

# UC Berkeley

## UC Berkeley Electronic Theses and Dissertations

### Title

Simulating the Effect of Microclimate on Human Behavior in Small Urban Spaces

### Permalink

<https://escholarship.org/uc/item/2pn2f0z7>

### Author

Lam, Fung Ki

### Publication Date

2011

Peer reviewed|Thesis/dissertation

# Simulating the Effect of Microclimate on Human Behavior in Small Urban Spaces

By

Fung Ki LAM

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Department of Architecture

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Prof. Yehuda Kalay, Chair

Prof. Ed Arens

Prof. Peter Bosselmann

Fall 2011



## Abstract

Simulating the Effect of Microclimate on Human Behavior in Small Urban Spaces,

by

Fung Ki Lam

Doctor of Philosophy in Architecture

University of California, Berkeley

Prof. Yehuda Kalay, Chair

This dissertation describes a behavior simulation model which could reveal spatial usage pattern of small urban places in association with the tangible physical built environment and the intangible microclimatic conditions. The simulation model extends the existing environmental assessments which do not include human interactions and human behavior simulations which do not take into account microclimatic conditions. It addresses the problem of predicting and evaluating the impacts of microclimatic conditions on the spatial usage of its human inhabitants, which has been studied, but not successfully implemented in the past.

The concept is to carry out a virtual post occupancy evaluation which virtual users would exhibit their spatial usage pattern according to the environmental conditions and physical environment so experienced. Evaluators then could see how virtual users perform under certain conditions and assess if the design intention is achieved.

The simulation model is developed using Wei Yan's (Yan, 2005) urban simulation model as a base. In addition Yan's usability-based building model and agent-based behavior model, an environmental model is included. It manages environmental data from user input, database and other simulation programs. It records the shading and air speed profile onto the building model to affect individual user behavior, develops outdoor activity comfort maps which virtual users would use to develop activity option maps, and control collective usage pattern in terms of level of usage, activity type distribution and spatial distribution.

To ensure quality results, the environmental model handles only relatively simple computation, like generating outdoor activity comfort maps. It does not handle assessments which require specialized algorithms and processes like air flow simulation and comfort evaluation. Rather, these assessments are handled by certified programs outside the system. The environmental model processes the result and distributes the

information to the building model and the agent model to control the behavior of the virtual users at both collective and individual levels.

At the collective level, the behavioral pattern is mainly governed by statistics obtained from a year round field study. At individual level, the behavior is based on well studied and defined behavioral rules which are derived from theoretical and practical environment-behavior studies.

The simulation generates both graphical and textual outputs. The two dimensional graphical output offers views of paths of virtual users; the three dimensional output offers shows spatial usage as a whole; and textual output provide information of usage and thermal states.

It is expected the result of this research to change how architects and environmental behavior experts will approach the design and evaluation of built environments.

# Contents

<b>Abstract.....</b>	<b>1</b>
<b>Contents .....</b>	<b>i</b>
<b>List of Figures.....</b>	<b>v</b>
<b>List of Tables .....</b>	<b>ix</b>
<b>Acknowledgement.....</b>	<b>x</b>
<b>Chapter 1 Introduction.....</b>	<b>1</b>
1.1 Motivation.....	1
1.2 Previous methods and a new solution - Virtual Users .....	4
1.3 Methodologies.....	5
1.3.1 Usability-based building model .....	8
1.3.2 Agent-based virtual user model.....	9
1.3.3 The environmental model.....	9
1.4 Challenges.....	10
1.4.1 Collecting and quantifying microclimate related behavioral data.....	10
1.4.2 Simulating the microclimatic environment and comfort.....	10
1.4.3 Establishing the comfort mapping.....	11
1.5 Contributions.....	11
<b>Chapter 2 Background .....</b>	<b>13</b>
2.1 Microclimate, outdoor thermal comfort and human behavioral studies.....	13
2.1.1 Qualitative studies .....	14
2.1.2 Quantitative studies .....	15

2.2	Concern and criteria of microclimatic environment for outdoor behavior.....	16
2.3	Assessment of outdoor thermal comfort .....	19
2.4	Design evaluation of and environment - behavior .....	21
2.4.1	General design evaluation methods for environmental behavior .....	22
2.4.2	Simulation of environmental behavior .....	24
2.5	Computer simulation of environmental behavior.....	25
2.5.1	Pedestrian simulation .....	25
2.5.2	Crowd and fire egress simulation.....	26
2.5.3	Urban microclimate simulation.....	26
2.5.4	Urban space simulation .....	27
2.6	Influences of the studies on the research.....	27
2.6.1	Criteria employed – independent variables .....	27
2.6.2	Criteria employed – dependent variables .....	28
2.6.3	Criteria employed - behavior.....	29
2.6.4	Simulation approach.....	30
<b>Chapter 3 Urban Spatial Behavior.....</b>		<b>32</b>
3.1	Urban setting – the Sproul Plaza.....	32
3.1.1	The physical environment .....	33
3.1.2	The microclimatic environment .....	34
3.2	Field study.....	38
3.2.1	Questionnaire .....	38
3.2.2	Video recording.....	38
3.2.3	Surveyed dates .....	39
3.3	The usage pattern .....	40
3.3.1	Number of users and time of usage .....	42

3.3.2	Activity types of users.....	44
3.3.3	Distribution of users.....	45
3.3.4	Duration of usage.....	47
3.4	Effects of microclimate.....	48
3.4.1	Influence of individual microclimatic factor.....	48
3.4.1.1	Influence of individual microclimatic factor from questionnaire.....	49
3.4.1.2	Influence of individual microclimatic factor from video record.....	55
3.4.2	Collective effects of microclimatic factors.....	59
3.5	Prediction of spatial behavior.....	63
<b>Chapter 4 The Simulation model Structure.....</b>		<b>67</b>
4.1	The usability-based building model.....	68
4.1.1	Geometrical model.....	69
4.1.2	Usability-based model.....	69
4.2	The agent-based virtual user model.....	72
4.2.1	Geometrical modeling and motion control.....	72
4.2.2	Perception modeling.....	73
4.2.3	Behavioral modeling.....	74
4.3	The environmental model.....	79
4.3.1	The structure.....	80
4.3.2	The intermediate information.....	81
4.3.3	The terminal information.....	86
4.4	The life of an agent.....	88
<b>Chapter 5 Simulation and Visualization.....</b>		<b>90</b>
5.1	The simulation process.....	90
5.2	Validation.....	93



5.3	Simulation for comparison of design alternatives .....	96
5.4	Limitations .....	98
<b>Chapter 6 Conclusion .....</b>		<b>100</b>
6.1	Conclusion .....	100
6.2	Potential applications .....	101
6.2.1	Design evaluation.....	101
6.2.2	Application domain.....	102
6.3	Contribution to architectural design practice and education.....	102
6.4	Future research directions .....	103
<b>References.....</b>		<b>105</b>
<b>Appendix: Sample survey.....</b>		<b>117</b>

