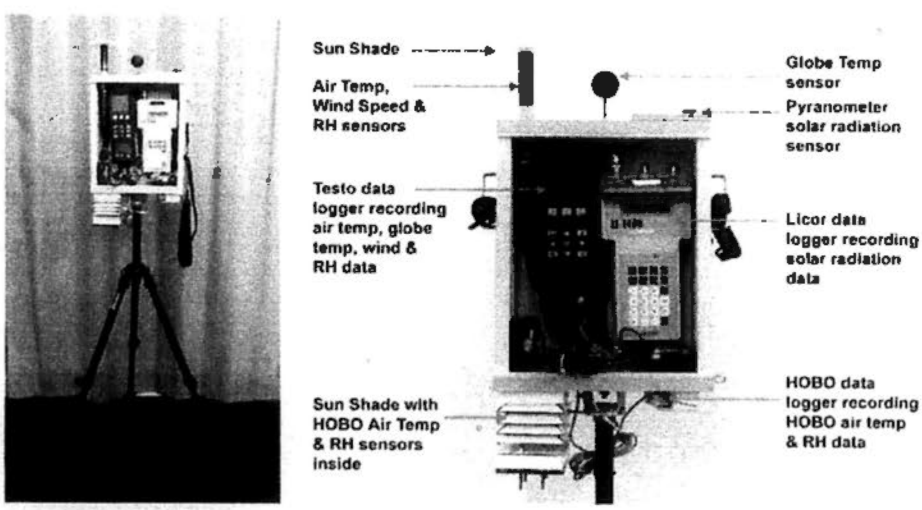


Figure 4.10 A mobile meteorological station used in the field measurement. Equipments used in this study are the globe thermometer for radiation measurement, the TESTO sensor for air temperature, relative humidity and wind speed measurement, and the TESTO data logger for instant data processing. After (Ng, Wang, et al., 2008).

Both measurements covered a total number of 24 points. However, the points need to be selected properly before they can be used in T_{mrt} estimation and compared with the SOLWEIG model. First, the version of SOLWEIG used in the study (v1.1) cannot deal with vegetation data, so measurement points where vegetation is present, such as in an urban park, are not used. Secondly, the climatic conditions of the two measurements are similar according to Table 4.2. In this sense the data obtained are compared to get rid of temporal fluctuation, i.e., if large discrepancies are found in the measurement results for the same point, then the point are not used. Thirdly, measurement points with extremely large wind speed (greater than 4m/s) are not used since in this case the estimation of T_{mrt} based on measurement is not reliable (refer to Equation 4.1). Eventually, only 8 points are selected, as shown in Figure 4.9. Two points are in sunlit area (Point a and c), and 6 points are in building shade area (Point b, d, e, f, g and h). A summary of the measurement results of the 8 points are given in Table 4.3.

Table 4.3 Summary of measurement results of the 8 selected points. Point IDs are as shown in Figure 4.9. Measurement results include air temperature (T_a), globe thermometer temperature (T_g) and wind speed (V).

Point ID	Measurement time	June 21			July 4		
		T_a (°C)	T_g (°C)	V (m/s)	T_a (°C)	T_g (°C)	V (m/s)

a	14:40	34.2	40	1.43	32.3	40.3	0.67
b	15:00	35	37.2	0.86	33.3	33.6	0.97
c	15:15	33.4	36.6	2.02	32.5	36.9	1.36
d	15:15	34.4	37.3	1.58	32.9	33.3	0.93
e	15:15	34.8	36.4	0.86	33.4	33.9	0.99
f	15:15	32.5	33.3	1.22	32.5	33.2	1.99
g	15:30	32.3	35.6	1.42	32.9	33.3	0.88
h	15:30	34.4	35.7	0.82	33.4	34	1.12

Thorsson et al. (2007) have shown that 38 mm globe thermometer gives accurate estimation of the T_{mrt} in an outdoor urban setting. In the same sense, the equation proposed by ASHRAE (2001) is applied to estimate T_{mrt}, as given by

$$T_{mrt} = \left[\left(t_g + 273\right)^4 + \frac{1.10 * 10^8 * V^{0.6}}{\varepsilon * D^{0.4}} \left(t_g - t_a\right) \right]^{1/4} - 273, \qquad \text{(Equation 4.1)}$$

where ε is emissivity and $\varepsilon = 0.95$ for a black globe thermometer,

D is the globe diameter and $D = 0.038$m,

V is air speed in m s^{-1},

and t_a is air temperature in °C and t_g is globe thermometer's temperature in °C. Based on Table 4.3 and Equation 4.1, T_{mrt} for the 8 points are calculated and is given in Table 4.4.

Estimation of T_{mrt} Using SOLWEIG

As introduced in the previous section, the SOLWEIG model models the spatial variations of T_{mrt} for an entire urban environment. The model asks for DEM as input data (Figure 4.9), together with the longitude/latitude information of the examined site. The model also requires the following meteorological parameters:

- absorption coefficient of short wave radiation for human body, which is set as the standard value of 0.7 in the study (Andreas Matzarakis, 2007);
- absorption coefficient of long wave radiation for human body, which is set as the standard value of 0.97 in the study (Andreas Matzarakis, 2007);
- surface albedo, which is set as 0.25 for aged concrete for Hong Kong (VanGeem, 2002);
- wall emissivity, which is set as the standard value of 0.9 (Oke, 1987);
- ground emissivity, which is set as the standard value of 0.95 (Oke, 1987).

The time resolution of SOLWEIG is 1 hour, meaning that it models the hourly average T_{mrt} of an urban environment. Considering the measurement time period, 2 hours of T_{mrt} for each measurement date are modeled using SOLWEIG, being 14:00 and 15:00. The modeled results are shown in Figure 4.11 to Figure 4.14. One thing to be noted is that, the hourly average T_{mrt} is represented as the condition of the middle of the modeled hour, for example, Figure 4.11 shows the spatial variation of T_{mrt} at 14:30 of 21 June, 2008 since the modeled hour is 14:00.

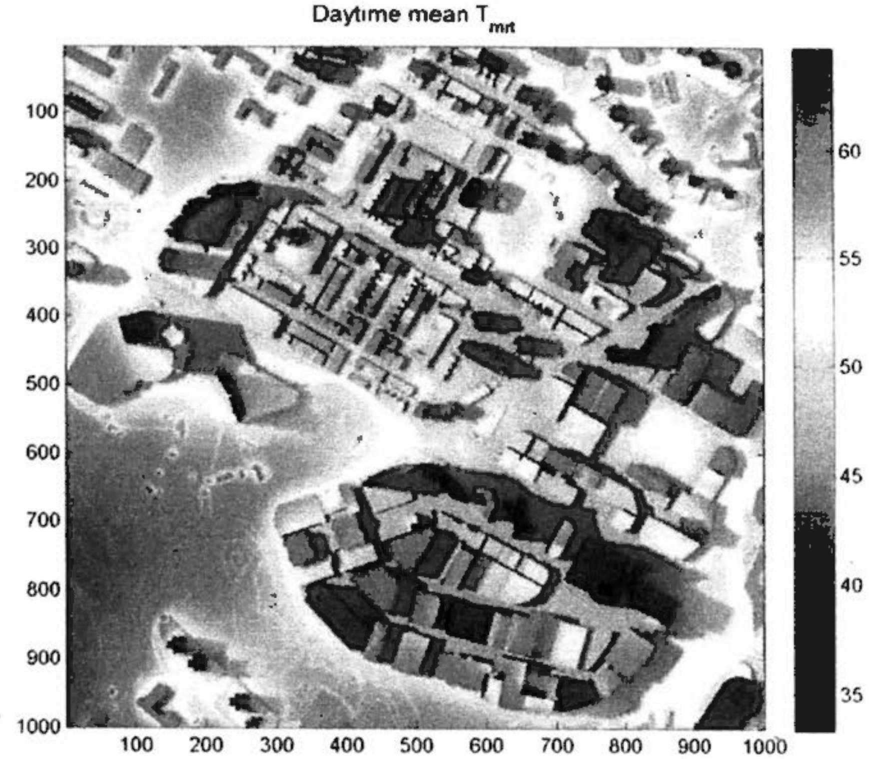


Figure 4.11 T_{mrt} map modeled by SOLWEIG for 14:00, 21 June, 2008, T_a = 31.5°C.

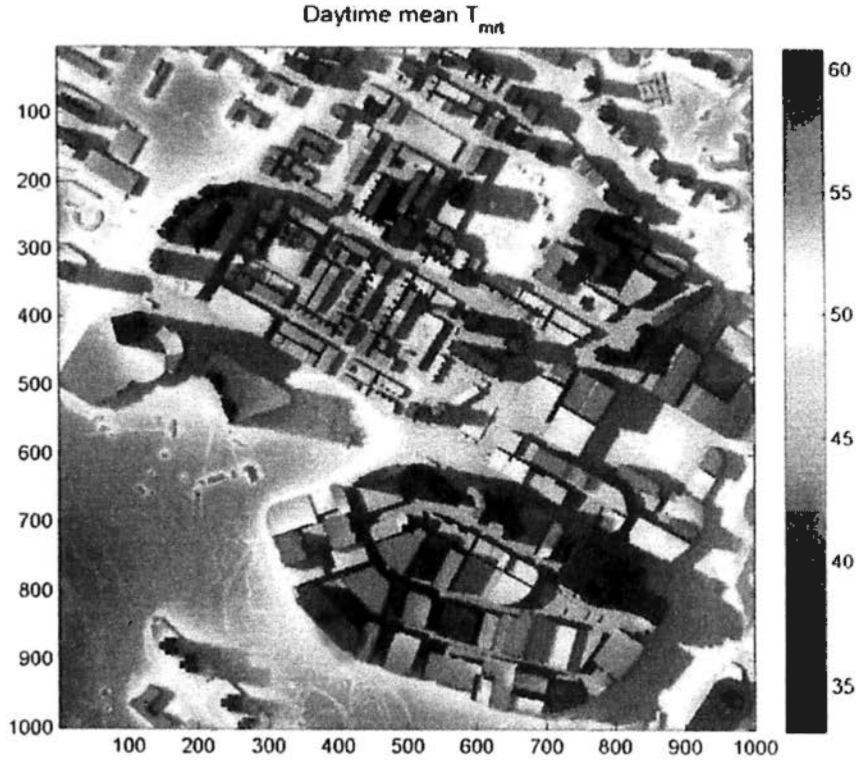


Figure 4.12 T_{mrt} map modeled by SOLWEIG for 15:00, 21 June, 2008, T_a = 31.5°C.

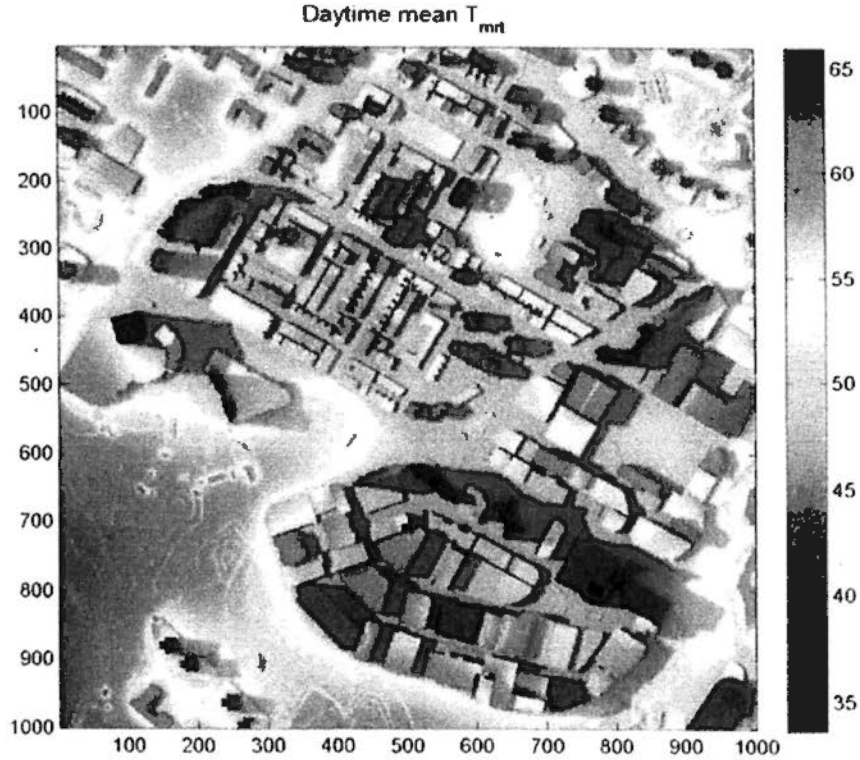


Figure 4.13 T_{mrt} map modeled by SOLWEIG for 14:00, 4 July, 2008, T_a = 32.0°C.

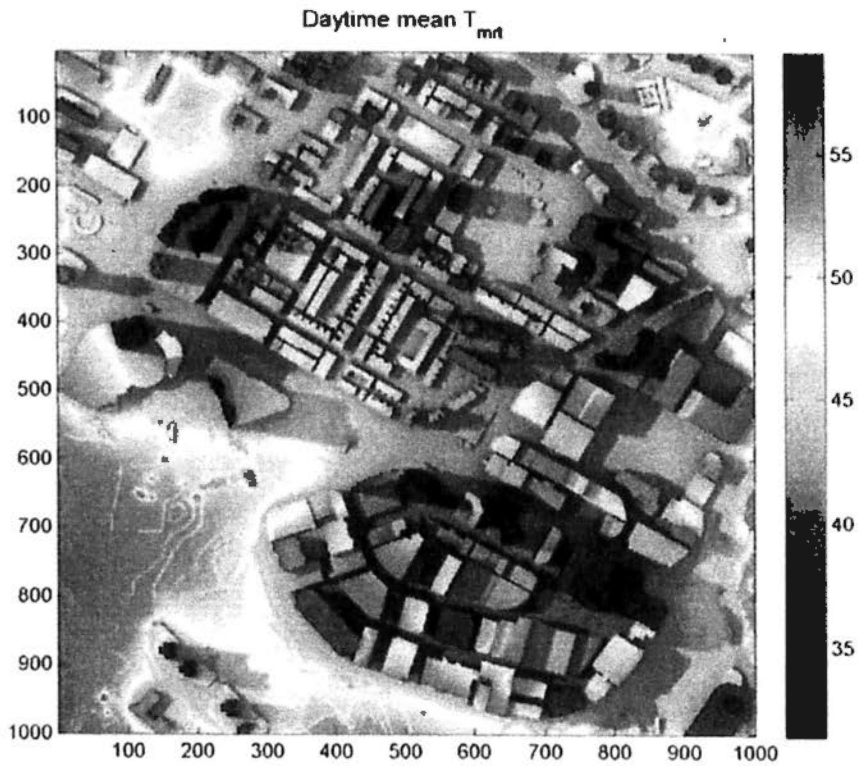


Figure 4.14 T_{mrt} map modeled by SOLWEIG for 15:00, 4 July, 2008, T_a = 30.5°C.

Since the field measurements were carried out at different time slots between 14:30 and 15:30 and it is impossible to normalize the globe thermometer temperature to a fixed time, an alternative approach is taken to compare T_{mrt} estimated from measurement data to T_{mrt} SOLWEIG modeling result of either the 14:00 hour or the 15:00 hour, depending on which is temporally closer. Admittedly this is not a rigorous way to test the model performance *per se*, nevertheless, given that the global solar radiation drops gradually from 14:00 to 15:00 in the site (Ng, Wang, et al., 2008), this comparison suffices the objective of the study which is to test whether the SOLWEIG model can be applied in Hong Kong's urban settings. The comparison is shown in Table 4.4. Modeled T_{mrt} for each point are extracted using the software built-in functions in ArcGIS system, which is easily done because of the GIS-friendly feature of the SOLWEIG model.

Table 4.4 Comparison of T_{mrt} estimated from field measurement (T_{mrt}-f) and modeled by SOLWEIG (T_{mrt}-m-1430 for the 14:00 hour modeling and T_{mrt}-m-1530 for the 15:00 hour modeling). ΔT_{mrt} is the difference between T_{mrt}-f and T_{mrt}-m-1430 or T_{mrt}-m-1530 depending on which is temporally closer.

Point ID	Measurement time	June 21				July 4			
		T_{mrt}-f (°C)	T_{mrt}-m-1430 (°C)	T_{mrt}-m-1530 (°C)	ΔT_{mrt}	T_{mrt}-f (°C)	T_{mrt}-m-1430 (°C)	T_{mrt}-m-1530 (°C)	ΔT_{mrt}
a	14:40	62.5	61	57.1	**-1.5**	60.2	61.8	55.1	**-1.6**
b	15:00	44.7	47.6	43.7	**1**	44.6	49.4	43	**1.6**
c	15:15	52.9	56.3	53.2	**-0.3**	54.4	62	55.5	**-1.1**
d	15:15	50.1	54.5	48.5	**1.3**	37.7	53.8	41.2	**-3.5**
e	15:15	41.6	55.5	43.8	**-2.2**	37.5	55.2	43	-5.5
f	15:15	38.6	55.5	43.8	-5.2	37	55.1	42.9	-5.9
g	15:30	49.4	48.7	44.6	-4.8	37.8	49.3	42.8	-5
h	15:30	39.8	55.5	43.2	**-3.4**	37.3	50	42.9	-5.6

Table 4.4 shows that the differences between measured and modeled T_{mrt} are reasonably small, most of which are within 3°C. Considering the fact that the estimation of T_{mrt} based on field measurement using ASHRAE's model is extremely sensitive to wind speed (refer to Eq. 4.1), the difference between the two methods can be considered as acceptable. The comparison is also in consistent with Lindberg *et al.*'s (2008) finding which is that on a clear summer day the difference of T_{mrt} values between SOLWEIG model and measurement is 2.3°C. Although there is more work to be done to refine the model, such as to implement spatially various surface albedo and higher temporal resolution (which is beyond the scope of the present study), the usefulness of the SOLWEIG model in Hong Kong's urban environment is confirmed

and the aforementioned parameter settings are shown to give satisfactory results. These settings are adapted in the PedNaTAS system. The T_{mrt} map of the study site is shown in Figure 4.15.

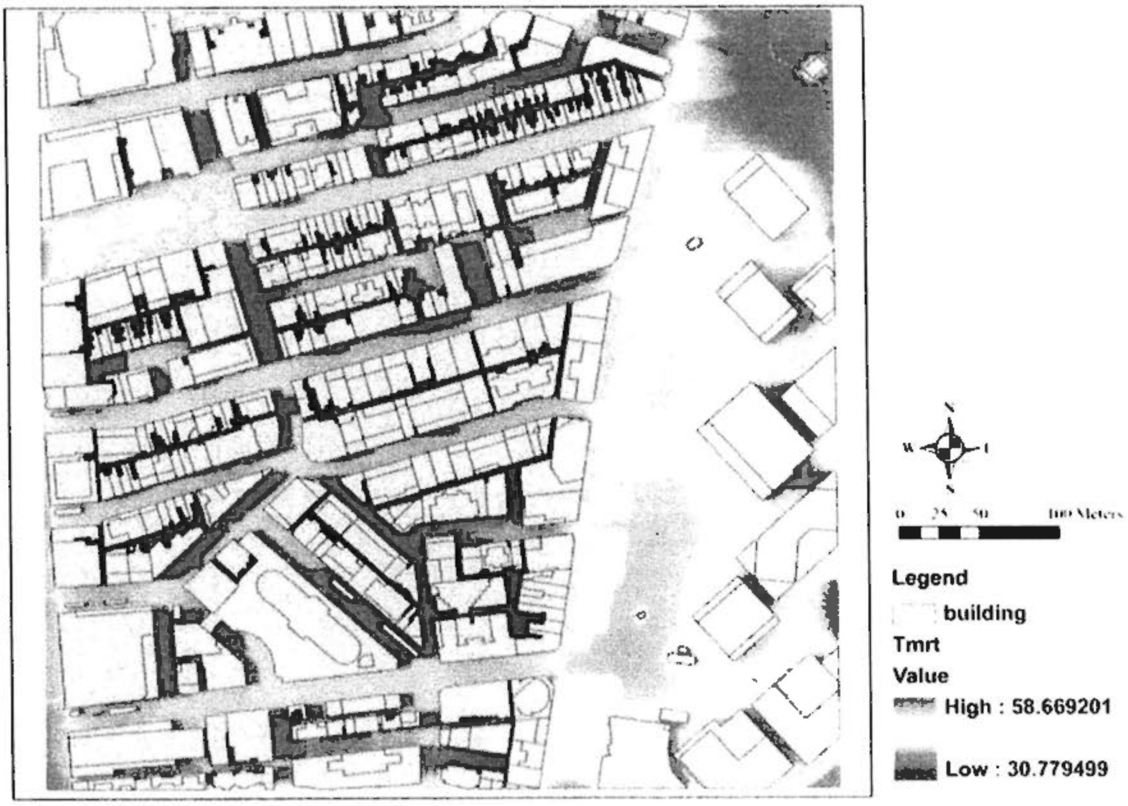


Figure 4.15 T_{mrt} map of the study site modeled by SOLWEIG for 14:00, 9 May, 2008, T_a = 27.3°C.

Shading Calculation

Another useful function of the SOLWEIG model is that it implements the "shadow casting" algorithm by Ratti and Richens (1999). The output is an ESRI ASCII format text file, which is directly loaded into the PedNaTAS system as the Shading grid. As the time resolution used is 1 hour, the modelled result represents the shading pattern at 14:30, which is in the middle of the modelled hour. The Shading map of the study site is shown in Figure 4.16, and the converted Shade shape file has already been shown in Figure 4.8.

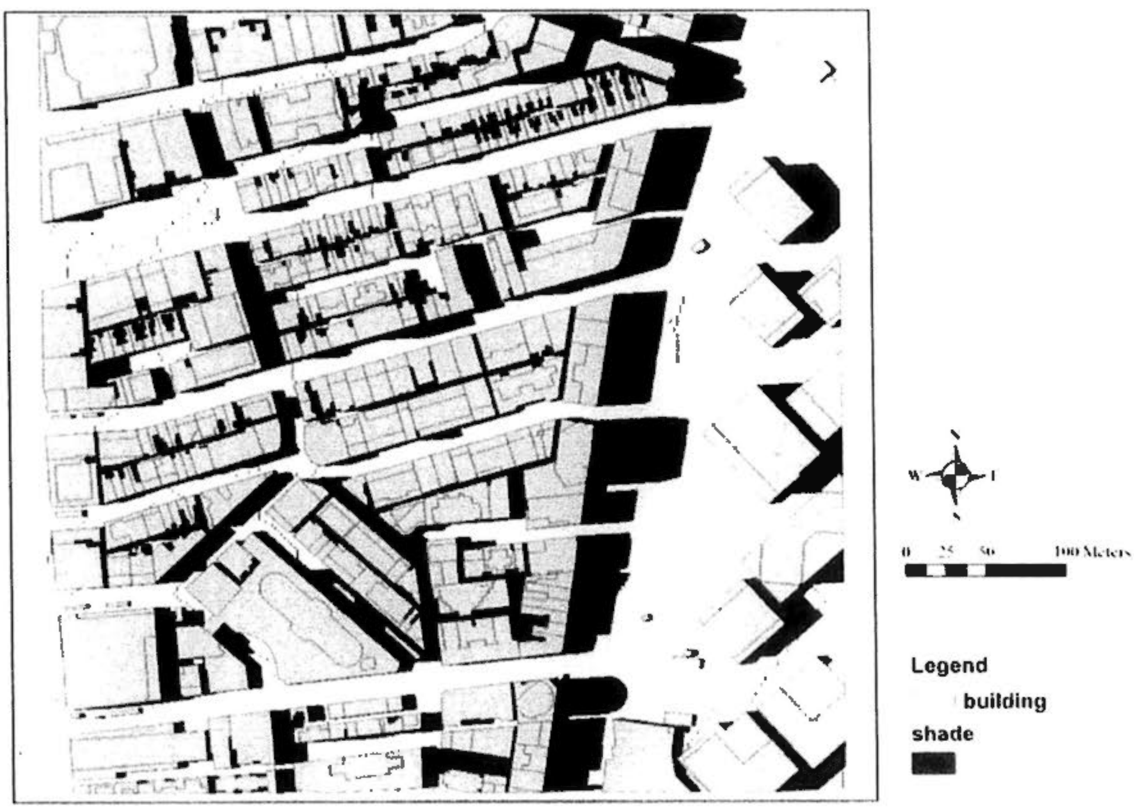


Figure 4.16 Shading map of the study site. The map represents the shade pattern at 14:30 because of the 1 hour time resolution used.

4.2.2.2 Wind Speed Modeling

The wind environment in PedNaTAS system is derived from a dataset obtained in an early Large-Eddy Simulation (LES) study (Letzel, Weinreis, Ng, An, & Raasch, 2010). This section introduces how the dataset is integrated into the system.

A Brief Introduction to the LES Feasibility Study

Letzel (2007) has carried out an LES study to test its feasibility in simulating Hong Kong's urban wind dynamics. A densely built-up area in Tsim Sha Tsui, Kowloon is used as a case study. The indicating parameter used in the study is the *velocity ratio* (v_r), defined as the ratio of absolute wind velocity v_p at pedestrian level (z = 2m) to the absolute wind velocity v_∞ above the urban fabric where the wind dynamic is not affected by the building bulk (z = 400m for the model). Prevailing East wind is selected according to the record at Hong Kong Observatory Station which is close to study site (http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm#table7). By comparing the simulation results with other data such as PArallelized LES Model (PALM) and wind tunnel study, the feasibility of LES is proved. In a more recent study (Letzel, et al., 2010), the model is extend to a larger domain which includes the study site of the present study, as shown in Figure 4.17. The study shows that the model performance is acceptable for the study site, therefore the dataset is selected to provide wind environment for the PedNaTAS system.

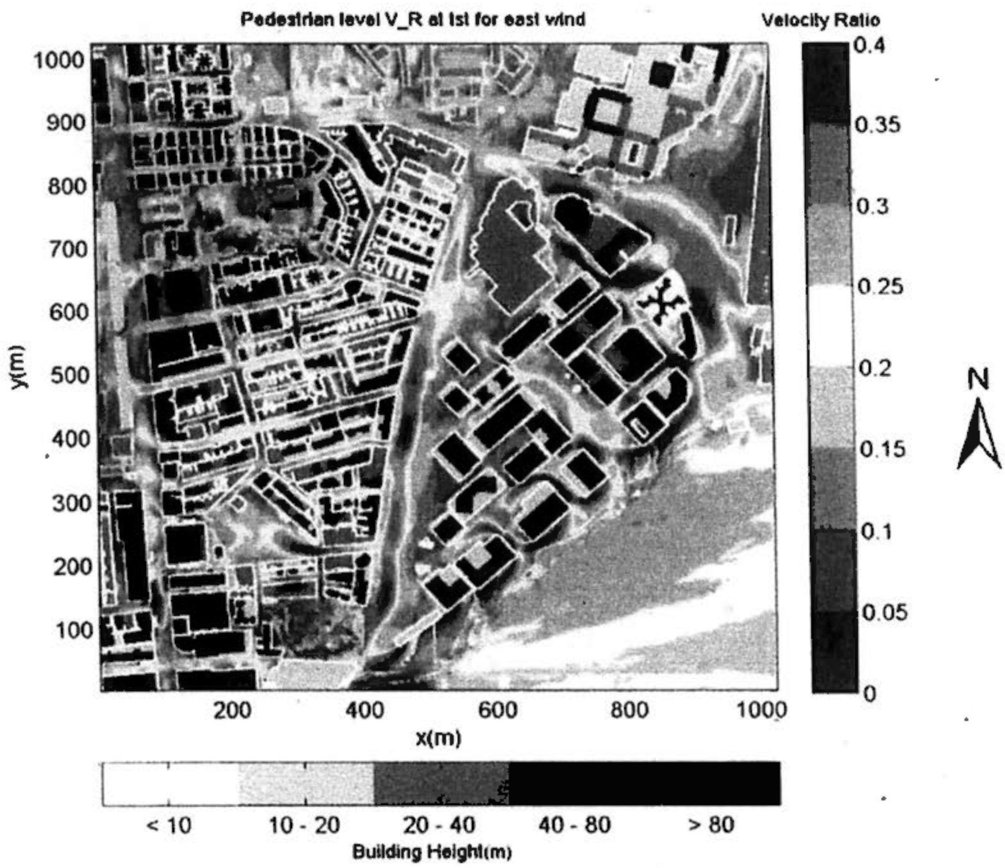


Figure 4.17 Pedestrian level v_r at TST for East wind. After (Letzel, et al., 2010)

Data Preparation and Integration

The dataset from the LES study needs to be processed properly before it could be used in the PedNaTAS system. Due to the nature of the mesh used in LES, the spaces close to buildings have no v_r values. This will be a problem for PedNaTAS as pedestrians in the system will make use of these spaces and the local wind information is needed for their thermal comfort assessment, i.e., every pixel of the walkable space requires a wind speed value. In this sense, empty pixels in the LES result are interpolated by assigning the nearest v_r available. This is rather rough estimation, nevertheless, considering the micro-scale of the empty spaces (normally in the order of 0.5~1m), it is reasonable to approximate its wind speed with a nearby pixel. In practice, an

ArcGIS embedded macro is implemented in VBA programming language to do the job. As mentioned in the previous section, East wind is used as the prevailing wind direction. Also, according to Hong Kong Observatory (http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm#table7), the wind speed recorded at the Waglan Island station, which is far from the urban area, is used as v_{∞} since it is not affected by urban structure. The normal wind speed for summer is ~ 20km/h. In practice, the speed of 6m/s is selected. Combing v_{∞} and the v_r map, a wind speed raster of the case study site is produced, as shown in Figure 4.18. The raster is output in ESRI ASCII format as the input wind speed environment data for the PedNaTAS system.

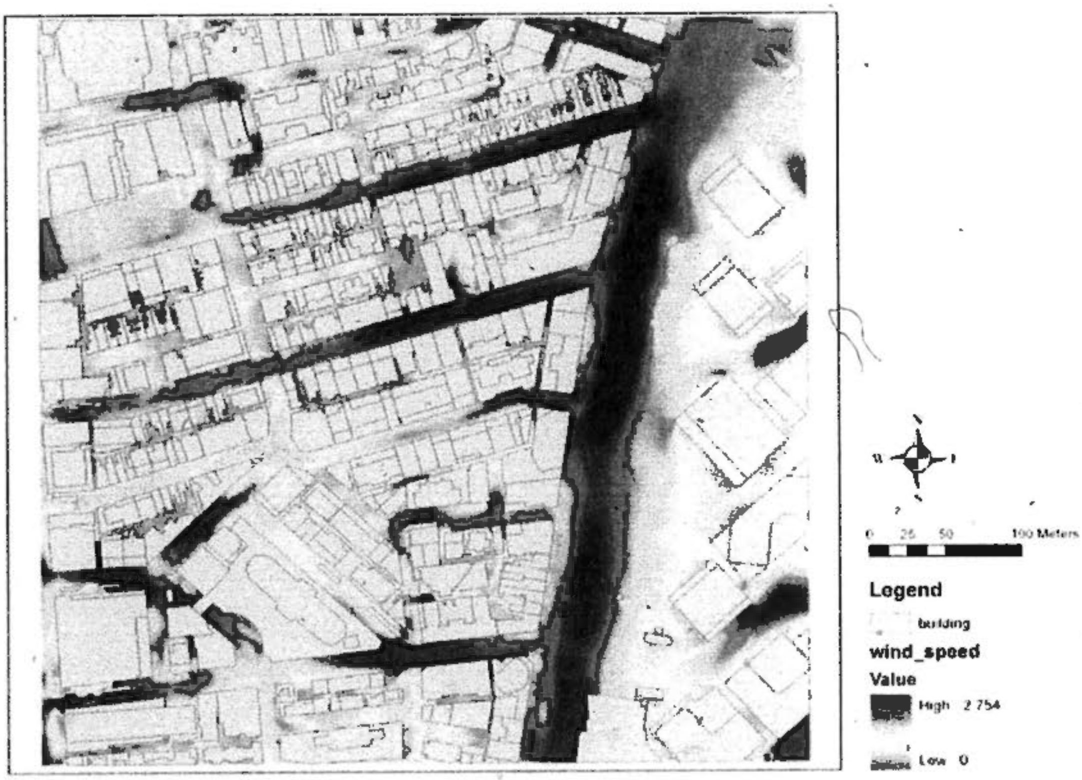


Figure 4.18 Pedestrian level wind speed map of the study site.