# List of Figures

Figure 1.1 Bamboo garden at 560 Mission Street, San Francisco, an enjoyable privately owned public space after the 1985 Downtown Plan.....	3
Figure 1.2 Modeling components of the simulation. The <i>Environmental Model</i> column is the major additional components to Yan's model.....	7
Figure 1.3 The generation of comfort mappings (partial).....	7
Figure 1.4 Survey dates on the sun path coverage. Shaded area covers the academic months and the lines represents the survey dates. <b>Error! Bookmark not defined.</b>	
Figure 2.1 Overshadowing image from the center of the Plaza.....	17
Figure 2.2 Left: Centrifugal effect. Adjacent tenants are isolated by the stair locations. Right: Centripetal effect. Adjacent tenants are brought into contact by the stair locations. ....	21
Figure 3.1 The upper Sproul Plaza in the morning.....	33
Figure 3.2 Berkeley temperature' .....	34
Figure 3.3 Berkeley precipitation. ....	34
Figure 3.4 Berkeley relative humidity. ....	35
Figure 3.5 Overshadowing at Jun 21 (Summer Solstice) .....	36
Figure 3.6 Overshadowing at Dec 21 (Winter Solstice).....	36
Figure 3.7 Wind rose at SFO, prepared by Pacific Environmental Services, Inc.....	37
Figure 3.8 Wind speed and wind direction at Berkeley. (Source: www.wunderground.com) .....	37

Figure 3.9 Recording setup. A digital video camera is connected to a laptop and a Hobo data logger (at the window) collects temperature and relative humidity.....	39
Figure 3.10 Sun paths of the survey days (lines) in the academic period (shaded area) .	40
Figure 3.11 Purpose of usage from questionnaire. ....	41
Figure 3.12 Frequency of usage of interviewees. ....	41
Figure 3.13 Time of usage from questionnaire.....	42
Figure 3.14 Number of users on the surveyed days.....	43
Figure 3.15 Number of walkers on the surveyed days.....	43
Figure 3.16 Number of sitters on the surveyed days. ....	43
Figure 3.17 Number of non-walkers-sitters on the surveyed days. ....	43
Figure 3.18 Number of users of different types of activity in the Plaza.....	45
Figure 3.19 Distribution of sitters.....	46
Figure 3.20 Distribution of standers. ....	46
Figure 3.21 Distribution of duration of users, excluding walkers. ....	47
Figure 3.22 Duration of usage from questionnaire.....	48
Figure 3.23 Difference between the asked sensation vote and the calculated thermal sensation.....	49
Figure 3.24 Previous activities of interviewees before entering the Plaza. ....	50
Figure 3.25 Temperature with thermal sensation from questionnaire. ....	50
Figure 3.26 Thermal Sensation against wind speed from questionnaire. ....	51
Figure 3.27 Thermal Sensation against relative humidity from questionnaire.....	51
Figure 3.28 Warmth, sun, shade and wind preferences against temperature.....	52
Figure 3.29 Warmth, sun, shade and wind preferences against wind speed.....	53
Figure 3.30 Warmth, sun, shade and wind preferences against relative humidity. ....	54

Figure 3.31 Warmth, sun, shade and wind preferences against exposed condition.....	55
Figure 3.32 Number of sitters against the surveyed days' temperatures. ....	56
Figure 3.33 Number of sitters against the normalized temperature.....	56
Figure 3.34 Number of sitters against wind speed.....	57
Figure 3.35 Number of sitters against relative humidity. ....	58
Figure 3.36 Number of sitters against the proportion of exposed area.....	58
Figure 3.37 Number of sitters against normalized sitting comfort. ....	59
Figure 3.38 Probability density function. ....	66
Figure 4.1 The modeling structure of the simulation.....	67
Figure 4.2 Graphical view of the SVG model displayed in a SVG viewer (Yan 2005)...	70
Figure 4.3 Graphical view of the discrete space model - the fountain side, fountain water, benches, steps are all marked with different colors (Yan 2005).....	71
Figure 4.4 The VRML model of the Sproul Plaza.....	71
Figure 4.5 Two-dimensional model of an agent. ....	72
Figure 4.6 Three-dimensional model of an agent. ....	72
Figure 4.7 Behavioral control hierarchy. ....	75
Figure 4.8 Poisson distribution for discrete probability process like arrival rate (Source: <a href="http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg">http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg</a> ). ....	76
Figure 4.9 Normal distribution for distribution like duration (Source: <a href="http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg">http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg</a> ) ....	76
Figure 4.10 Uniform distribution curves for distribution like meeting acquaintance (Source: <a href="http://en.wikipedia.org/wiki/Uniform_distribution">http://en.wikipedia.org/wiki/Uniform_distribution</a> ).....	76
Figure 4.11 Virtual users' social spaces (Yan 2005).....	77
Figure 4.12 User interface.....	80

Figure 4.13 Processes in the environmental model. ....	81
Figure 4.14 Outdoor comfort determination procedure. ....	82
Figure 4.15 The process of generating thermal comfort map. ....	83
Figure 4.16 The process of generating wind comfort map. ....	84
Figure 4.17 A chart depicting different wind chill temperatures for givens and wind speeds. (Source: <a href="http://www.weather.gov/os/windchill/images/windchillchart3.pdf">http://www.weather.gov/os/windchill/images/windchillchart3.pdf</a> ) .....	85
Figure 4.18 The process of generating wind chill map. ....	85
Figure 4.19 The process of generating outdoor thermal comfort. ....	86
Figure 4.20 The process of generating activity option map. ....	87
Figure 4.21 Model flow of an agent intended to sit. ....	89
Figure 5.1 The simulation window. ....	91
Figure 5.2 Two dimensional simulation with textual output. ....	92
Figure 5.3 Two dimensional display of the path list. ....	93
Figure 5.4 Photo of field survey show majority of sitters at the fountain were in shade. ....	94
Figure 5.5 Plaza usage simulation using the same parameters as field record. ....	94
Figure 5.6 Simulation of the scenario with majority of fountain sitters at shade. ....	95
Figure 5.7 Field record showing limited people using the Plaza. ....	95
Figure 5.8 Simulation also shows low level of usage. ....	96
Figure 5.9 Comparison of a low usage scenario in a cool and windy morning. ....	96
Figure 5.10 Left: simulation with 26.3 °C; right: simulation with a lower temperature, 16.3°C. ....	97

# List of Tables

Table 2.1 Mechanical effects of standard equivalent mean wind speed.....	18
Table 2.2 Wind speed ranges for basic outdoor activities, based on 20% probability of exceedance. ....	19
Table 3.1 Correlation of various factors with total number of users. ....	60
Table 3.2 Correlation of various factors with different types of activities. ....	61
Table 3.3 Correlation of various factors with distribution.....	61
Table 3.4 Correlation coefficients of usage at the fountain, ASUC, Sproul stairs and the benches.....	62
Table 3.5 Correlations of various factors with duration of usage.....	63
Table 3.6 R-squared for numbers of walkers at different class peaks. ....	65
Table 4.1 Thermal sensation (TSENS) scale .....	83
Table 4.2 Wind speed ranges for activities, based on 20% probability of exceedance ....	84
Table 5.1 Comparison of sample scenario with simulation.....	95
Table 5.2 Comparison of sample scenario with simulation.....	96
Table 5.3 Comparison of sample scenario with different temperatures. ....	97
Table 5.4 Comparison of sample scenario with different temperatures. ....	98

# Acknowledgement

I would never have been able to finish my dissertation without the guidance of my committee members, help from friends, and support from my family. Because of them, my graduate experience has been one that I will cherish forever.

My deepest gratitude is to my advisor, Prof. Yehuda Kalay. I have been amazingly fortunate to have an advisor who gave me the freedom to explore on my own, and at the same time the guidance to recover when my steps faltered. Yehuda gave me a lot of opportunities experiencing my ideas. His patience and support helped me overcome many crisis situations and finish this dissertation. I hope that one day I would become as good an advisor to my students as Yehuda has been to me.

My committee member, Prof. Ed Arens' insightful comments and constructive criticisms at different stages of my research were thought-provoking and they helped me focus my ideas. I am deeply grateful to him for the long discussions that helped me consolidate the knowledge base of my work.

Prof. Peter Bosselmann is one of the best teachers that I have had in my life. He has been always there to listen and give advice. He sets high standards for his students and he encourages and guides them to meet those standards. I am also thankful to him for commenting on my views and helping me understand and enrich my ideas.

I am also indebted to the members of the Center for the Built Environment with whom I have interacted during the course of my graduate studies. Particularly, I would like to acknowledge Hui Zhang and Charlie Huizenga for the many valuable discussions that helped me understand my research area better.

I would like to acknowledge also members of the Digital Design Research Group. Particularly, I would like to thank Dr. Wei Yan for his endorsement and support in using his model; Yongwook Jeong, Cecilia Kim, Seung Wook Kim, Gokce Kinayoglu, Bauni Hamid, Emelie Cheng and Hsin Hsien Chiu for numerous discussions and lectures on related topics that helped me improve my knowledge in the area. I greatly value their friendship and I deeply appreciate their belief in me.

I am also grateful to Lois Koch for the various forms of support that I can stay focused on my graduate study.

Finally, I would like to thank my husband, Jingsong Wu. He was always been patient and stood by me through good times and bad times.

# Chapter 1

## Introduction

### 1.1 Motivation

With the high urban population density, public open space is important to cope better with the stresses of living in large urban areas. People in urban areas frequently use small urban spaces for recreation and outdoor activities. Though so, new research highlights how little access urbanites may have to parks and other green space (Fuller and Gaston, 2009). The study found that in some European cities there are only 3-4 square meters of green space per person. With increasing urbanization, there is even more pressure on open spaces. It is not that these green spaces aren't protected, but rather that new green space is not created at the same rate as the increase of urban population. At the same time, existing public open spaces might not be designed appropriately that they became uninviting, which put even more pressure on average open space per person.

In fact, public open spaces are omnipresent. Central Park in New York and Union Square in San Francisco are of course popular public open spaces open for everyone. Street side cafes and promenades also serve good public open spaces. Spaces between building blocks, street corners and sidewalks could also serve as good public open spaces if designed appropriately. Then, how public open space should be designed, and how to define good public open space?

Traditionally, public open spaces were not designed for leisure. Common public spaces like market streets and squares in front of buildings, public fountains that draw people and plazas with monuments that terminate long, straight streets, are mostly for ceremonies. The idea of having public parks open to everyone, like the Central Park in New York City, emerged in the nineteenth century, so as streets which serve as leisurely public promenades. In fact, the idea that cities should have many urban outdoor spaces, open to all, without an admission charge or the need to patronize a cafe, relates great deal to the modern movement in architecture (Zacharias, Stathopoulos and Wu, 2004). Tall buildings need space around them, and architects began designing this space to provide an appropriate setting for towers. The initiative was to create an impressive approach to



the building. That is, these open spaces were not always intended to encourage people to spend time there. Sometimes, owners even placed spikes on ledges so that people would not sit or lie on them. Subsequently, a lot of urban open spaces are left empty, despite all the resources and effort paid on the design, construction and maintenance (Whyte, 1980).

Generally, open spaces are designed based on aesthetics, social environment, and character within the narrowly defined parameters of physical design and site planning. Yet, these do not equivalent to generating welcoming urban open spaces. Whyte (1980) had identified seven key elements for an urban space to be successful: seating, relationship with the street, sun and wind, water, trees, food and triangulation. However, it is not always easy to implement all these features in urban open spaces, particularly those related to microclimate. In dense cities like San Francisco and New York, without a good care of microclimate, often there would be strong downdrafts from the building when it was windy, blinding sunlight on hot days, and large unsheltered expanses in winter. In fact, with the increased concern of human comfort and sustainability, there has been more effort to incorporate microclimatic conditions in open space design. This is particularly critical for urban open spaces as weather produces local microclimatic conditions that vary remarkably in built-up environments with large buildings. The massing, layout and materials of the built environment, and prevailing winds account for a large proportion of the local variations in microclimatic conditions. Cities such as San Francisco, Boston, Toronto, and others have even required that projects satisfy certain microclimatic performance criteria, with the intention of supporting public activity. For example, since 1985, San Francisco required that publicly accessible open spaces to be provided in all new office building projects, and the microclimatic environment of existing privately owned spaces to be protected (San Francisco (Calif.), San Francisco (Calif.) Board of Supervisors, 1985). The plan was a response to perceived overbuilding in downtown San Francisco which tall and bulky buildings reduced sunlight on plazas and contributed to air turbulence. As a result, the heights and volumes of some new buildings were severely reduced from permissible levels to protect plazas already in existence in the downtown area. Yet, how does the protected microclimate support usage in the public open spaces? How important are the different microclimatic factors in determining open space usage, or more accurately, the behavior in public open spaces?



**Figure 1.1 Bamboo garden at 560 Mission Street, San Francisco, an enjoyable privately owned public space after the 1985 Downtown Plan.**

Various studies were carried out to study the outdoor human comfort or impact on activities associated with single climatic factors. Little could be found on the collective impact of multiple climatic factors on human behavior. For example, Nikolopoulou et al. (2001) and Katzschner (2002) studied the thermal comfort in urban plazas. Nikolopoulou et al. confirmed that there is a strong relationship between microclimatic and comfort conditions. However, the relationship of microclimate and comfort conditions with the level of activities was not discussed. Katzschner developed the thermal comfort mapping in urban plazas based on the microclimatic conditions recorded and activities observed in the urban plazas studied. The thermal comfort mappings provided valuable information in post occupancy evaluation. However, it could not help in the design phase when human behavior could only be predicted but not observed. Lam and Tsou (2002) studied the relationship of climatic factors and behaviors in open spaces of urban residential development. Results showed that temperature, wind, and sun and shading conditions explain to some extent the great variations in uses and use levels of such spaces, but the variation in use has gone largely unmeasured. Zacharias et al. (2001) attempted to establish causal relationship between microclimate and outdoor human behavior. Results showed that measured microclimatic conditions accounted for most of the variance in activity level and types. It is also potential to assess the usage level under different climatic conditions. However, no further attempt was carried out for the assessment.