This section has discussed how the environmental characteristics of the study site are modeled in the PedNaTAS system, with special emphasis on the T_{mrt} and wind speed modeling. The modeling results provide detailed microclimatic information of the local environment. The modeling process makes use of other climatology models and integrates the results from different models in a GIS framework into the PedNaTAS system.

4.2.3 Pedestrian Modeling

Pedestrians are different. One great advantage of the PedNaTAS system is that the agent-based approach allows each pedestrian's characteristics to be modeled individually. In implementation, these characteristics are modeled as "attributes" of the pedestrian agents and are assigned to the agent when it is populated and enters the domain. This section introduces the modeling method.

4.2.3.1 Inherent Attributes

As the name implies, the inherent attributes of a pedestrian describes "what a pedestrian is". There are 4 inherent attributes for a pedestrian: gender, age, height and weight.

Gender

The Gender attribute of a pedestrian has a simple 50/50 probability being either male or female. In practice, a random number between 0 and 1 following a simple *Uniform distribution* is generated. If the random number is smaller than 0.5, the Gender attribute is set to male, and female vice versa.

Age

Different from the Gender attribute, the Age attribute of a pedestrian follows a *Normal distribution* $N(\mu, \sigma^2)$ where the mean μ is 40 and the standard deviation σ is 8. Figure 4.19 shows a 100-sample probability density curve. It shows that under the current setting, the Age attribute is within 10 and 70 yr old.

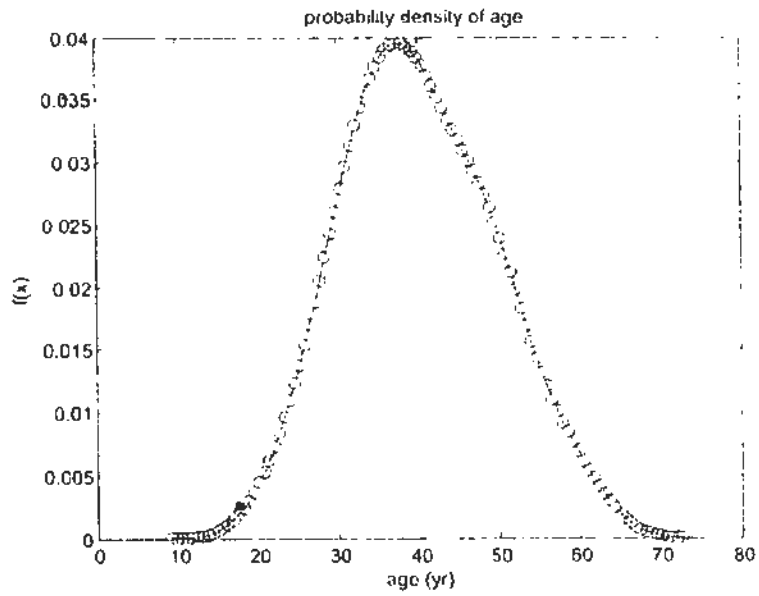


Figure 4.19 Probability density curve of 100 samples of Age attribute under the $N(40, 64)$ setting.

Height

Same as the Age attribute, the Height attribute of a pedestrian also follows a *Normal distribution* $N(\mu, \sigma^2)$ where μ is 1.75 for males and 1.60 for females, and σ is 0.05. Figures 4.20 and 4.21 show 100-sample probability density curves for male case and female case respectively. It can be said that the pedestrian's height is within reasonable range under the current setting.

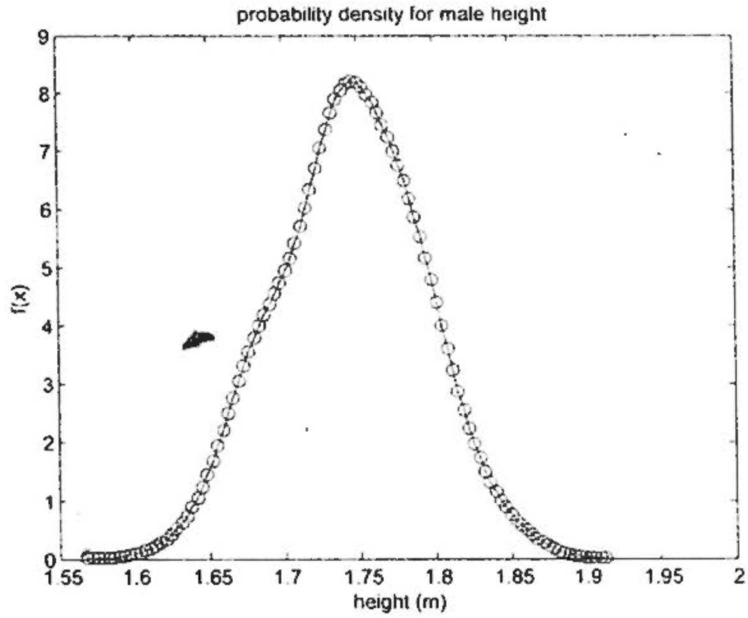


Figure 4.20 Probability density curve of 100 samples of Height attribute for male pedestrians under the $N(1.75, 0.0025)$ setting.

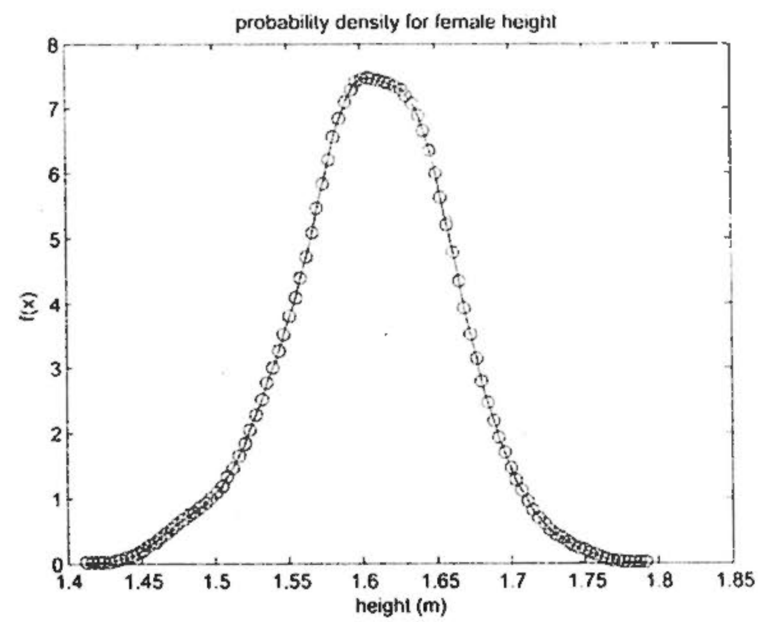


Figure 4.21 Probability density curve of 100 samples of Height attribute for male pedestrians under the $N(1.60, 0.0025)$ setting.

Weight

The Weight attribute of a pedestrian is selected to be dependent on the pedestrian's height. The modified *Broca's formula* (Broca, 1874) commonly applied in China is adapted, where

$$\text{Weight(male)} = (\text{Height} - 100) \times 0.9 \qquad \text{(Equation 4.2)}$$

and

$$\text{Weight(female)} = (\text{Height} - 105) \times 0.92 \qquad \text{(Equation 4.3)},$$

where Weight is in kg and Height is in cm. This is not rigid estimation, but the estimation is based on well-adapted common knowledge, and should provide reasonable representativeness in modeling the pedestrian's individual features.

4.2.3.2 Activity-Based Attributes

The activity-based attributes describes "what a pedestrian does". There are 3 activity-based attributes: Speed, Clothing insulation, and Work.

Speed

The speed is the most important activity-based attribute as it is closely related to pedestrian's walking activity. Worldwide studies have shown that the mean walking speed is between 1.0 to 1.5 m/s (Knoblauch, Pietrucha, & Nitzburg, 1996; Polus, Schofer, & Ushpiz, 1983; Virkler, 1998). In Hong Kong's transportation research, pedestrians' mean walking speed is often considered to be the constant of 1.2 m/s (Lee

& Lam, 2008), which is adapted in this study. In this case, a pedestrian's Speed attribute follows a *Normal distribution* $N(\mu, \sigma^2)$ where μ is 1.2 and σ is 0.3. Figure 4.22 shows a 100-sample probability density curve for the Speed attribute.

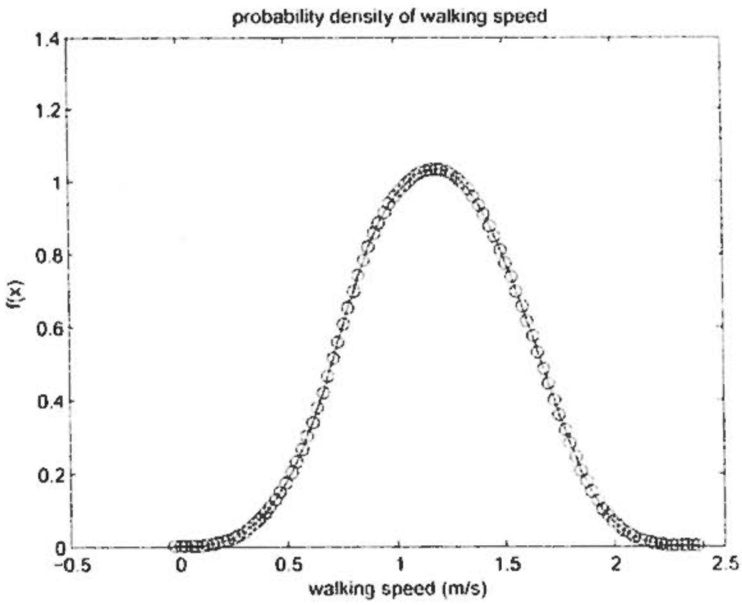


Figure 4.22 Probability density curve of 100 samples of Speed attribute under the $N(1.2, 0.09)$ setting.

Clothing Insulation

The Clothing insulation, or Clothing, describes the heat transfer resistance. It is a value ranges from 0 to 4, where 0 indicates naked status with none insulation and 4 indicates complete insulation. Because the simulation period is summer afternoon, pedestrians' Clothing is set to a constant, being 0.6 according to (ISO, 1989), which is also the parameter selected by (A. Matzarakis & Mayer, 1996).

Work

The Work attributes describes the metabolic rate of a pedestrian during physical activity. As the study only focuses on pedestrians' walking activity whose walking speeds are normally lower than 3m /s (refer to Figure 4.22), the physical activity should be categorized as "Light activity" according to (Occupational Safety and Health Administration, 1999). Therefore a constant Work of 80 w is selected, which is also consistent with (A. Matzarakis & Mayer, 1996).

To this stage, pedestrian's characteristics have been successfully modeled in the PedNaTAS system. One thing to be noted is that these settings are not intrinsic to the structure of the system, therefore they could be easily fine-tuned in the future study if new knowledge is available.

4.3 Pedestrian Thermal Comfort Assessment

This section introduces the pedestrian thermal comfort assessment methodologies. The first part of the section presents a traditional approach to give "static" assessment of the study site based on standard settings. The second part presents a simulation approach that considers pedestrian's behaviors and activities in the assessment. Both assessing processes are carried out exclusively in the PedNaTAS system. The analysis and visualization of the modeling result are partially conducted in the ArcGIS system.

4.3.1 Static Assessment Methodology: Steady State Modeling

4.3.1.1 Static Modeling

A widely adapted approach to give assessment of an urban environment in terms of human thermal comfort is the "static" way, which is to treat the urban space homogenously and give spatial variation of a particular thermal comfort index, commonly PET (Ali-Toudert & Mayer, 2006; Lin, Matzarakis, & Hwang, 2010; Andreas Matzarakis, et al., 1999). Along this line, we assess the thermal comfort pattern of the domain based on environmental modeling result as introduced in the previous sections. The meteorological condition of the modeling period is given in Table 4.1. We select a "standard person", which is a 1.75m tall, 75kg in weight and 40 yr old male, and calculate his PET value at different locations in the domain. One thing to be noted is that to calculate PET will require the vapor pressure instead of relative humidity percentage (refer to Section 3.4.1), therefore the vapor pressure of 27.8 hPa is selected which is the mean value of May based on HKO's long term meteorological data record (http://www.weather.gov.hk/cis/normal/1971_2000/normals_e.htm).

The PedNaTAS system makes it quite easy and straightforward to give this type of static assessment in practice. A Person agent is created with all the standard settings assigned. Then the agent is moved to each pixel of the domain and "perceives" the local climatic condition, including T_a, T_{mrt}, wind speed, etc. In this way, a high-resolution PET distribution map (0.5m resolution) is generated. The map is exported as an ESRI ASCII format raster file, and loaded and visualized in the ArcGIS system. Figure 4.23 shows the map. A summary of the statistics of the modeling result is shown in Table 4.5. The probability density curve is shown in Figure 4.24.

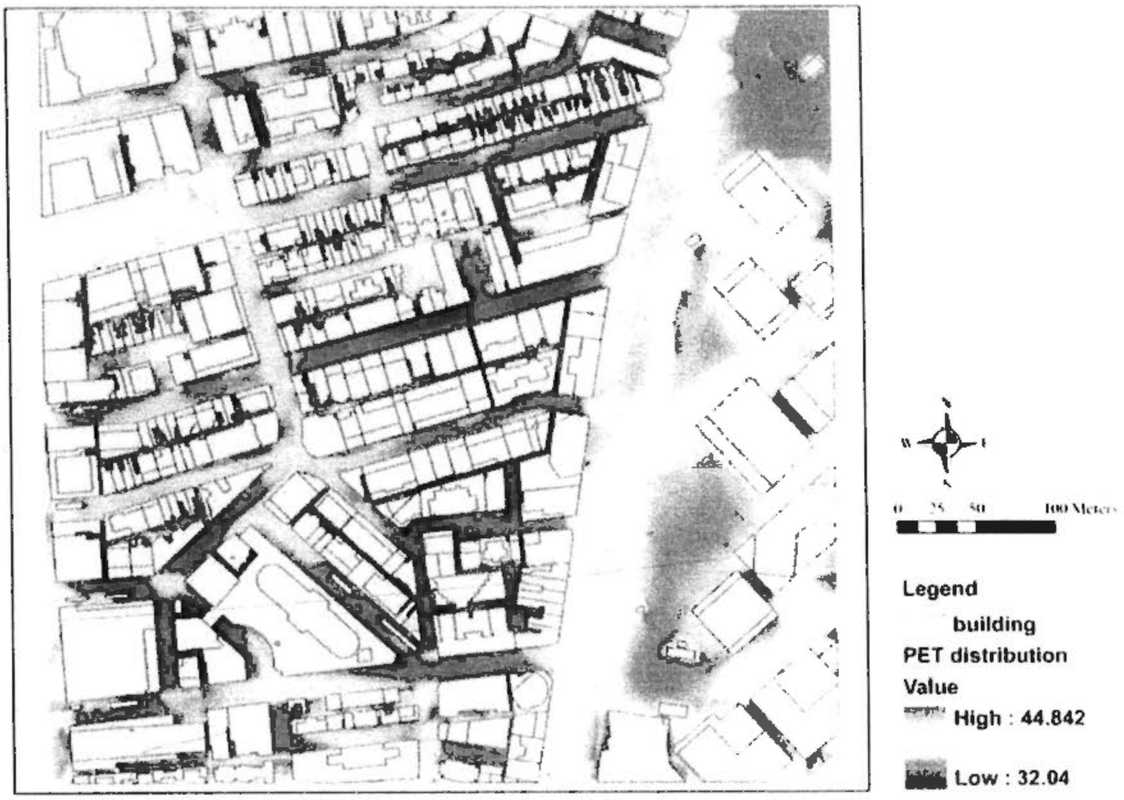


Figure 4.23 Map for the spatial distribution of PET of the modeling period based on standard human body settings. The map is 0.5m resolution.

Table 4.5. Summary of statistics of PET modeling in the domain.

Non-built up pixels	Min (°C)	Max (°C)	Mean (°C)	Standard deviation
501,712	32.04	44.84	37.95	2.23

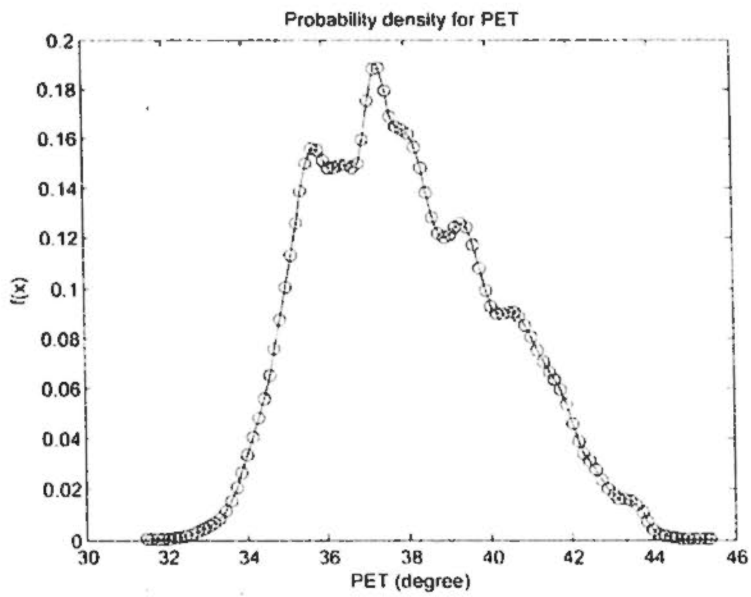


Figure 4.24 Probability density curve of modeled PET result in the domain.

4.3.1.2 Analysis and Discussion

1. Based on the modeling result, the lowest PET value is 32.0°C, which is still substantially higher than the observed comfort PET based on field survey, which is around 29°C (Ng, et al., 2007). This indicates that in the early afternoon of summertime, people in Hong Kong have very small opportunities to feel thermally comfortable in outdoor spaces like the study site. Therefore, the mitigation of the thermal discomfort, and the means to avoid long-term thermal discomfort exposure should be an important concern in the urban design.

2. According to Figure 4.24, most of the PET values are in the spectrum of 35°C ~ 39°C, which according to (Ng, et al., 2007) is classified as "strong heat stress". A classified PET distribution map is shown in Figure 4.25. The PET class of [35°C, 37°C] is indicated by light blue color, and the PET class of [37°C, 39°C] is indicated by yellow color. By observing the map, it is found these areas are normally the spaces

between buildings, which are normally close to building facades and in shade. A direct implication of this is that, by changing the building surface and pavement to materials with lower emissivity, the radiation, measured as T_{mrt} is expected to be reduced, therefore the thermal discomfort is expected to be mitigated.

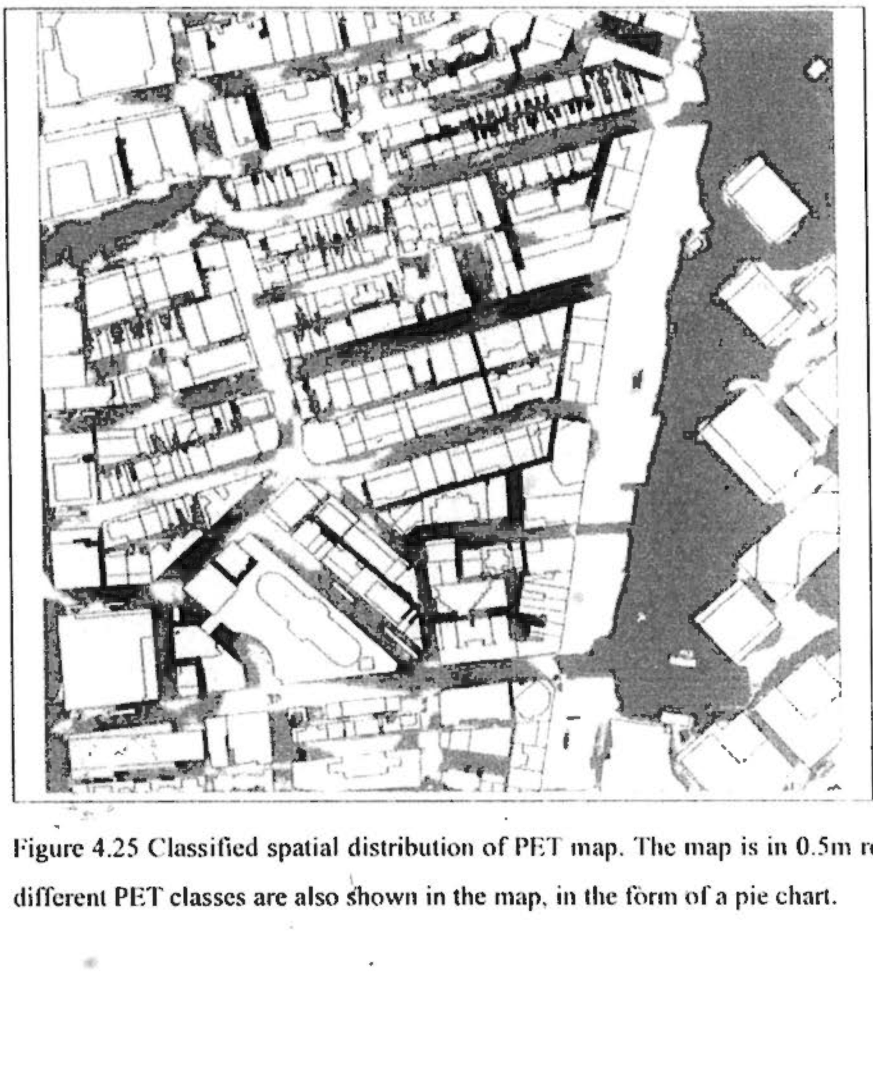


Figure 4.25 Classified spatial distribution of PET map. The map is in 0.5m resolution. The statistics of different PET classes are also shown in the map, in the form of a pie chart.

In this sense, a comparison test is carried out: in the SOLWEIG model for T_{mrt} estimation, the average albedo of the domain is changed from 0.25 to 0.2; the wall emissivity is changed from 0.9 to 0.85; and the ground emissivity is changed from 0.95 to 0.9. These modifications represent the selection of low-emissivity material in the domain. The PET map is generated under the same Peron settings as introduced in the previous section. A summary of the statistics of the comparison modeling result is shown in Table 4.6. The probability curve of the comparison modeling is shown in Figure 4.26. A classified PET distribution map is shown in Figure 4.27.

Table 4.6. Summary of statistics of the comparison PET modeling in the domain.

Non-built up pixels	Min (°C)	Max (°C)	Mean (°C)	Standard deviation
501,712	30.95	43.81	36.84	2.29

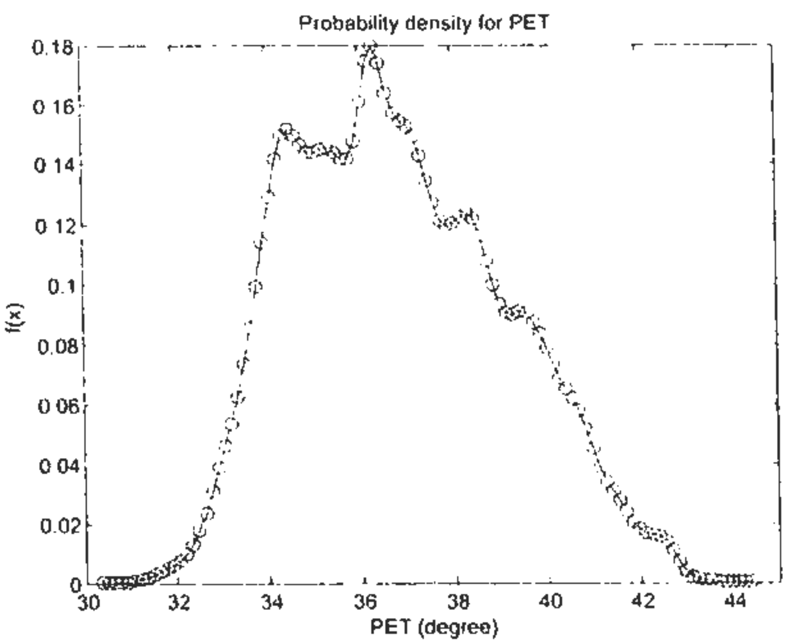


Figure 4.26 Probability density curve of the modeled PET result for comparison test in the domain.

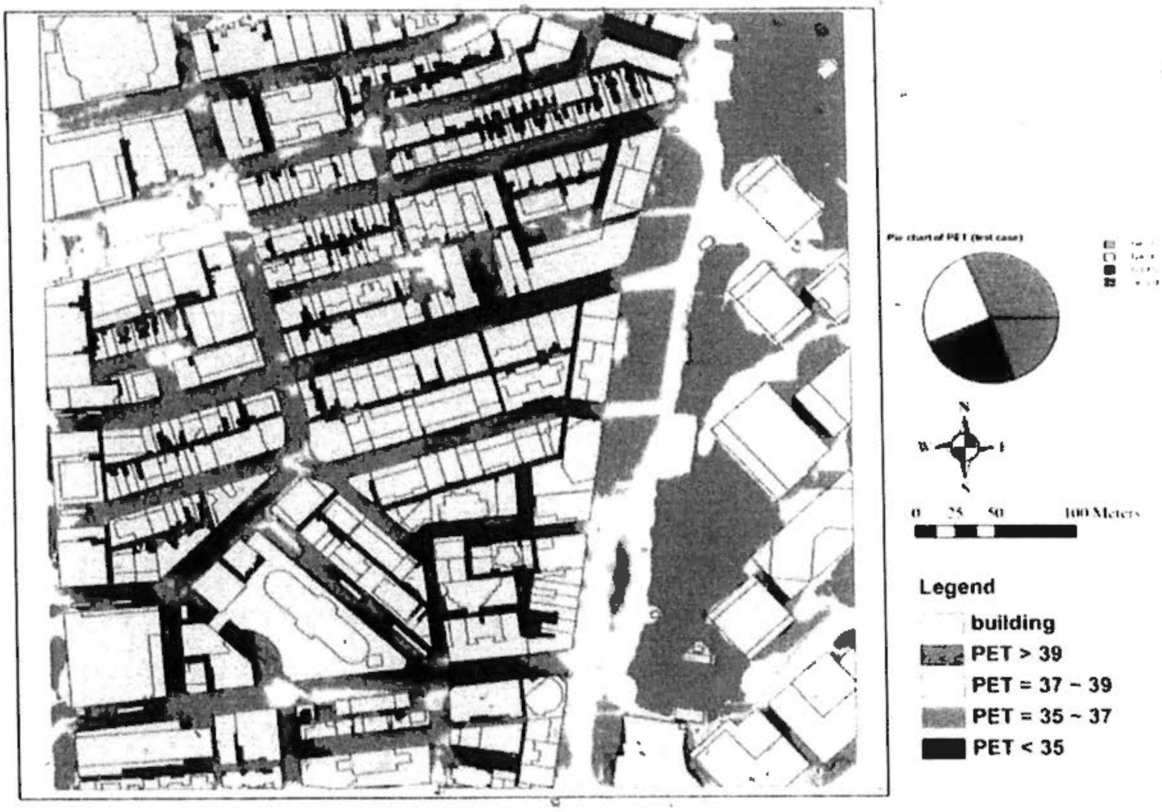


Figure 4.27 Classified spatial distribution of PET map for the comparison test. The map is in 0.5m resolution. The statistics of different PET classes are also shown in the map, in the form of a pie chart.

Table 4.6 and Figure 4.26 show that the comparison test shows a ~1°C PET decrease compared with the original modeling result. Figure 4.27 shows that in the comparison test, most of the outdoor spaces have relatively lower thermal discomfort, shifting from "strong heat stress" towards "moderate heat stress" according to (Ng, et al., 2007). This suggests that, careful control of building surface material and pavement material will provide substantial benefits to the thermal environment that pedestrians experience.

3. Sidewalks and the spaces close to buildings are supposed to be crucial to outdoor thermal comfort, as intuitively they are the outdoor spaces where most of the walking activities take place. Figure 4.23 depicts the "static" spatial distribution of PET

understanding. A limitation of this approach is that, though areas with low or high thermal comfort have been identified, how to assess their impact on pedestrians' walking activity quantitatively is yet an open question. The questions to be asked are: are the areas with low thermal comfort level actually avoided by pedestrians? Or the other way around, are the areas with high thermal comfort level actually used by pedestrians? In other words, how crucial is a location to pedestrian's trips? To allow these questions to be examined and ultimately answered, a simulation approach is needed, and this is the place where the core of the PedNaTAS system comes to play.

4.3.2 Pedestrian Simulation Based Thermal Assessment: Dynamic Assessment of Transient and Non-Steady State

4.3.2.1 Single Pedestrian Walking Mode: Individual Scale

The most straightforward case will be to monitor the thermal process experienced by a single person while he/she walks in the urban environment. In this sense, a series of walking simulations are conducted to assess a single pedestrian's thermal comfort in the domain using TNM (refer to Section 3.4.2.1). The local meteorological conditions, such as T_{mrt} and wind speed are also investigated and compared with the thermal comfort condition of the pedestrian. The nature of the PedNaTAS system makes it quite straightforward to carry out this task. A "standard person" as adapted in Section 4.3.1, i.e., a male person who is 40 yrs old, 1.75m tall, 75kg in weight and has a walking speed of 1.2m/s is selected and monitored.

A Preliminary Case: Short Distance Walking

The first test case simulates a very simple scenario of short distance walking. As shown in Figure 4.28, the origin of the trip is selected to be Gate Point O_1, which is a street end point; this is the spot from where the person enters the domain and carries out the walking activity. The destination of the trip is selected to be Exit Point D_1, which is the entrance of the *Carnarvon Mall* (refer to Figure 4.3: the map of the domain). The reasons for these 2 points to be selected as origin and destination are: 1) the two points are quite close to each other (~ 130m in distance) so the walking course is quite simple and straightforward; 2) there are various shading and sunny conditions along the path so diverse thermal comfort conditions of the person are expected to be observed.

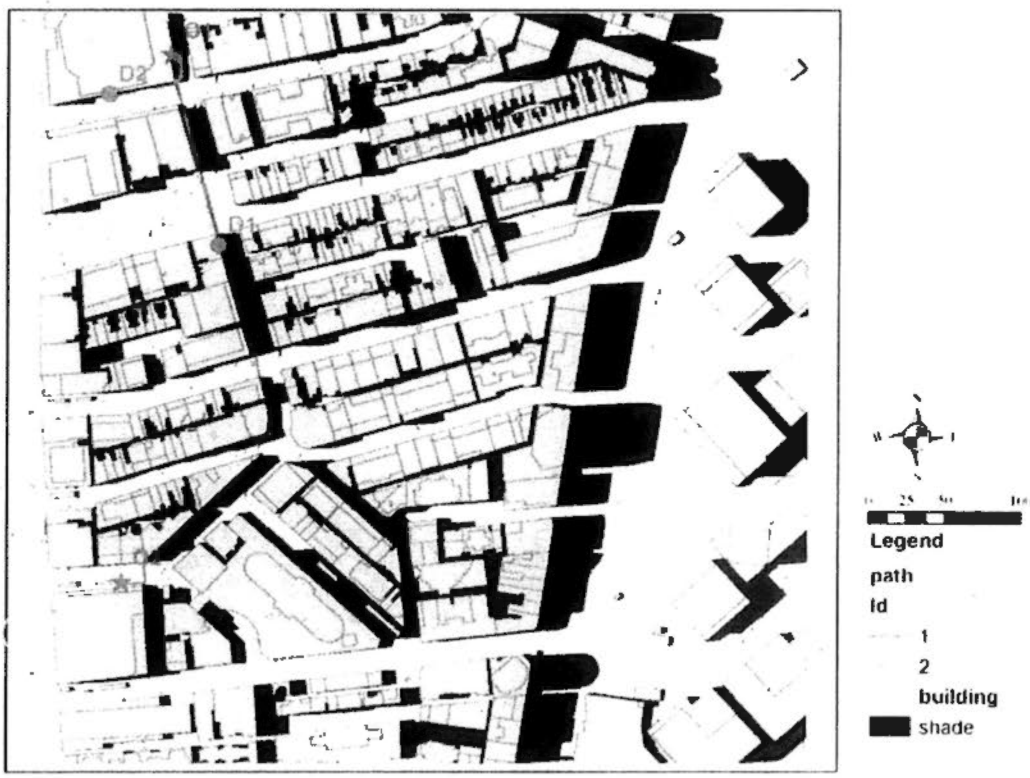


Figure 4.28 Map showing the origin, destination and path of the two walks. Origin points are represented by red stars, being O_1 and O_2; destination points are represented by green dots, being D_1 and D_2; the two paths, $Path_1$ and $Path_2$ are represented by green color and red color, respectively.