## 1.2 Previous methods and a new solution - Virtual Users

As microclimatic conditions are important in the level and types of use in an open space, and it is desired to raise the level and diversify the uses of such spaces, it is essential that a study of microclimatic conditions should accompany the preliminary design studies.

Many tools help architects design climatically appropriate environments, like scaled physical models, or computer programs like *Radiance* for lighting, *Fluent* for airflow, and *Ecotect* for lighting, acoustics and heat flow etc. However, these tools evaluate the climatic conditions of the environment itself; not the responses of the individual who inhabit it. These tools provide quantitative assessment of performances of different climatic attributes. The impacts on individuals are left to the determination of evaluators. Different people respond differently to the same environmental conditions, based on their own physiological conditions, activities and preferences etc. Moreover, these tools cannot help evaluate design quality in terms of human behavior due to the absence of users in the models. That is, we would not know if the microclimate brought about can meet users' needs, like for resting, gathering, playing, people-watching and other activities, as there are no users are included in the model. Therefore, even the designed environment is highly appraised by the assessment, how does it support the usage of people in such spaces is not known.

Most current environmental computer simulations pay more attention to the physical qualities of built environments—such as lighting, energy use, and thermal comfort—than to human spatial behavior. Unlike physical attributes of built environment, human spatial behaviors are affected by physical, psychological and social factors which are more difficult to be evaluated. Human spatial behavior simulations that exist are often limited to some well-defined areas of human activities where there has been considerable empirical research that can help develop the requisite cognitive models. Some of the areas for which such cognitive models have been developed are pedestrian simulation, and fire egress simulation. These simulations are often aimed at testing the *Level of Service*—the amount of space people need to conduct certain activities, such as walking on walkways and through corridors and doors, under normal or emergency situations. Human spatial behavior simulations involve wider spectrum domain knowledge and hence empirical research. The development hence is much slower, compared to pedestrian simulation and fire egress simulation.

Another approach is by carrying out post occupancy evaluation (POE), such as the study of New York City plazas by William Whyte (1980). Contrasting to predictive tools, POE consists of post-facto assessments of the occupants' satisfaction. It is costly in many ways, including legal exposure, client disruption, lack of time and extensive cost etc. Even if POE is conducted, retrofit for existing construction is not always feasible because of time, cost, and opposition from different parties etc. Though so, it could be useful for

designing similar future buildings and plazas. Yet, it might not be easy to translate results to proposed development for other projects due to the difference in nature and conditions of different projects.

A probable solution to the problem is to have a new computational model that simulates the built environment, its microclimatic conditions, its users and their activities in order to evaluate the spatial usage of the environment during the design phase. The idea is to conduct a virtual “post occupancy evaluation” during the design phase to assess the design quality before construction. This is done by assessing the design based on the behavior of *virtual users* in the design phase. That is, the *virtual users* will *act* in the simulated environment as would real people in reality. The simulated environment has physical features and associated climatic information embedded. The virtual users are embedded with carefully designed cognition model which they could respond to the environment as real people. The information generated like number, distribution and activities of users could help designers assessing the success of the environment so designed.

This approach is new for architectural design, where traditionally only the buildings and the environment have been modeled and simulated, not the people who use them, with the exception of way finding and fire egress prediction. Way finding and fire egress simulations focus on a very narrow range of human behavioral needs, and an even narrower spectrum of environmental attributes. On the other hand, human behavior simulation models, of the kinds developed by the gaming and movie industries, have very specific, yet straight forward reaction structure. They focus on the fulfillment of the lines of the games or movies, rather than real human behavioral needs. The virtual users would simply react as designed, rather than based on the environment. Therefore, there is no need to model the relationships with the environment or the microclimatic conditions as if in reality.

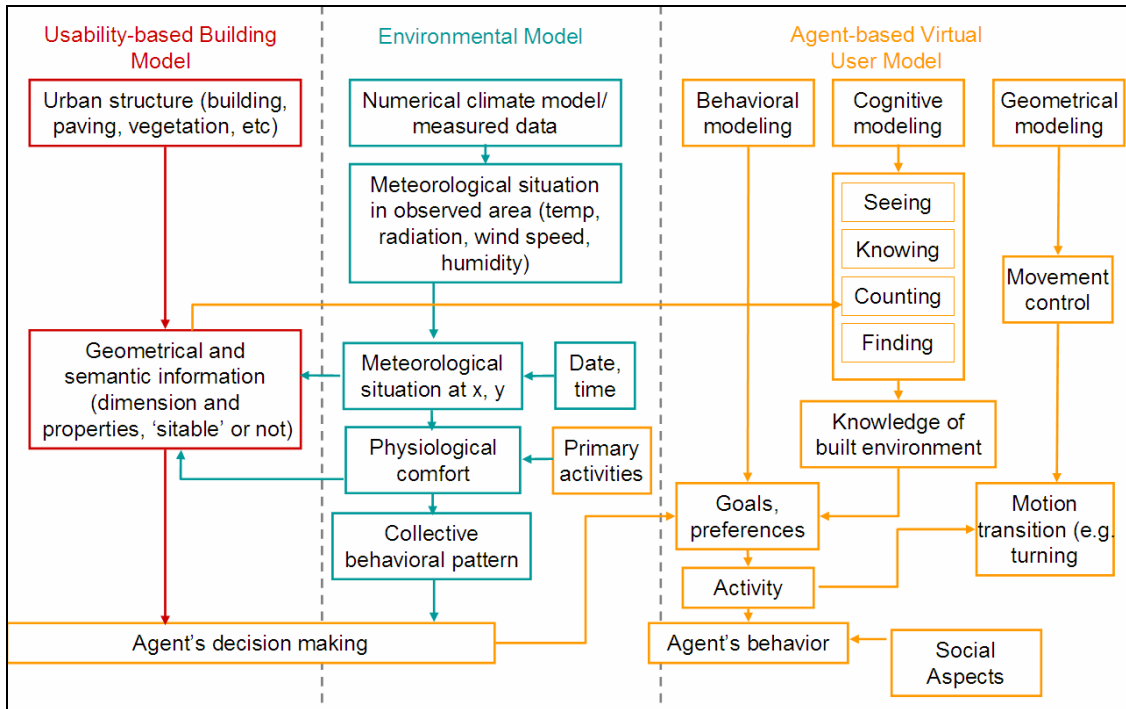
### **1.3 Methodologies**

The approach is to model the environment, the induced microclimatic condition and the people who would use it and simulate the interaction between them. The interaction is revealed by the behavior of the virtual users inhabit in the environment. The simulation is based on the human-environment simulation model developed by Prof. Wei Yan in 2005 (Yan, 2005). Yan’s model simulates the spatial usage of virtual users in an environment based on the architectural configuration. It does not have time and microclimatic components. That is, the behavior of virtual users would change with changes in architectural configuration, but not with time and seasonal climate. The focus is therefore to include microclimatic features in the environmental setting and to modify the