The subject is initially set to have a core temperature (T_{core}) of 36.8 °C, and a skin temperature (T_{skin}) of 33.7°C, which is the neutral state (refer to Section 3.4.2.2). Detailed temporal physiological condition variation of the subject is shown in Figure 4.29. In parallel, the subject's steady state is also calculated, including his steady state core temperature ($T_{core-st}$) and steady state skin temperature ($T_{skin-st}$). In practice, this is done by applying TNM to derive the subject's steady thermal condition after an "infinitely" long period of time, i.e., to get convergent solutions to the thermoregulation equations. Also, the subject's local T_{mrt} and his PET value are calculated based on the local meteorological condition and shown for reference.

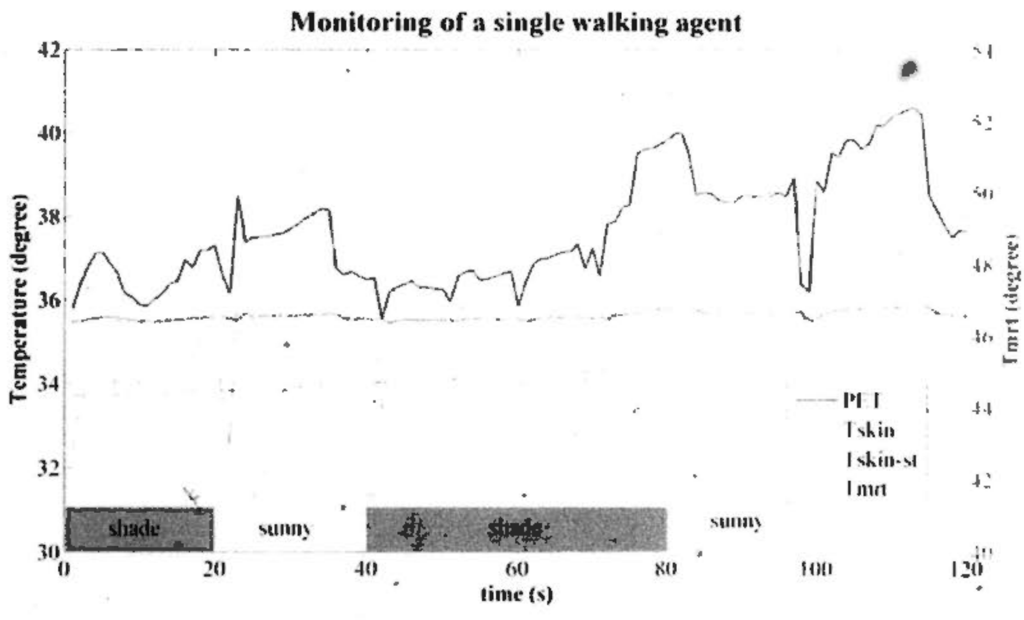


Figure 4.29 Temporal variation of a walking agent's thermal comfort state, described by skin temperature (T_{skin}) and core temperature (T_{core}). The subject's steady state condition is also calculated, including his steady state core temperature ($T_{core-st}$) and steady state skin temperature ($T_{skin-st}$). T_{mrt} and PET are also shown for reference.

As shown in Figure 4.29, during the 120 second walking in the urban environment, a pedestrian's thermal stress is quite high, with T_{skin} increasing from 33.7°C to 34.8°C, which is still substantially lower than the steady state ($T_{skin-st}$) of ~35.5°C under the given climatic condition. Under shaded area the pace of the increase is relatively lower, as illustrated by the course from 40s to 80s, the temperature changing rate is 9.44×10^{-3} °C/s; while under insolation the pace is higher, as the courses from 20s to 40s, and 80s to 100s, with temperature changing rate being 1.02×10^{-3} °C/s and 1.22×10^{-3} °C/s, respectively. This changing rate difference is consistent with the spatial variation of T_{mrt}. On the other hand, T_{core} shows a much slower changing rate, which is only increased by 0.18°C after the walking and is constantly 0.2 to 0.3 °C lower than the steady state. This suggests that under hot condition, the core part of human body has a much slower adaptation rate compared with the skin part. This observation agrees with findings revealed in other studies, such as (M. Bruse, 2005; Höppe, 2002).

In order to have an overall picture of the selected subject's thermal load, his temporal energy balance condition is calculated and plotted, as is shown in Figure 4.30. This is the summation of the energy gained from the ambient environment, the convective heat loss, the radiative heat loss and also the clothes convection. The effect of the local microclimate, predominantly T_{mrt}, on the overall energy balance of the walking pedestrian can be well observed from the figure. The pedestrian has a constantly positive energy balance in the order of 290W/m^2 to 200W/m^2. This indicates that, during the 2-minute walk, the pedestrian's thermal stress is quite high, so the body keeps "heating up".

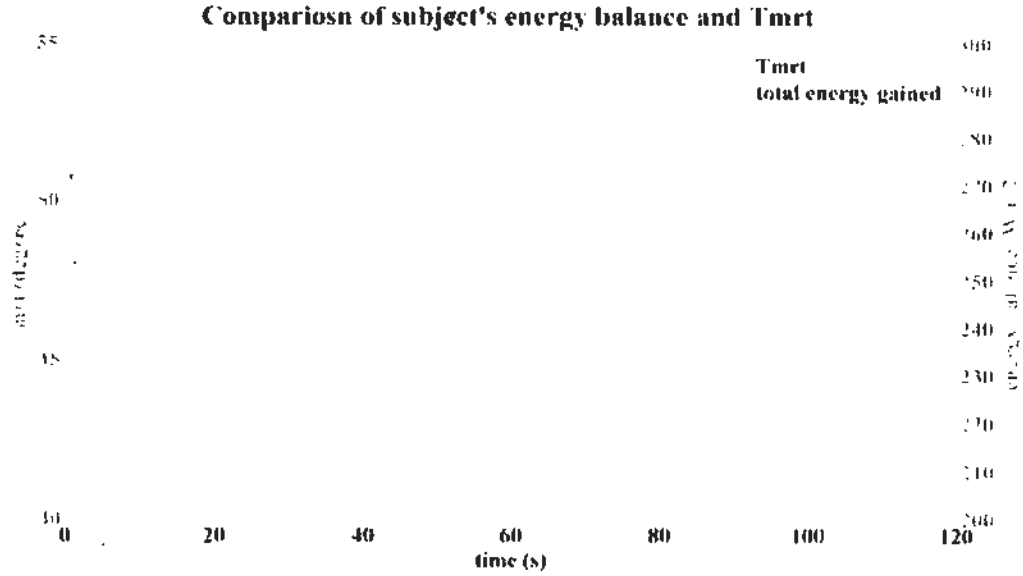


Figure 4.30 Temporal course of a walking agent's energy balance condition (W/m^2) compared with the local T_{mrt}.

Long Distance Walking Case

The second test case simulates a slightly complicated scenario: a long distance walking of approximately 450m. The origin, destination and path are shown in Figure 4.28. The origin of the trip is selected to be Gate Point O_2, which is a main exit of the MTR station (*Exit D2*). The destination of the trip is selected to be Exit Point D_2, which is the entrance of the *Miramar Mall*, the biggest shopping mall in the domain (refer to Figure 4.3: the map of the domain). Seen from the urban context, it can be concluded that this is a path that is commonly taken by pedestrians entering the domain. Variations of shading and sunny conditions along the path can be observed. Because of the relatively longer distance and therefore longer exposure time, the walking person agent has a longer period of time for thermal adaptation.

To explore the thermal condition for different groups of people, the subject in this test is selected to be a 25 yr old female, who is 1.60m tall, 50kg in weight and has a walking speed of 1.3m/s. Similar to the previous case, the temporal variation of the subject's thermal adaptation condition is shown in Figure 4.31, and her energy balance condition compared with T_{mrt} is shown in Figure 4.32.

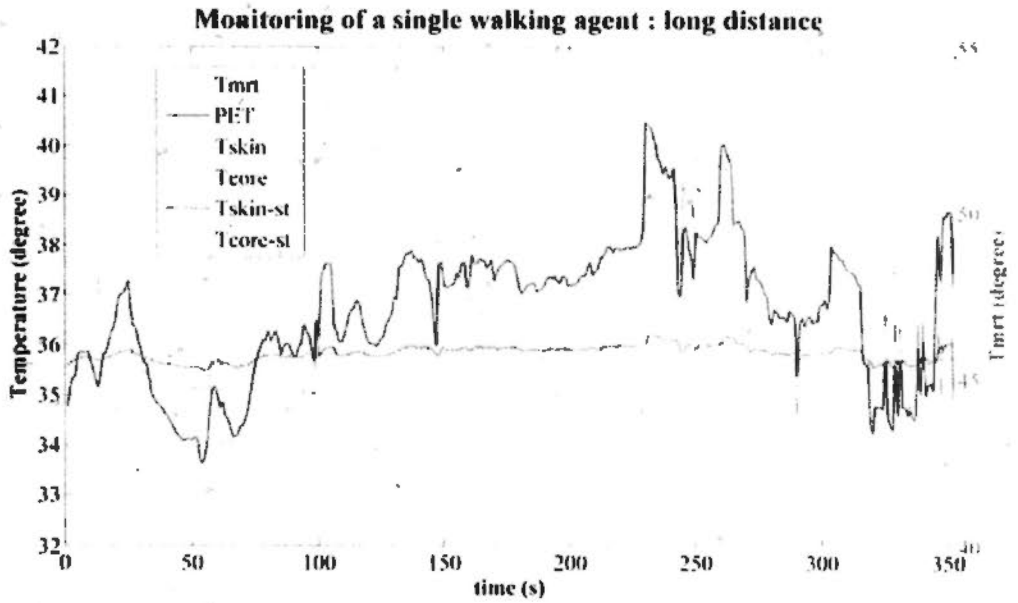


Figure 4.31 Temporal variation of a walking agent's thermal comfort state in a long distance walk, described by skin temperature (T_{skin}) and core temperature (T_{core}). The subject's steady state condition is also calculated, including his steady state core temperature ($T_{core-st}$) and steady state skin temperature ($T_{skin-st}$). T_{mrt} and PET are also shown for reference.

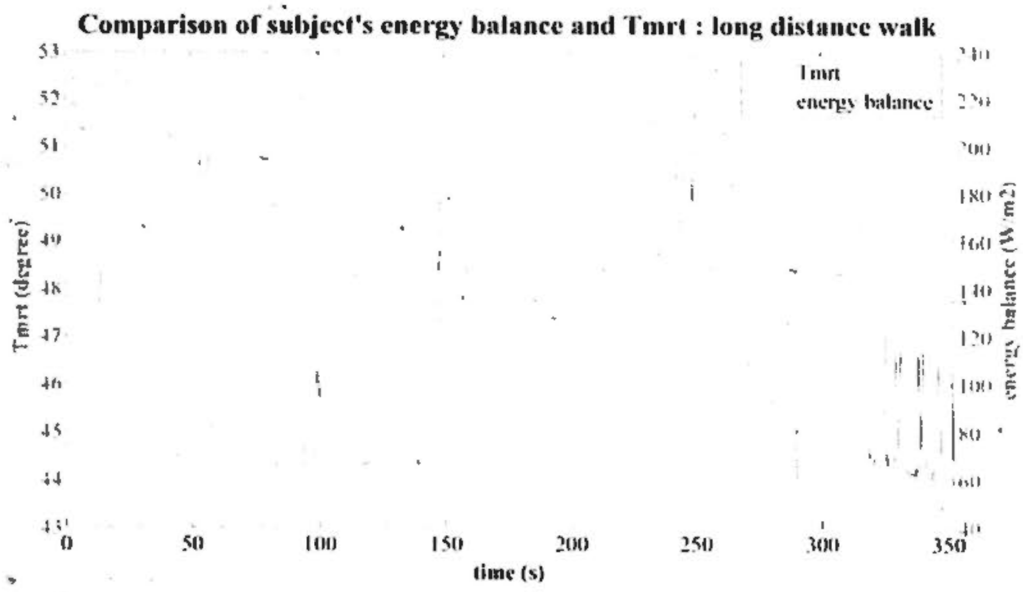


Figure 4.32 Temporal course of a walking agent's energy balance condition (W/m^2) compared with the local T_{mrt}: a long distance walking case.

In this test case, the walking period is about 6 minutes, allowing the selected subject to have a longer time for thermal adaptation. Effectively, the subject's T_{skin} increases from 33.7°C to 35.8°C at the end of the walking, which is quite close to steady state $T_{skin-st}$ of 36.1°C as is shown in Figure 4.31. Similar to the short distance walking case, T_{core} still shows a much slower adapting rate, increased from 36.8°C to 37.0°C, also approaching the steady state $T_{core-st}$ of 37.2°C. Along the walking course, the subject has a constant positive net energy gained, with an overall declining trend as the subject approaches her steady state. However, at the end of the walking course, the subject still has a total energy balance of ~ +60W/m^2.

Seen from the two test cases introduced above, it is confirmed that for the purpose of pedestrian thermal comfort assessment, the steady state models are not suitable, as the pedestrians seldom reach their equilibrium conditions, i.e., with an energy balance of 0. Instead, as exposed in the microclimate defined by the case study, the pedestrians normally have a substantially high thermal stress and therefore keep gaining heat from the ambient environment. This suggests that, in a high thermal stress dominant environment, the effect of shading in mitigating pedestrians' thermal stress will be overestimated by the steady state model, such as PET as shown in Section 4.3.1. This is because along the walking course, the pedestrians are in a transient state, so even under shading condition they still have a positive net energy balance (as illustrated by Figure 4.30 and Figure 4.32), and keep heating up, though maybe with a slower rate (as illustrated by Figure 4.29 and 4.31). In such cases, the climatic variation, as the 4 to 5°C PET difference between shading and sunny areas as shown in Figure 4.29, will not be effectively felt by the subject. Therefore the shading patches could not be as mitigating as the steady state models suggest. It is only after the pedestrians have reached their steady states (as illustrated by Figure 4.32, at the end of the walking) can these models be applied with credibility. The temporal monitoring approach is proved to be a more effective way in investigating the pedestrians' transient thermal states along walking.

It is to be noted that, because of the agent-based feature of the PedNaTAS system, it is very straightforward to "probe" the detailed thermal condition of a selected person agent, which is referred to as "virtual interview" by (M Bruse, N/A). Indeed, a lot of other thermoregulatory indictors, such as *clothing temperature*, *skin blood flow*, *sweating rate* and *net metabolic heat production* can all be investigated using the system. Admittedly these indicators are not quite informative for people without domain knowledge in climatology and physiology, which is commonly the case for planners; nevertheless, given that there is still lack of commonly accepted methodology for dynamic thermal assessment, a combination of these indicators, such as the examples demonstrated above, can suffice to depict to a substantial degree the dynamic course of pedestrian's dynamic thermal adaptation processes.

4.3.2.2 Multi-Pedestrian Walking Simulation Mode: Spatially Aggregated Scale

The previous section introduces the detailed monitoring of a single pedestrian's thermal condition and shows it to be an effective approach in examining the impact of the local microclimatic on pedestrian's thermal comfort on the individual scale. On the other hand, in order for the system to be practically applicable in planning, the investigation needs also to be conducted on the spatially aggregated scale - the meso-scale. This is also one of the advantages of the ABM approach as it allows the emergent behaviors based on a large number of individuals to be simulated and analyzed accordingly, and yet keeps track of each individual agent so the mechanism of the emergent pattern can be well reasoned. In this section, a multi-pedestrian walking scenario is tested for the entire model domain, simulating the actual condition of the outdoor environment in the case study. The thermal comfort assessment is based on the analysis on the spatially aggregated scale.

As introduced in Section 4.2.1, all pedestrians enter the domain from the Gate points, and leave from the Exit points. In this test case, the Gate points are set to have populating rates ranging from 60 person/min to 120 person/min. Admittedly this rate setting is a big simplification of the reality, and the small number of pedestrians in the domain might impose limitation of the simulation system; nevertheless, considering the scope and objective of the study, a proof-of-concept test case should be sufficient in showing the effectiveness of the model on the meso-scale. Possible improvements to deal with the restriction of the model complexity will be discussed in the final chapter.

The pedestrian agents are defined based on the setting introduced in Section 4.2.3, with a vast diversity in physical condition and also walking speed. The simulation is run for a total number of 15 minutes, assuming the climatic condition to be constant during the simulation course. Again, there is also an argument of system limitation here, which will also be covered in the final chapter.

A total number of around 13,500 pedestrians are generated. The simulation takes about 1.5 hr clock time. At the end of the simulation, there are in all around 6,300 pedestrians alive in the domain. The others have all reached their destinations and therefore left the domain. Figure 4.33 shows a snapshot of the system interface at the end of the simulation. The figure shows the diverse spatial distribution of the pedestrians.

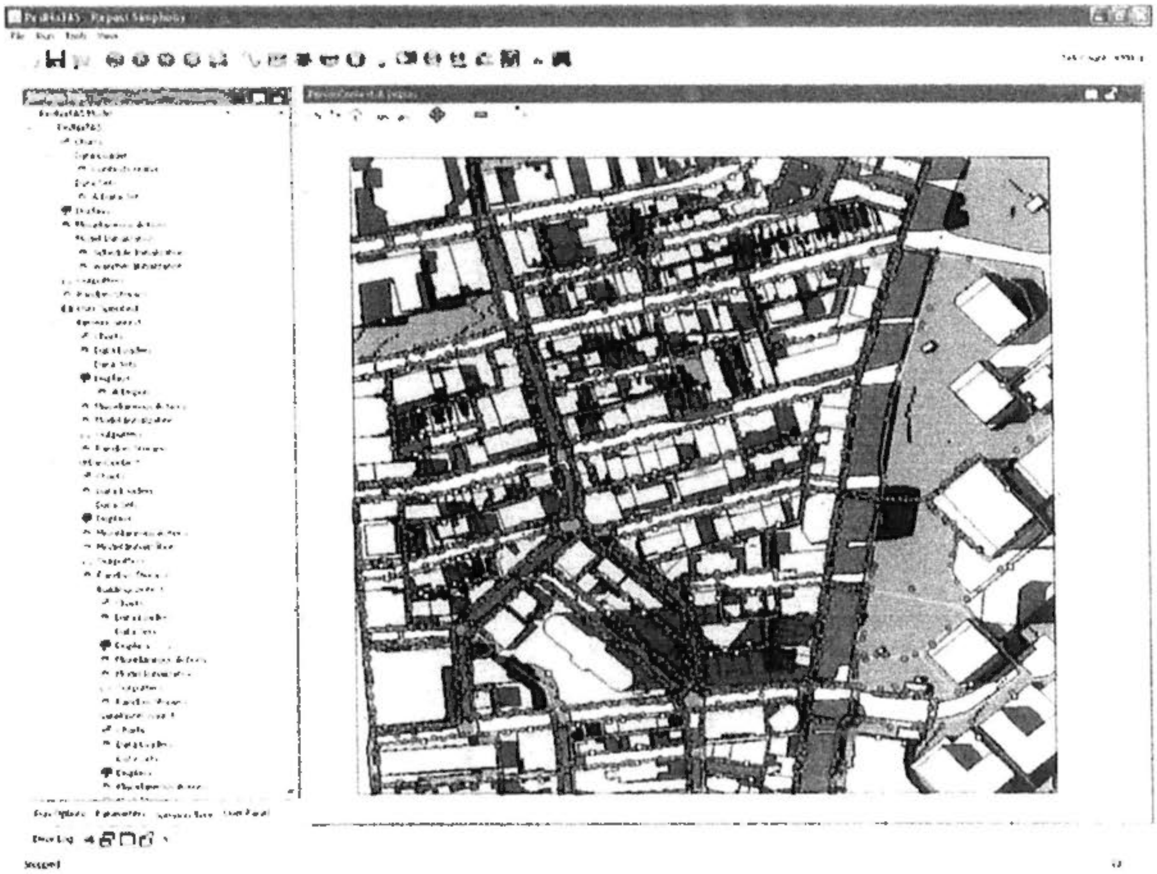


Figure 4.33 A snapshot of the PedNaTAS system interface at the end of the simulation. Pedestrian agents are represented by the light blue circles. The simulation time, represented in the unit of Tick Count (1 Tick = 0.1 second clock time) is shown at the upright corner of the panel.

Spatial variations of pedestrian frequentation, their average skin temperature, and average energy balance are recorded and analyzed to investigate the impact of the urban environment on pedestrian thermal condition on the aggregated scale. A series of maps are generated. What is to be noted is that the high-resolution of the individual scale, i.e., 0.5m will make the map rather coarse: there will be occasions where white cells are found in the center of a group of valued cells. In such cases, in order to generate meaningful and easy to interpret results, the initial maps are interpolated to generate "smooth" patterns. In practice, a 5m×5m neighborhood average is calculated. The result is therefore aggregated. Figure 4.34 shows an illustration of the map of the spatial distribution of pedestrian frequentation. Figures 4.35 and 4.37 show the maps of the spatial distribution of pedestrians' average skin temperature and average energy balance, respectively. And Figures 4.36 and 4.38 give illustrations of the statistics of pedestrians' average skin temperature and average energy balance, respectively.

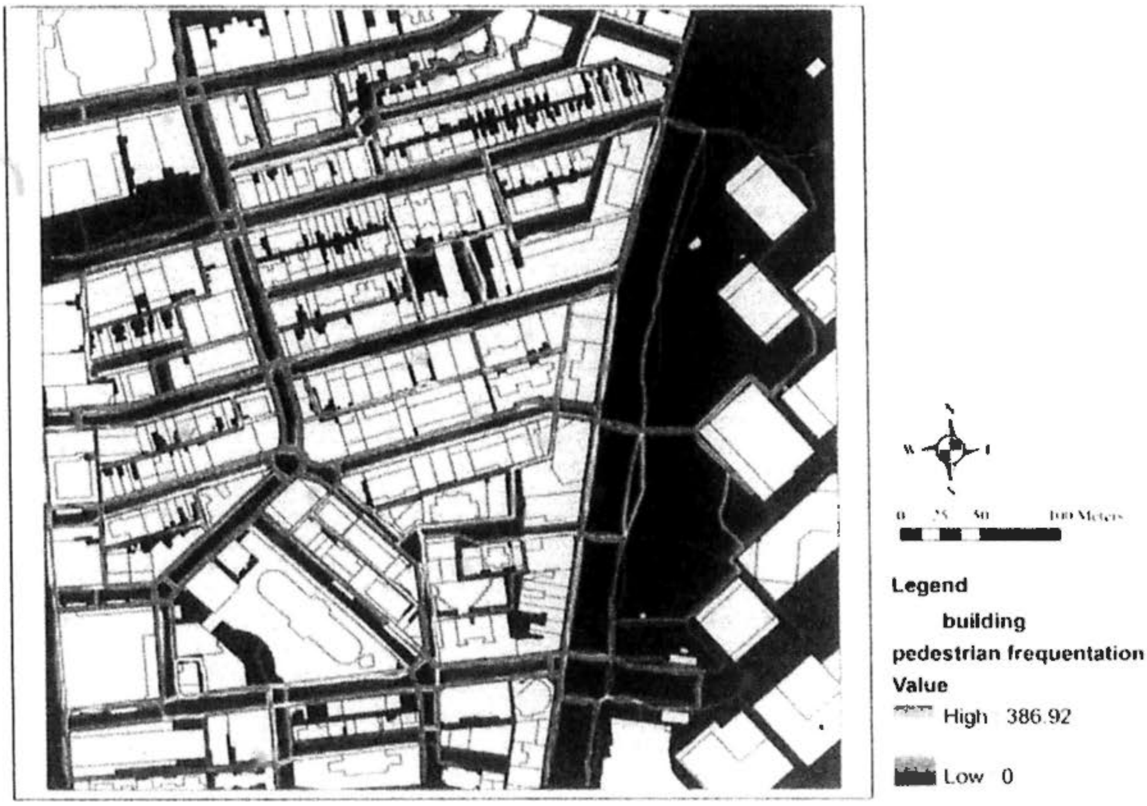


Figure 4.34 Map of the spatial distribution of pedestrian frequentation. The result is already interpolated.

Figure 4.35 Map of the spatial distribution of pedestrians' average skin temperature during the simulation course. Grey color means no data, i.e. the space is not used by pedestrians, e.g. car road or unwalkable space.

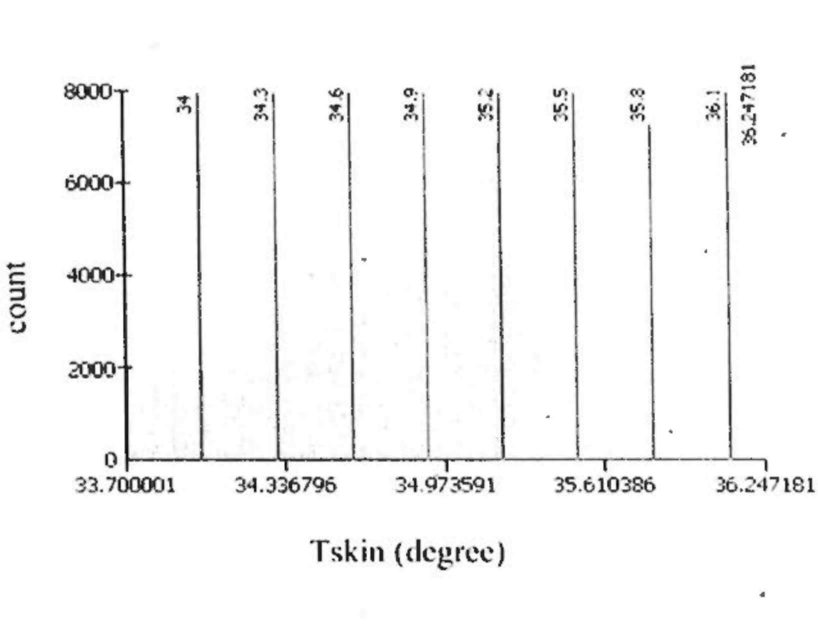


Figure 4.36 Illustration of the statistics of pedestrians' average skin temperature.

Figure 4.37 Map of the spatial distribution of pedestrians' average energy balance during the simulation course. Grey color means no data, i.e. the space is not used by pedestrians, e.g. car road or unwalkable space.

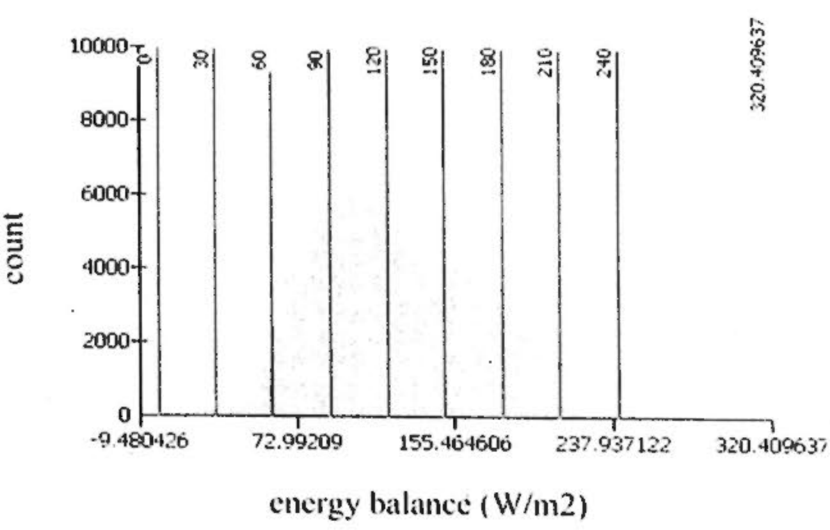


Figure 4.38 Illustration of the statistics of pedestrians' average energy balance.

The results generated by the simulation should be interpreted with caution. It is shown from the emergent pattern across the whole domain, that when pedestrians enter the urban environment, the dominant thermal stress in the domain will normally heat them up, making them very uncomfortable. Their skin temperature could be normally above 35.0 °C, and for some severe case, such as a long-distance walk mainly under sunlit area, their skin temperature could even reach up to 36.25°C. Therefore, the central area could be considered as the most uncomfortable in the domain. During their walking activity, the pedestrians are commonly exposed to the high thermal load environment therefore keeps gaining energy from the ambient environment, normally in the order of +100W/m^2, which is a significantly high value. On the other hand, the central area is the place where most pedestrians are approaching their steady thermal condition, therefore some mitigation of the thermal stress, e.g., shading, will cause a little negative energy gained, normally below 10W/m^2. The results are generally consistent with the findings revealed on the individual scale as introduced in the previous section.

4.3.3 Urban Design Implication

4.3.3.1 Discussion: A Note on System Validation

The above sections present the assessment of the global thermal environment based on multi-pedestrian simulation in a context-sensitive manner. Different to the monitoring of an individual pedestrian's thermal condition, a lot of pre-assumptions and predefined parameters have been setup in this case to make the simulation generate interpretable results. Therefore, despite the fact that the system has been demonstrated to generate results that "look right" based on common wisdom, as is shown above, it still needs to be validated with domain knowledge to show it is able to provide genuine results.

Validation of ABM is a research challenge *per se* (refer to Section 2.3.3). In the scope of the study, the validation of the thermal assessment result is also not evident. The greatest challenge will be the lack of empirical data, since little research has been conducted along this line of research investigating the dynamic and context-based aspects of pedestrian thermal comfort in Hong Kong. Therefore a rigid validation process seems hardly possible, at least at this stage. Nevertheless, the formalized modeling process itself should speak to the system credibility to some degree: the modeling is highly hierarchical, with each level of modeling either validated with field measurement data, e.g., T_{mrt}, or compared with empirical data in the literature, e.g., pedestrian traffic modeling. In this sense the system should suffice as a reliable foundation for this type of assessment.

Also, the study takes an alternative validation approach by comparing the simulation results with another urban climate evaluation study, the Hong Kong Urban Climatic Analysis Map (UCAnMap) (Ng, in press; Ng, Kwok, et al., 2008). The UCAnMap, though strictly speaking is not based on dynamic assessment, has a number of concerns in common with the objectives of this study. To name the most relevant ones 1) it also deals with summer afternoon conditions; 2) it is also meso-scale; 3) it also provides bio-meteorological understanding; 4) it use synergetic knowledge to consider the combined effect of urban climate on people's thermal comfort. In this sense, a section of the UCAnMap showing the model domain is extracted from the original map covering the entire scope of Hong Kong, and is shown in Figure 4.39.

Figure 4.39 Hong Kong UCAnMap for the model domain. The map is in 100m resolution. The values indicate bio-meteorological understanding of the impact of the urban climate on people's (pedestrian) thermal comfort condition. Higher values suggest higher level of thermal discomfort. The evaluation is based on synergetic climatic understanding.

Comparing Figures 4.34, 4.35 and 4.37 with Figure 4.39, it can be said that the overall pattern agrees with each other. Meanwhile, there are also a few areas that deserve a more careful look, as indicated by Zone A, Zone B and Zone C in Figure 4.39.

Zone A: the feature of Zone A is downtown center. Pedestrians walking in Zone A normally have very high skin temperatures. Meanwhile they have experienced relatively long heat exposure therefore are reaching the steady state with less energy gained from the environment. This implies that the static assessment also applies to some degree. Judging from the high skin temperature and also the high thermal discomfort level suggested by the UCAnMap, this area is with no doubt the place with high thermal stress.

Zone B: it is relatively open space around buildings near major traffic route. In general, this area has a less thermal stress compared with Zone A. However, it must be noted that since pedestrians are normally in heat-gaining states so they actually experience a more severe thermal stress than the static evaluation suggests.

Zone C: it is the densest area with chief traffic route. Any thermal stress elevation in this case will be crucial as it will affect a wider community.