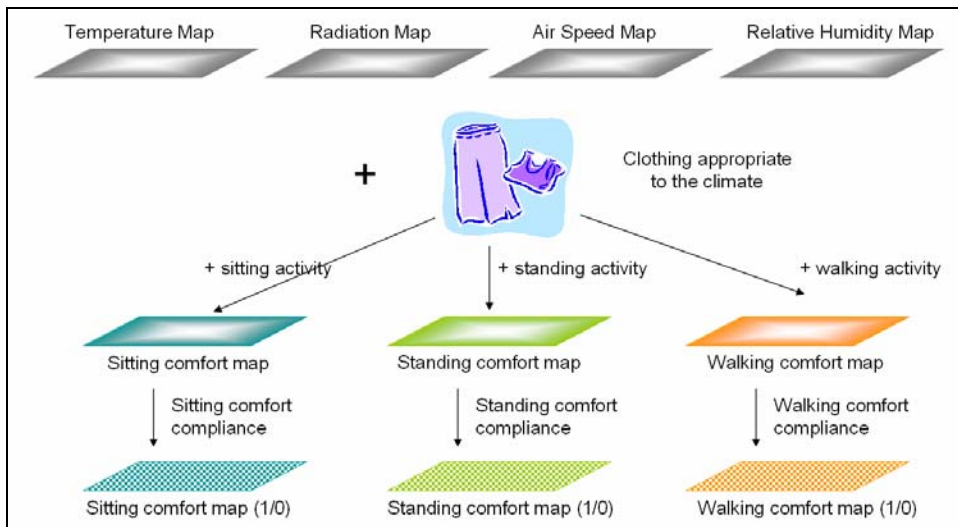
intelligence of the autonomous artificial users to reflect the influence of microclimate and hence outdoor thermal comfort in the activities and the collective behavioral pattern. Instead of establishing assessment of physical quantities like wind force, temperature, radiation and thermal comfort etc in the simulation itself, the idea is to direct the assessment load to available certified tools rather than handled entirely by the simulation prototype. Results from external assessments will be parsed to the simulation system and be used as information for decision making of the artificial users. In this case, we could first, ensure quality of the environmental assessments and second, focus the simulation load onto the behavior simulation itself. In Chapter 2 we will discuss the background of our simulation in more details.

Yan's model consists of a usability-based building model and an agent-based virtual user (or VUser) model. The usability-based building model defines the properties of design elements that may be encountered by the virtual users, such as buildings, doors, stairs, fountains, trees, and benches. It is an object-centered model, in which attributes that are relevant to human spatial behavior are explicitly represented, and the environmental information is structured in a way that makes it perceivable and interpretable by the virtual users so that they can behave accordingly. The VUser model modeled virtual users as autonomous agents that emulate the appearance, perception, social traits and physical behavior of real users.

To include the effect of microclimate, an *environmental model* is included in addition to Yan's model (Figure 1.2). The environmental model consists of maps of various environmental parameters, including temperature, radiation, air speed and relative humidity. The environmental parameter maps are transformed into comfort mappings based on the activity and clothing of virtual users in the environment (Figure 1.3). The comfort mappings reveal the comfort "perceived" by the virtual users in different locations in the environment. The comfort information, like the environmental information, is perceivable and interpretable by the virtual users which they can behave accordingly.



**Figure 1.2 Modeling components of the simulation. The *Environmental Model* column is the major additional components to Yan's model.**



**Figure 1.3 The generation of comfort mappings (partial).**

To test and validate the simulation, a virtual urban plaza emulates a real one is created. In urban plazas, the intentions and behaviors are relatively simple and have been well documented (e.g. Whyte, 1980). This simplified the simulation, yet provided sufficient

complexity for demonstrating its validity. Meanwhile, with the urban built form, there are apparent microclimatic variations in the environment which the variations in human behavior could be easily recognized. In this study, a virtual urban plaza emulates the Sproul Plaza at the University of California at Berkeley is used. The Sproul Plaza hosts general users' needs as resting, gathering, and playing, etc. It has places with different microclimatic qualities, like windy and shady places. Also, the Sproul Plaza is the birth-place of the Free Speech Movement of the 1960s, and has, therefore, been studied extensively by researchers such as Marcus & Wischemann (1990). In the simulation, the virtual users are modeled to exhibit goal-oriented and deliberate behaviors like crossing from one side of the plaza to the other, negotiating obstacles and other virtual users, seeking a place to sit, and avoiding or preferring shade etc. The microclimatic qualities are therefore associated with the preferences of individuals.

To ensure the correspondence of the simulation to reality, the simulation is based on a large amount of quantitative, real-world behavior data collected from the Sproul Plaza. The Plaza was surveyed systematically from morning (before 9am) till evening (around 5:30pm). Each survey session consists of two week days during the months with academic schedules. The survey covers a year round data (excluding summer when there are limited users) in which seasonal variations are captured.

### **1.3.1 Usability-based building model**

The usability building model consists of both the graphical/geometric information of design elements and non-graphical information about usability properties of these elements. As this simulation focuses on the human behavior in built environments, virtual users need more than just the graphical/ geometrical information of design elements to perceive and understand the environment. Including the usability properties to the design elements would provide a semantically rich environment for the virtual users to behave properly, following their built-in behavior rules.

To be more practical, the building model is not created from scratch but instead, it is built on top of existing CAD models that come from everyday architectural design practice. It is then converted to usability-based building model which semantic information of the environment is embedded with the geographical information. As a modification, the assessed environmental information is also included in the usability-based building model to enrich the semantic information to be "perceived" by the virtual users.

### **1.3.2 Agent-based virtual user model**

The agent-based virtual user model defines all characteristics and functioning of the virtual users. It defines the physical traits, personality, preference, behavior, and goals of each user in the simulated environment. It also enables the virtual users to execute certain functions, e.g. calculate the shortest paths, walk to a location, and have certain properties, such as walking speed. Indeed, the virtual users are modeled as autonomous, environment-sensitive agents, which have the ability to ‘understand’ the environment and adjust their behavior to match it. The virtual user model includes three major components: (a) geometry modeling and motion control; (b) perception modeling that enables virtual users to access the environment models; and (c) behavior modeling that simulates users’ behavior in reality. By linking the virtual users with the usability-based building model, the virtual users are able obtain necessary information of the built environment (including the assessed microclimatic information) to make decision on behavior. With the implementation of the environmental model, the decision of each virtual user might change with the different microclimatic inputs, so as the overall spatial usage pattern. This is revealed in the system output which shows the interrelationship between the environment and its users.