The above discussion is rather simple interpretation of the comparison of the simulation results to the UCAnMap. On the other hand, it reveals that the climatic evaluation of zones with different context should also be differentiated, and should suffice as a proof-of-concept of how the context-sensitive and dynamic assessment could possibly complement static meso-scale evaluations such as the UCAnMap. More pertinent recommendations are expected to be provided with more realistic urban settings.

4.3.3.2 Urban Design Implication

Based on the discussions in the previous section, a simple scenario test is carried out to demonstrate the implications the system could provide in urban design. As suggested by different zones in Figure 4.39, different measures are taken to mitigate the thermal stress in the domain, including:

a. Vegetations are added around main Gate point, i.e., MTR exits, to create "transitional spaces" after the pedestrians enter the heat-dominant study site;

b. Vegetations are added along the most dense route to benefit the majority of pedestrians efficiently;

c. Low-emissivity materials are selected for building walls and sidewalk pavements to reduce the local radiation pedestrians experience.

An illustration of the scenario test is shown in Figure 4.40. Detailed specifications of the scenario setting are given below.

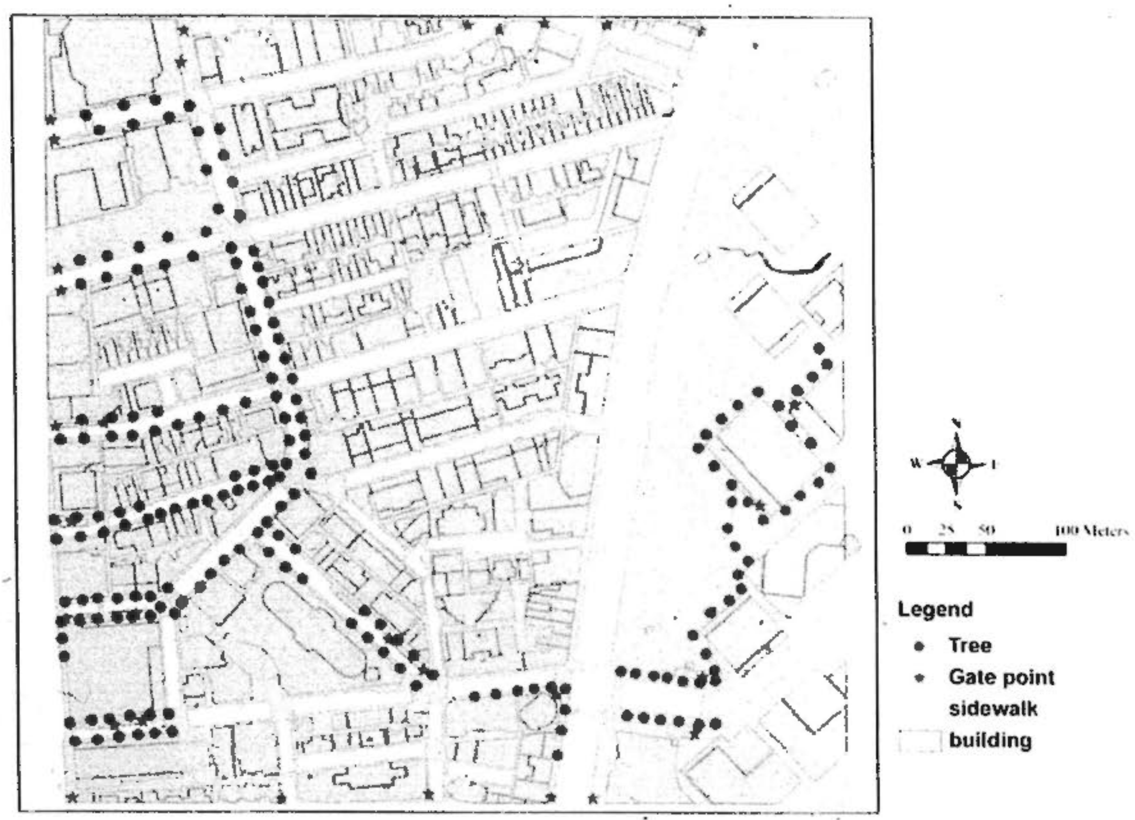


Figure 4.40. An illustration of the scenario test. It is to be noted that the Tree shapes are used only for illustration purpose but not drawn to scale.

A recently updated version of SOLWEIG, the SOLWEIG v2.1

(http://www.gvc2.gu.se/ngeo/urban/URBAN.HTM) allows vegetations to be added to the domain in radiation estimation. In practice, a tree is set to be a deciduous tree, with crown diameter = 5m, height = 6m and trunk = 3m, representing a typical middle-size sidewalk tree. The trees are placed to have a distance of 10 ~ 20m from each other. This setting creates a rather sparse lineup; however given that SOLWEIG can only support a very limited number of trees, this compromise appears to be the only feasible solution at this stage. Also, the building wall emissivity is changed from 0.9 to 0.85, and the sidewalk pavement emissivity is changed from 0.95 to 0.9.

Figures 4.41 ~ 4.44 show the new spatial distributions and illustrations of statistics of pedestrians' average skin temperature and average energy balance for the modified scenario. Comparing the new statistics with the old ones, it is found that both the average skin temperature and average energy balance have shifted towards smaller values, proving that the thermal stress in the domain has been effectively mitigated to some degree. Admittedly, we can not plant a lot of trees on sidewalks nor change the surface material for the entire domain; nevertheless this simple scenario test suffices as a proof of concept demonstrating what possible measures could be taken in urban design to improve the thermal condition of the outdoor space.

Figure 4.41 Map of the spatial distribution of pedestrians' average skin temperature during the simulation course for the modified scenario. Grey color means no data, i.e. the space is not used by pedestrians, e.g. car road or unwalkable space.

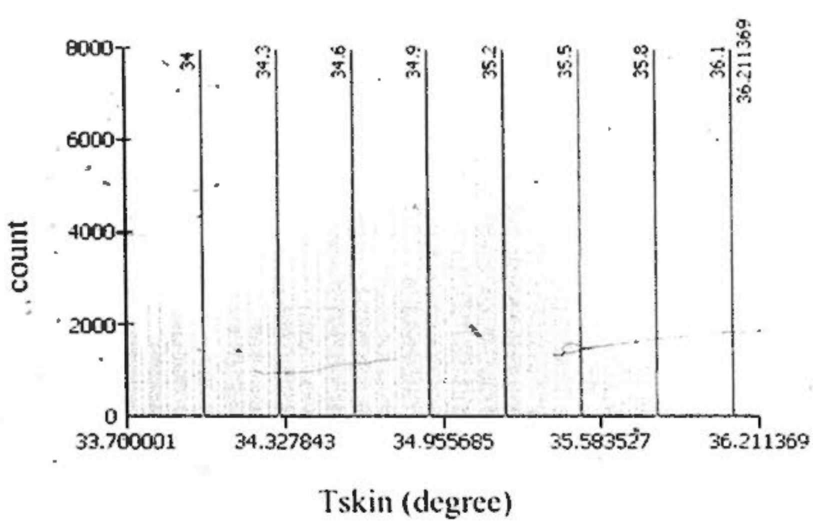


Figure 4.42 Illustration of the statistics of pedestrians' average skin temperature for the modified scenario.

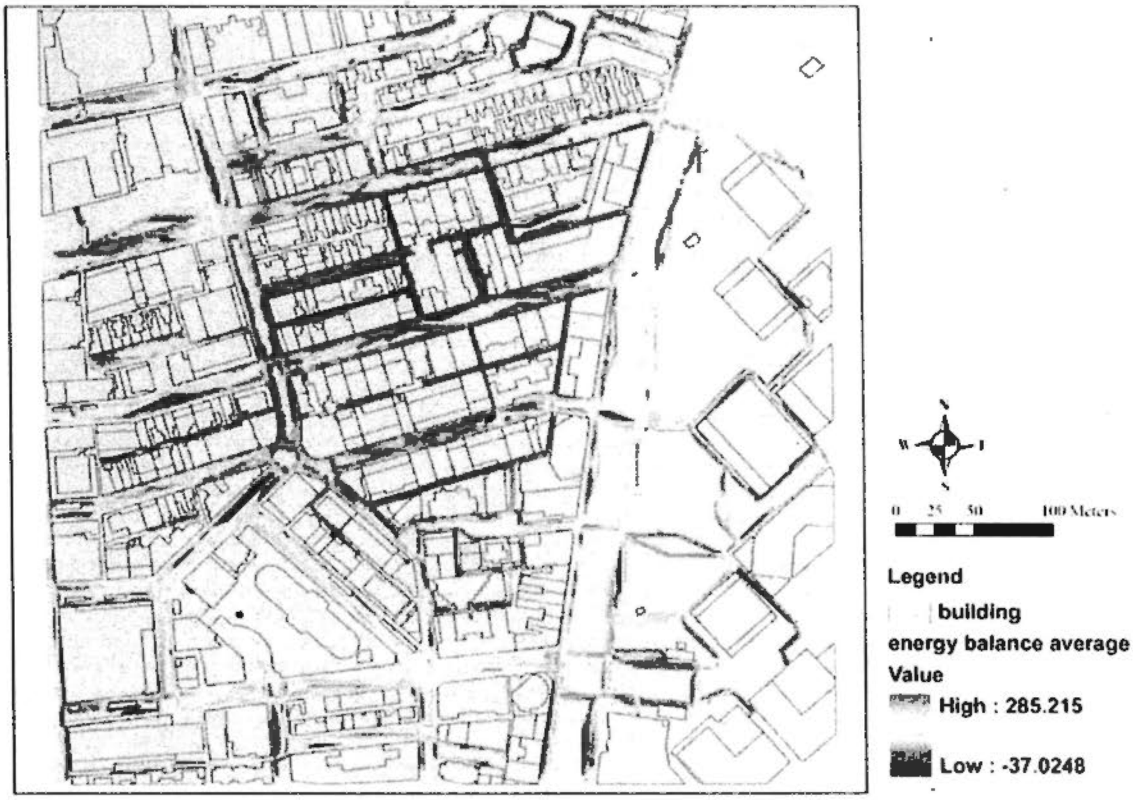


Figure 4.43 Map of the spatial distribution of pedestrians' average energy balance during the simulation course for the modified scenario. Grey color means no data, i.e. the space is not used by pedestrians, e.g. car road or unwalkable space.

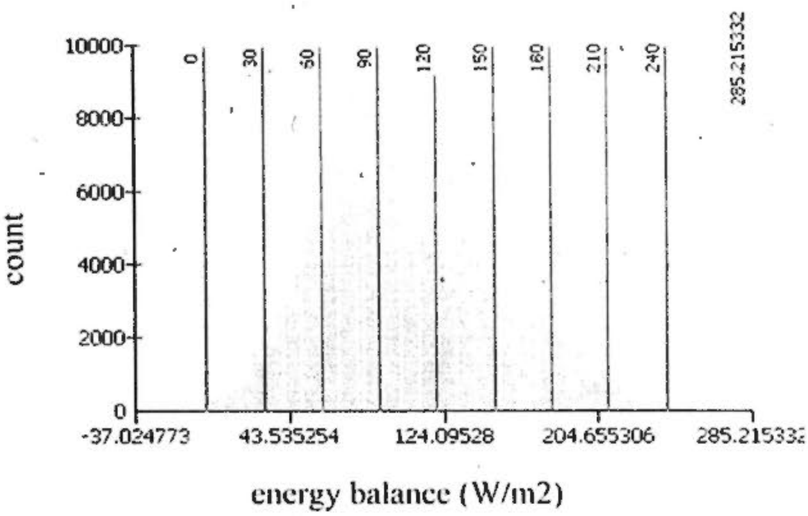


Figure 4.44 Illustration of the statistics of pedestrians' average energy balance for the modified scenario.

4.4 Chapter Summary

In this chapter, a comprehensive case study in real world context is presented to show the work flow of the PedNaTAS system. A highly structured modeling process of the urban environment is conducted within the system's framework. Complicated urban climatic conditions are modeled, and pedestrian thermal comfort is assessed from both static and dynamic aspects with the system. In particular, the dynamic assessment considers the individual scale and also the spatially aggregated scale, and links the local bio-meteorological monitoring to the global emergent pattern analysis. This type of analysis is only possible with a computational ABM framework such as the PedNaTAS system. How the GIS support allows complex urban environment to be modeled effectively is also demonstrated. Through the case study, a proof of concept is carried out showing how the context-sensitive thermal comfort assessment could effectively complement traditional methods using the system.

Chapter 5 Conclusion

In this chapter, the effectiveness of the agent-based simulation approach in assessing people's outdoor thermal comfort is concluded. The limitation and possible future research and improvements are also discussed.

5.1 Significance and Contributions

The thesis has significance from conceptual, technical and practical perspectives in terms of developing a spatial decision support tool (SDSS).

5.1.1 Conceptual Significance

Conceptually, through the comprehensive literature review, the thesis identifies the need for the development of a methodology for the integration of outdoor microclimatic assessment and pedestrian behavior investigation in providing effective recommendations for outdoor space planning, which is described by the author as "context-sensitive" assessment. By reviewing theories and applications of the agent-based modeling (ABM) paradigm, the thesis adopts an agent-based simulation approach to account for pedestrian's dynamic and individualized features in their thermal comfort assessment. On this foundation, the thesis further establishes a conceptual framework of SDSS for climatic planning with pedestrian thermal comfort concerns.

5.1.2 Technical Significance

Technically, the most significant contribution of the thesis is the design and implementation of a prototypical SDSS, the integrated simulation system of PedNaTAS. The system has a list of technical significance, as follows:

1. The system implements a comprehensive representation of the urban context, including building geometry, street network, route points, and climatic conditions such as the spatial distribution of radiation, shading, and wind environment. This representation sets up the scope for the proposed "context-sensitive" thermal assessment scheme.

2. The system designs and implements a 3-level modeling of pedestrian's downtown travel behavior. This modeling methodology links pedestrian's local movement with their higher-level activities, and therefore puts the investigation of the outdoor space use in the comprehensive urban context on the meso-scale.

3. The system implements a simulation module modeling pedestrian's microscopic movement. The micro-scale of the module, which is in the resolution of 0.5m, allows a pedestrian's immediate microclimatic condition to be investigated in much detail. The module is verified with empirical data in the literature. The module can manage several thousand of agents simultaneously in the domain.

4. The system implements a thermal comfort assessment module with functions for both steady state assessment and dynamic and transient state assessment. The steady state module can generate high-resolution spatial distribution of PET based on selected human settings, and the dynamic state module can examine detailed thermoregulatory condition of selected subjects in a temporal manner. Both modules

are verified with other implementations in the literature.

5. With functions provided by the Repast Simphony development toolkit, the system is implemented in a GIS framework. Both vector data and ESRI format ASCII raster data are supported. A GIS database management system is maintained, with functions such as data import and export implemented.

6. With functions provided by the Repast Simphony development toolkit, a graphical user interface (GUI) is implemented. The urban context is visualized through the GUI, and the pedestrian simulation course is animated.

7. In line with the object-oriented programming (OOP) paradigm, the system is implemented in Java programming language, with a highly modularized software structure. The data structure, including both the urban context representation and pedestrian attributes representation, is also implemented in a hierarchical manner.

5.1.3 Practical Significance

The system also has the following major practical significance in real world application:

1. The GIS support of the system allows real world context application. Complex urban environment including complicated urban climatic environment could be effectively modeled or integrated in the system.

2. Because of the ABM feature, by adjusting the person property, the system can be pre-setup to focus on specific groups of subjects, e.g., elder people, younger people,

females, etc. Therefore the system could be used to carry out thermal comfort analysis for different communities.

3. The system links the individual monitoring to the emergent pattern investigation, and yet provides understanding and reasoning for the pattern. Therefore it could be used to represent the thermal comfort condition of the domain on different scales from micro to meso-scale, in a "zoom-in and out" fashion.

Based on the discussion above, going back to the objectives setup in Chapter 1, it is affirmative that the objectives have been met.

5.2 Limitations

Due to the limited scope of the present study, it also has several limitations, which are discussed below.