### **1.3.3 The environmental model**

The usability building model handles the *figure* information of the urban morphology. Contrasting the usability building model, the environmental model handles the *ground*, the intangible physical environment. It manages meteorological conditions at the simulation area as well as the induced physiological comfort for different types of activities. The meteorological information stored is based on data from feasible meteorological station as well as the urban morphology. The urban morphology, due to the mass, distribution and material, would affect local microclimate, making it different from what was obtained from the meteorological stations. For example, building blocks would redirect air flow and block direct sunlight. Meanwhile, the combination of different activities and microclimatic conditions would yield different comfort conditions. The different comfort levels for different activities in the studied area are stored as comfort maps in the environmental model. The environmental model would then provide useful information to individual virtual users for decision making.



## **1.4 Challenges**

### **1.4.1 Collecting and quantifying microclimate related behavioral data**

As the simulation should resemble the reality, a year round field survey was carried out to collect real world data. The survey was carried out at the Sproul Plaza of the University of California, Berkeley on days with similar school schedules. Consider behavior is mainly affected by the tangible physical environment, the intangible microclimatic environment, and the state and need of individual users, a year round survey would leave the intangible microclimatic environment and the physiological state of individual users as the main contributor to the difference in the spatial usage.

Meanwhile, the microclimatic environment is composed of influence of different factors, the different combinations of the factors would yield different comfort and hence response to individuals. It is then essential to assess the effects of different microclimatic factors as a whole, rather than assessing them separately. That is, we have to evaluate the composite effect of the microclimatic environment on the spatial usage which normal causal relationship study is not applicable. For this reason, regression analyses were used to assess some of the main behavioral data, like the number of visitor, the activity type, spatial distribution and duration of usage.

### **1.4.2 Simulating the microclimatic environment and comfort**

Shading, radiation, airflow and comfort require different information and computational models in simulation. If all the microclimatic and comfort simulations are handled merely by the behavioral simulation, the computational model has to be very sophisticated to meet the concerned standards. Also, it might take a long time to run the simulation even for a minor modification. At the same time, the behavioral simulation by itself does require computational resources. These make it not sensible to embed all the microclimatic and comfort simulations into the behavioral simulation. Therefore, to reduce computational load and simulation time, the microclimatic environment and comfort simulations are directed to other professional tools. The results are parsed in the environmental model. In this case, during the behavioral simulation, the virtual user will call in related information from the environmental model instead of real time simulation from scratch.

### **1.4.3 Establishing the comfort mapping**

Thermal comfort is a complex physiological response. With different thermal preferences, comfort assessment becomes more complicated than just thermal comfort assessment. Consider the behavioral simulation could involve hundreds of users, it is essential to have an effective comfort assessment method to limit the computational load while providing the concerned information in an effective and efficient way. In the behavioral simulation, we established a comfort mapping mechanism which provides each virtual user a binary comfort map. That is, each user has a comfort map of the environment which states the comfortable and uncomfortable area of the environment so exposed to.

The comfort mapping is originated from the outdoor thermal comfort map stored in the environmental model. It is derived from the local microclimatic conditions, clothing appropriate to the climate and different types of activities. The outdoor thermal comfort map by itself is a binary map which shows thermally comfortable and uncomfortable area. On the other hand, with different individual microclimatic preferences like to be in sun or in shade, we can generate binary map of the environment to show satisfactory and unsatisfactory areas. Overlaying the outdoor thermal comfort map and preference map would yield another binary map, the comfort option map. Note that the outdoor thermal comfort mapping is universal to all users with the same activities while the preference map and the comfort option mapping are unique to each individual.

## **1.5 Contributions**

The proposed research will contribute to academia and building professionals. Academically, the statistics would help extending the knowledge of impact of microclimatic conditions from physiology to behavioral level. Also, the methodology used to formulate an analytical procedure could be reapplied for study of open spaces in other cultural or climatic settings.

For building professionals, the design evaluation tool help designers to acquire better understanding of human environmental behavior with respect to microclimatic conditions. The evaluation framework provides an objective approach to evaluate the matching of intent and outcome of architectural designs. By presenting artificial users in modeled of built environments, designers could examine and analyze the behavior of prospective users, hence identify potential areas for improvement. This helps to allocate resources efficiently and effectively right in the design phase and avoid retrofit. Also, the better understanding of the designed environment helps to prolong the usage period of

urban spaces. In general, a longer thermally comfortable period can draw more users and extend the staying period. This is particularly favorable in dense environment with extreme climate.

Specifically, the major contributions of our research include the followings:

- The process of the system modeling includes (a) collecting and analyzing behavioral data in a public space, (b) mapping behavior data with microclimatic data, and (c) applying the statistical results of the analysis to simulating and visualizing users' behavior. This process is new in the field of spatial behavior modeling. It is expected that this process to be an effective and efficient modeling approach that many environment-behavior researchers would find useful.
- Mapping thermal comfort conditions or behavioral information with microclimatic conditions is not new. However, previous approaches tend to be manual and are labor intensive. Applying computational method to correlate the information could process significantly larger amount of data with relatively fewer errors.
- The system integrates theoretical and practical environment-behavior studies and real world data from field studies. This behavior simulation approach is new and the simulation results will be close to reality.
- The availability of input of microclimatic variables to provide real time non-choreographed animation of built environments as they will be used by their inhabitants, for presentation purposes, allows advantage over pre-animated, "closed" presentation. It is expected that the result of this research will change how architects and environmental behavior experts will approach the design and evaluation of built environments.

## Chapter 2

# Background

To understand the impact of microclimate on human behavior, we need to know how humans respond to microclimatic conditions. In particular, we need to know first if behavior is invariant across different microclimatic factors; and second, how the different microclimatic factors affect human behavior; and third, how important are those microclimatic factors in determining human behavior. Indeed, these have been interest for researchers in different fields for the past 30 years, including those from biology, sociology, architecture and psychology. These studies have different directions and focuses. In brief, they can be categorized as follows:

- Qualitative and quantitative studies of relationship of microclimate, outdoor thermal comfort and human behavior.
- Concerns and criteria of microclimate or thermal comfort to support outdoor urban environmental design. Models and methodologies developed for assessing thermal comfort in outdoor environments. Design evaluation of environment - behavior. In some of the studies, *thermal comfort* was studied instead of individual *microclimatic factors*. Thermal comfort represents an overall physiological response to the integrated microclimatic environment. In this section, we will discuss previous studies of microclimate, thermal comfort, and behavior, based on the mentioned categories:

### 2.1 Microclimate, outdoor thermal comfort and human behavioral studies

Urban parks and recreational areas play an important role in people's recreational life and outdoor activities. There were many studies on outdoor environment and human behavior. Many were focused on how the architectural and landscape design promote and support social and cultural environment. Little could be found on the influence of microclimate on human behavior. In fact, a comfortable climate is an important prerequisite for outdoor relaxation. Meanwhile, studies also showed that microclimate does affect people's behavior in urban open spaces.

### 2.1.1 Qualitative studies

In 1970's, Whyte (1980) carried out behavioral studies in different urban plazas in New York. He found out that apart from seating, relationship with the street, water, food and triangulation, there is a strong relationship between microclimatic factors, particularly the sun, wind and tree effects, and human behavior in urban plazas. He found out that people tend to sit under the sun in Seagram Plaza (New York) in May which the same pattern did not repeat in June when the environment was warmer. Meanwhile, absence of winds and drafts are as critical as sun as people seek for suntraps. Appropriate planting of trees provides combination of shade and sunlight. Also, it is always cooler under trees.

In fact, numerous downtown corporate plazas, concentrated in city centers, exhibit great variations in usage level and activity type. A city may typically have a small number of such highly patronized spaces but many others have little used or nearly abandoned. Clearly, downtown workers choose from among a variety of alternatives to spend recreational and leisure time. A study conducted by the San Francisco Planning Department in 1983 showed that plaza users in a city walked an average of 70 m from their workplaces. Temperature, wind, and sun and shading conditions explain to some extent the great variations in uses and use levels of such spaces (cited in Zacharias, 2001), but the variation in use has gone largely unmeasured.

Similar study was carried out by Lam and Tsou (2002) for residential open spaces in Hong Kong. With the hot and humid climate in Hong Kong summer, residents tended to stay in areas with shade, breeze and good views which was not quite the same Whyte had experienced in New York. Meanwhile, with residential open spaces surrounded by the high rise residential blocks, there was a very dramatic difference in usage between different areas. Seats with shading devices not necessarily attracted more users as they usually stayed under shade for only a short period of time. High rise building blocks provided much longer shading effects for seats which seats shaded by buildings were more popular. Also, seats near building blocks were less popular as they were subjected to high wind speed due to down drafts. Trees served more for cooling than shading.

Subjective human response to ambient environmental conditions tends to be shared. An early cross-cultural meta-analysis showed that subjective judgments of climatic conditions in indoor environments are remarkably similar across nations and climates even while societal norms of heating and cooling varied considerably (Humphreys, 1976). Designs with sun traps sheltered from the wind are likely to attract people in the "hinge" seasons in temperate climate cities (Arens & Bosselmann, 1989). Also, modest reductions in wind contribute to perceived major increases in outdoor comfort in temperate climates (Tacken, 1989). Such results strongly suggest the existence of shared perceptions with regard to microclimatic conditions in the outdoor environment. How these preferences influence behavior is not yet evident, but this is precisely what cities need to know if they are to do anything about those microclimatic conditions.

For example, humans adapt after a period of exposure to local conditions. For this reason, some researchers suggest that activities are maintained through a wide range of

conditions (Westerberg, 1994). In a field study in New York City, it was observed that usual activities by regular visitors were modified when air temperature descended to 4°C, that is, below the level we normally associate with sedentary activities in public places (Li, 1994). Walking behavior reached local norms in sharply different climatic conditions after a period of days or weeks. Expectations of climatic conditions at particular times of year may result in human adaptation to those conditions rather than an abandonment of outdoor activity altogether. In an environment of multiple space alternatives, adapting may lose out to a walk to a preferred place.

### **2.1.2 Quantitative studies**

Apart from these qualitative studies, Zacharias et al. (2001, 2004), Thorsson, Honjo, Lindberg, Eliasson, Lim, (2004), Katzschner (2002; 2003), Thorsson, Lindqvist, and Lindqvist (2004), Knez and Thorsson (2006) carried out similar studies quantitatively. They attempted to establish causal relationship between microclimate and human behavior in urban spaces.

Zacharias et al. (2001, 2004) studied the number of users and activities for various local climatic conditions in urban spaces in San Francisco. Microclimatic factors concerned include presence of direct sunlight, temperature, humidity and wind speed. Results showed that the measured microclimatic conditions accounted for most variance in activity levels and types, with temperature the most important variable. Though great variation in level of usage cannot be explained solely in terms of microclimatic differences, use with spaces varies chiefly as a function of microclimate. Also, when preferred environmental conditions were in limited supply, users accepted slightly higher levels of crowding in the preferred condition. When a threshold density of persons was reached, users opted for less ideal conditions, moving into the preferred condition when space became available.

Katzschner (2002; 2003) studied the behavior of people in open spaces in dependency of thermal comfort conditions. He carried out interviews and observed the behavior of people in open spaces in parallel with meteorological measurements. Results showed that the behavior of people in open spaces was dominantly affected by solar radiation and wind speed. In general, people prefer moderate warm comfort situation rather than neutral, as this is balanced by clothing. Also, by mapping the spatial distribution of major activities with that of thermal conditions, he found out that people use open spaces search as much as possible for their individual acceptable location and also react on thermal conditions by means of clothing.

Thorsson's study focused on thermal comfort and usage of urban parks. She found out that thermal environment, access and design were important factors in the use of parks. She plotted the number of users against mean radiant temperature (MRT) and found out that there was an increase in the number of users with increasing MRT which proved that

warm and sunny conditions are important factors in the use of the park. When the thermal conditions become too cold or too hot, people improve their comfort conditions by modifying their clothing and by choosing the most supportive thermal opportunities available within the place.

In summary, as Gehl (1987; 1996) stated, climatic factors do influence how many people and events use the public spaces, how long individual activities last, and which activity types can develop. Meanwhile, as people's thermal comfort in outdoor environment is subjected to personal modification and could be affected by psychological aspects (Nikolopoulou et al., 2001; Nikolopoulou and Steemer, 2003), there would be a wider or narrower range of acceptable comfortable conditions than which could be determined by common thermal comfort assessment (Thorsson et al., 2004).