5.2.1 Drawbacks of the ABM Approach

As a modeling paradigm of investigating complex systems and processes, ABM has always been criticized to be "prone to use in unreflective and uncritical ways" (O'Sullivan & Haklay, 2000). Indeed the PedNaTAS system bares quite a number of simplifications in order to produce interpretable results in a feasible manner, e.g., the multi-pedestrian simulation case. Arguably these simplifications or pre-setups may impose limitations and restrictions to the effectiveness of the system. Nevertheless, an ABM, the system shouldn't be considered as an accurate predicting tool to provide deterministic or optimum solutions. Instead, it should be seen as a platform allowing different determining factors to come to play, interact, and contribute to the understanding of the complex issue of pedestrian thermal assessment. Quoting Axelrod's (1997a) defense of the ABM approach in general: "It is not the aim of ABM to provide accurate representation of a particular empirical application; rather, the goal of ABM is to enrich the understanding of processes that may appear in a variety of applications." As complex as the present system is, only after these factors having been made tractable is it possible to observe and investigate the complex consequences. In this sense, the system developed in the study serves its proof-of-concept purpose.

5.2.2 Requirement of Computation Resources Using Repast

In terms of computation efficiency, the system is rather slow. Because of the thread management mechanism of Repast Simphony and also the large load of graphic updating tasks, to simulate a 15 minute multi-pedestrian walking case with dynamic thermal assessment will normally take about 1.5 hr on a daily used desktop PC. This may be problematic if a large number of simulations are needed. Of course the most ambitious solution will be to implement the system from scratch using a particular programming language, such as Delphi as used by BOTworld, therefore optimizations could be made from inside. A shortcoming of this, however, is that the GIS-support provided by Repast written in Java programming language will be completely lost. A more feasible solution is the distributed computing approach, which is to divide the computation task to a number of CPUs to run in a parallel manner. A new beta version of Repast, the Repast for High Performance Computing (Repast HPC), which was just released in December, 2010 is certainly something worth looking into: http://repast.sourceforge.net/repast_hpc.html.

5.2.3 Dependency on Other Environmental Modeling Applications

Another limitation of the PedNaTAS system is its partial dependency on other environmental modeling applications when modeling some aspects of the urban climate: the SOLWEIG model for T_{mrt} modeling and LES model for wind environment modeling. These models are effectively "loose coupled" with the system, meaning that their results can be directly fed into the system as input. Despite the fact that these applications have been proved to be reliable and are also publicly accessible, the loose coupling integration is still a limitation of the system in terms of a formal modeling process. Ideally these models should be tight coupled, i.e., re-implemented in the system as the PET module or TNM module, however it is not the focus of the present study to model the radiation or aerodynamic environment, therefore this part of the implementation is left out in the system.

5.2.4 Lack of Direct Manipulation/Edit of Scenario

Currently the editing of the urban context, e.g., Gate point creation, pedestrian sidewalk definition, etc., is carried out with the ArcGIS software. Therefore, once a scenario is loaded in the system, the user could no longer edit the scenarios directly through the system interface. So if the user wants to examine the impact of the changes made to the urban context, she will have to edit the scenario in ArcGIS, re-model the urban environment with respective applications, and load it again in the system and run. The graphical aspect of direct manipulation of scenario will require support for graphical interaction of GIS dataset, which is beyond the scope of the thesis. And the holistic modeling aspect is discussed in 5.2.3. Though an integrated system with graphic editing and holistic modeling functions will facilitate the operating circle to a great extent, due to the limited scope of the study, a redundant operating circle has to be taken at this development stage.

5.2.5 Drawbacks in Directing Policy Making

It must be noted that the current development stage of the system will impose limitations when immediate applications in directing policy making are attempted. Firstly, on the spatial dimension, the relatively small scale (500 m) of the modeled urban domain should be expanded to a bigger scope with boundary conditions to ensure that the analyzed quantities in the concerned area have higher confidence level, and this will requires the capability of the system to model larger-scale urban environment. Secondly, on the temporal dimension, the narrow modeling window (15 min, 2 PM) is a very specific snapshot of daily scenarios. Therefore it is difficult to generalize the results and analysis to provide planning implications for real use. In such a case, a long-term modeling with different weather conditions is needed. Future research recommendations addressing these spatial and temporal modeling drawbacks will be discussed in the next section. Meanwhile, it must be stated again that it is not the attempt of this study to produce an SDSS and test its usage with real planning cases. Rather, it aims to establish a direction of decision support research, and has proved the concept it proposes with a prototypical computational system.

5.3 Recommendations for Future Research

Because of the interdisciplinary feature of the thesis work, and also the highly complicated feature of the integrated system developed, it is not exaggerating to say that each module of the system should have the potential to be expanded to an individual PhD work. Indeed, apart from the possible solutions with respect to system limitations as discussed in the previous section, there are also a number of major research directions for system improvement, which are discussed in this section.

5.3.1 System Calibration for Practical Application

The most obvious vein for future research will be calibration of the system. Because of its highly complicated feature, the system has a large set of parameters that are yet to be fine-tuned with realistic data before practical application. Admittedly this may impose enormous work. On the other hand, everything in the system, including both data structure and control mechanism, is highly hierarchical and modularized. Therefore the system could be refined in a systematical manner with improved understanding and new knowledge if available, e.g., detailed pedestrian frequentation data, destination selection propensities, etc.

5.3.2 Empirical Data Collection

The present study has established a computational framework to investigate pedestrians' thermal comfort condition in a virtual sense, i.e. through simulation. Understandings in this aspect will with no doubt be complemented by observations in the realistic sense, which is to conduct interviews and surveys to collect empirical data. Though the study has used a broad set of data obtained in on site measurement of field survey (meteorological measurement, people's neutral PET, etc.), these data are mainly based on static condition or subject's steady states. In this sense, more in-depth surveys and long term measurements are to be conducted with respects to pedestrians' behaviors and dynamic states. A good example will be the temporal monitoring of subjects' actual thermal transient state as proposed by (Potvin, 2004).

5.3.3 Simulating a Longer Period

Another possible improvement of the system is to simulate a longer period. At this stage the system can simulate a walking scenario up to 15 minute long. With the assumption that the climatic condition in the domain stays constant during the simulation, 15 minutes seem to be the longest period that is reasonable. For a longer simulation period, e.g., 1 hour, this assumption will not be suitable. This implies that the climactic condition should be able to progress during simulation course in order to make the system "really" realistic. To fulfill the task will require tight coupling with other environmental modeling applications, or at the very least the pre-calculation of a series of climatic conditions as the "repertoire" to provide updated climatic input to the system in a timely manner.

5.3.4 User Friendly Interface

Because the system is only designed and implemented as a proof-of-concept prototypical model, user-friendliness is not covered in great depth. Parameter settings are all hard coded in the system. In this sense, a more user friendly graphical interface will make the system more useful in practice. Possible user interactions include selecting a route for investigation, setting person attributes, defining climatic condition, etc. Together with the discussions in Section 5.2.4, all these speculations point towards a holistic modeling and analyzing system.

5.3.5 Complement with Other Modeling Approaches

The ABM approach the study takes manages to investigate the urban climatic condition on the individual scale. On the other hand, there are also studies aiming to model and analyze the urban environment and structure from other scales, such as the space syntax theory and urban structure analysis (Croxford, Penn, & Hillier, 1996; Ratti, Sabatino, & Britter, 2005). These examples provide complementary modeling approaches to the present study. And the combination of different approaches are expected to reveal more comprehensive understandings in environmental studies

There are also other research directions that will improve the system from trivial aspects, though the problem itself may not be trivial *per se*, such as 3-D visualization. It must be noted that the great diversity of the future research as identified and discussed in this section should not speak to the weakness of the system. Instead it should reflect the richness and comprehensiveness of the defined framework.

5.4 Concluding Remarks

The thesis has established an agent-based computational framework for pedestrian thermal comfort assessment and proposed the idea of "context-sensitive" assessment. An integrated system, the PedNaTAS (**Pede**strian **Na**vigation **T**hermal **As**sessment **S**ystem) is implemented. Through a comprehensive case study in real world context with detailed modeling of the urban environment, the system is shown to be an appropriate tool in accounting for pedestrian's individualized and dynamic characteristics in evaluating their thermal condition. In general, the study has suggested that the ABM paradigm can open up new avenues in investigating complex systems as apposed to the traditional top-down approaches.

In addition, looking back at the entire process at the end of this long journey, there are two final remarks the author would like to share:

On Simulation Systems

"Models do not explain history, but they may tell us where to look." (Bowles, 2004, p.88) The statement is originally made on economic models, but it applies with equal force to models in general. Indeed, a simulation system such as PedNaTAS can help to frame the problem, enrich our understanding of the problem and contribute toward a structured reasoning of the problem. Nowadays there has been a shift of the advocated modeling objective from KISS (Keep It Simple & Stupid) to KIDS (Keep It Descriptive & Stupid) (Edmonds & Moss, 2005). However stupid the model is, *descriptive* should be the key concern: the model needs to be informative. This principle should be kept in mind for all model development.

On Subjective Evaluation

On a related issue, which is the modeling of people's subjective response, the question reads: Will subjective response, such as the ASV (Actual Sensation Vote) used by (M. Nikolopoulou, et al., 2001), be necessarily drawn and predicted by the system? The short answer is no. It is not the attempt of the model to create knowledge of human behavior. Rather, it aims to provide an objective assessment tool with all the protocols to communicate with the "soft factors" exhibited by humans. In cases when knowledge about people's subjective response is available, such as the premise of "10 minute sunny exposure implies discomfort", its likely consequence will be revealed by the model.

To this point, I would like to end this thesis by quoting a manifesto by Allan Jacobs, the renowned urban designer. This statement (A. B. Jacobs, 1995) is part of a comment on his classic book, "Great Streets" (A. B. Jacobs, 1993):

> *"People say it is people who make great streets. That may well be true, but I can't design people and wouldn't want to if I could. I can't design or build activities. Those non-physical qualities may be more important than the physical, designable qualities. But I don't control them. As a designer I might be able to control the physical qualities."*

Echoing Gehl's reflection about the relationship between people and cities as quoted at the very beginning of this thesis, it is hoped that this thesis work will contribute towards a better planning of our cities, and therefore a better life.

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Appendix A: Java Project Structure

- PedNaTAS
  - PersonContext
    - Person
      - Attributes
      - Styles
    - PersonGeography
    - Attributes
    - Styles
  - UrbanContext
    - BuildingContext
      - Building
      - BuildingGeography
      - Attributes
      - Styles
    - GatePointContext
      - GatePoint
      - GatePointGeography
      - Attributes
      - Styles
    - RasterContext
      - MyGrid
      - WalkingSurface
      - OccupiedGrid
      - ReservedGrid
      - ShadeGrid
      - TmrtGrid
      - WindSpeedGrid
      - Attributes
      - Styles
    - ExitPointContext
      - ExitPoint
      - ExitPointGeography
      - Attributes
      - Styles
    - JunctionContext
      - Junction
      - JunctionGeography
      - StreetNetwork
      - Attributes
      - Styles
    - StreetContext
      - Street
      - StreetGeography
      - Attributes
      - Styles
    - Attributes
    - Styles
  - Attributes
  - Styles

Appendix B: Person Agent Object Structure

B.1 Major Properties:

```
//a unique ID of a Person
private int ID = 0;
//Person's location
private Coordinate coord; //lon/lat
private Coordinate coordXY; //needs to be updated with coord
//grid index
private int i;
private int j;
//target grid displacement
private int di = 0;
private int dj = 0;
//travel distance between grid
private double grid_distance = 0;
private double grid_distance_traveled = 0;
private boolean half_grid_distance_traveled = false;
//a raster space to record walkability, grid occupation, tmrt, wind speed,
shading, etc.
RasterContext rasterSpace;

//personal data for thermal assessment
private int age;
private int gender; //1 for male; 2 for female
private double mbody;   //mass of body in kg
private double ht;  //height in m
private double work;    //work
private PETTER petObject;
private TNM tnmObject;  //a two-node model object

//data for walking simulation
private double maxSpeed = 3;
private double minSpeed = 0.3;
private double preferredSpeed = 1;
private double speed = 1;
//heading index: 0=0, 1=pi/4, 2=pi/2, 3=3/4pi...
```

```
private int heading = -1;

//interaction with other persons
//other persons moving to the next grid tried
//array value: persons' id
private ArrayList<Integer> othersHeadingToNextGrid;

private List<Coordinate> route; //a list of Coordinates, with both
origin and destination, all points
//rounded to grid center, so this is the "physical" route points for a
person's movement
private List<Coordinate> route_not_centered;
private List<Integer> IsRouteJunctionList; //1: route point is
junction, 0: not
private GatePoint origin; //NOT rounded to grid center
private ExitPoint destination; //NOT rounded to grid center
private Coordinate current_target_route_point;

//private boolean current_targe_route_point_reached = false;
private boolean target_reached = false; //reach target
private boolean target_grid_reached = true; //reach the center of the
grid, false means in the middle of a journey between two grid, so heading
is fixed;

//a variable to test if reach a grid center, unit: meter
private double grid_epsilon;
```

B.2 Major Methods:

```
//set person attributes: gender/age/ht/mbody/speed/ based on
distribution
public void setPersonAttributesRandom()
//set person attributes: gender/age/ht/mbody/speed/ based on assigned
value
public void setPersonAttributesAssigned(int sex, int yr, double weight,
double height, double v)
//set origin point, target point and target route point
```

```
public void init_walk(GatePoint origin)
//assign destination point for a person according to its origin, individual
characteristics, etc.
public ExitPoint assignDestination()
//do all the necessary task at each step
public void step()
//housekeeping task for movement at each step
public void move_step()
//to update coordinate when moveTo function is used
public void setCoordinateToPoint(Coordinate c)
//to update coordinate when moveByVector function is used
public void setCoordinateByVector(double distance, double direction)
//try to move to a grid
public boolean tryMoveTo(int i, int j)
//decide target grid
public void decide_target_grid()
public void decide_target_grid_close_to_route_point()
public void decide_target_grid_far_from_route_point()
//if current target route point is a junction
public boolean congestionJunctionAhead()
//in case no next target grid is available, have to pause for this step
public void pause()
//a person looks along a particular heading to calculate the length of
visible line, including road and sidewalk
public int calculateVisibleLine(int a_heading)
//dynamic routing
public void reroute(Coordinate coord_origin, Coordinate
coord_destination)
//other persons heading to (i, j)
public ArrayList<Integer> GetOthersHeadingTo(int i, int j)
//after target is reached, the person leaves the environment
public void leave()

//get spatially variant environmental data
public double getCurrentTmrt()
public double getCurrentWindSpeed()
//probe thermoregulatory conditons
public double getPET()
```

```
public double getTskin(){
public double getTcore()
public double getTskin_st() //steady state
public double getTcore_st()
public double getEres()
public double getCres()
public double getDry()
public double getEsk()
public double getSkinBloodFlow()
public double getEnergyBalance()
public double getSkinWetness()
public double getClothTemp()
//timely update of raster files, be it frequentation, etc.
//when a pedestrian steps on to a grid cell
public void updateRaster()
```

Appendix C: Major Class Methods

C.1 ContextCreator.java

```
//convert HK_1980 lon/lat (decimal degree) to x/y
public static Coordinate convert2XY(Coordinate c)
//convert x/y to HK_1980 lon/lat (decimal degree)
public static Coordinate convert2LonLat(Coordinate coordXY)
//get grid index [i][j] from a XY coordinate
public static int[] getGridIJ(Coordinate coordXY)
//round a coordinate read from .shp file to a grid center
//return a lon/lat coordinate
public static Coordinate setGridCenter (Coordinate coord)
```

C.2 GatePoint.java

```
//populate person agents
public void populate()
//for utility estimation
public void calculateDist2ExitPoints()
//roulette function to select a destination
public ExitPoint roulette()
```

C.3 RasterContext.java

```
//get the walkability at this i, j coordinate
public int getWalkabilityAt(int i, int j)
//get and set the occupancy at this i, j coordinate
public int getOccupiedAt(int i, int j)
public void setOccupiedAt(int i, int j, int id)
//get and set the reserved at this i, j coordinate
public int getReservedAt(int i, int j)
public void setReservedAt(int i, int j, int id)
//get Tmrt at this i, j coordinate
public double getTmrtAt(int i, int j)
//get wind speed at this i, j coordinate
public double getWindSpeedAt(int i, int j)
// get and set frequentation at this i, j coordinate
public int getFrequentationAt(int i, int j)
public void setFrequentationAt(int f, int i, int j)
```

C.4 ASCIIReader.java and ASCIIWriter.java

```
//load file
public void load(String File)
//export file
public void export(String File)
```