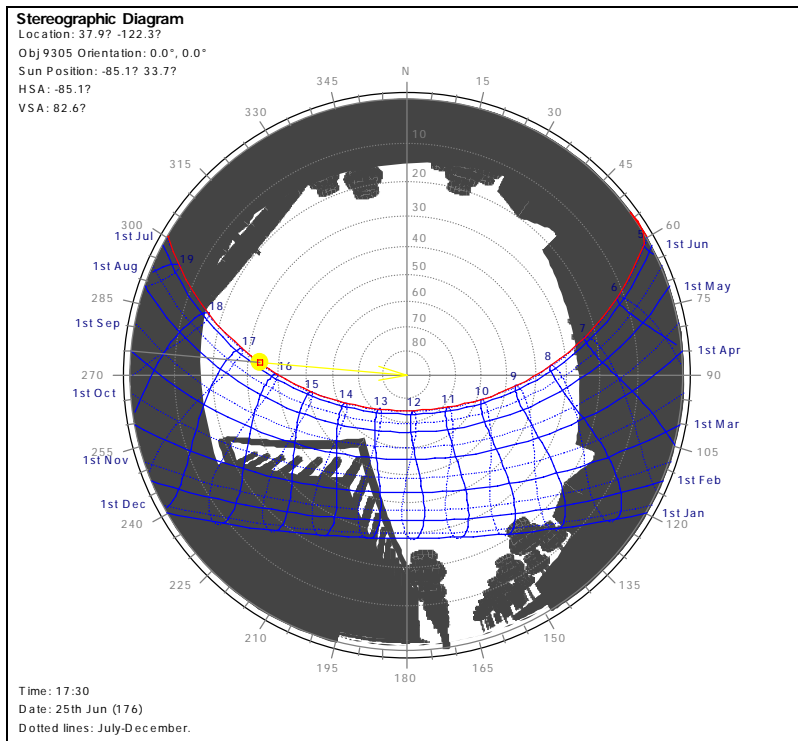
## **2.2 Concern and criteria of microclimatic environment for outdoor behavior**

Despite the fact that there are limited studies focusing on relationship of microclimate and behavior, there are many more studies focused on concerns and criteria microclimatic environment for outdoor behavior, like Arens (1986), ASCE (2004), Arens and Bosselmann (1989) Bosselmann (1983, 1984, 1990a, 1991), Givoni (1998), Givoni et al. (2003), Olgyay (1963) and Tacken (1989) etc.. Though they do not directly associate microclimate with human behavior, they raised the significance for good microclimate to support outdoor behaviors.

The main microclimatic factors in concern are temperature, humidity sunlight and wind. As there can only be little control over outdoor temperature and humidity, focuses were made on sunlight and wind. Direct access of sunlight by means of planning is significant in providing warmth for outdoor activities, particularly for cool seasons. Breeze is preferable in hot seasons while care has to be taken to avoid high wind speeds which impede outdoor activities. This is particularly important for metropolitan areas like San Francisco and Boston where the density and height of buildings significantly block direct sunlight access and change the wind environment on the pedestrian level.

Sun has definite paths throughout the year. The major concern is access to direct sunlight at preferred hours and time of the year. At tropical and subtropical regions, too much radiation in urban space usually is not preferable which contrasts to mild and cool climate further away from the equator where sunlight is essential to provide warmth even in day time. Access to direct sunlight of a place in a year can be determined very easily by *overshadowing* study (Marsh, 2001). That is done by projecting the fish-eye view of neighboring building blocks onto a stereographic sun path diagram (Figure 2.1). Area of

sun path not covered by the projection indicates times when direct access to sun is available. Hence the number of yearly solar access hour could be determined.



**Figure 2.1 Overshadowing image from the center of the Plaza.**

In temperate and cool climates, a required amount of sunlight may be specified in planning codes. This level is often defined as some proportion of the open surface area in sunlight over the course of the day. The fall equinox is normally selected as the day for sunlight calculation, although that particular day may have little to do with sunlight as a factor in human comfort. Sunlight is most desired when temperatures are low and when low temperatures are combined with wind, conditions that may escape the equinox sunlight rule.

Wind, on the other hand, is much more complicated. It does not have definite path and time of occurrence as in the case of sun. Also, urban environment alters natural air flows in ways that can create problems unless care is taken. Also, tall building could deflect wind force downwards, causing an extremely high speed at areas around bottoms of building. On the sides and roofs, eddy flows frequently occur. With more than one building, different effects occur which wind disturbances can become more complicated and severe. The different effects include downwash vortex at the foot of buildings, corner effect, wake effect, gap and channel effect, and shelter effect etc. (Stathopoulos, 1985).

Therefore, instead of descriptively controlling times for wind access as in the case of sun, performance based criteria are more commonly used. Mechanical effects of wind at



different speeds are observed and studied. An example given by Arens (1986) is shown in (Table 2.1). Acceptable wind conditions are usually defined in municipal planning bylaws as some maximum proportion of the number of days in a year when the wind speed exceeds comfort levels defined in wind tunnel tests. The wind tunnel evaluations may not represent the sensations and subjective response individuals have in public spaces and cannot be used to evaluate usual outdoor activities.

**Table 2.1 Mechanical effects of standard equivalent mean wind speed.**

<b>Wind speed (m/s)</b>	<b>Effects observed or deduced</b>
0	Calm, no noticeable wind
1.9	Clothing flaps
3.9	Newspaper reading becomes difficult
5.9	Hair disarranged, dust and paper raised, rain and sleet driven
7.9	Control of walking begins to impaired
9.8	Umbrella used with difficulty
11.8	Blown sideways, inconvenience felt walking into wind, hair blown straight
13.8	Generally impedes progress
15.7	Difficulty with balance in gust
18.7	People blown over in gust
21.6	Cannot stand

Over the years, a number of wind criteria have been developed for assessing pedestrian comfort and safety, based on field observations and wind-tunnel experiments. Several reviews and comparisons of criteria have been published, like Melbourne (1978), Ratcliff and Peterka (1990) and Durgin (2002). Melbourne (1978) considered the different criteria are quite consistent. Ratcliff and Peterka (1990) found sufficient differences to recommend considering several different sets of criteria and then forming a judgment based on overall results. Durgin (2002) focused on optimizing the probability level at which the criteria are set. Below (Table 2.2) is an example of criteria for some basic outdoor activities (ASCE, 2004).

**Table 2.2 Wind speed ranges for basic outdoor activities, based on 20% probability of exceedance<sup>1</sup>.**

Activity	Comfortable range for mean wind speed (m/s)
Uncomfortable for any activity	>5.4
Walking	0-5.4
Standing	0-3.9
Sitting	0-2.6

### **2.3 Assessment of outdoor thermal comfort**

Despite the fact that microclimate significantly affects human behavior, more researchers focused on emphasizing thermal comfort. In some sense, thermal comfort could be considered as a derivative of microclimate.

Assessment of microclimate is usually done individually for each microclimatic factor. For example, assessment of daylighting provision is always separated from assessment of wind force as the methodologies involved are totally different. Also, even the microclimate of the same three dimensional environment is to be assessed, information required for simulating different microclimatic factors is different. Moreover, assessments of different microclimatic factors often generate quantitative results which do not directly associate with human perception. For example, amount of radiation implies different sensation to different people at different localities. It would induce different human perception under different wind speed and humidity. Thermal comfort, on the other hand, is an integrated assessment of microclimate and personal factors by itself. It is defined by ASHRAE as the state of mind that expresses satisfaction with the surrounding environment (ASHRAE Standard 55). It takes into account relative humidity, air temperature, radiant temperature, air velocity, activity and clothing in the assessment. It can therefore reflect the human perception of a combination of various microclimatic factors.

The most commonly used thermal comfort standards models are Predicted Mean Vote (PMV) and Pierce Two Node Model. PMV employs a steady state heat transfer model which is good for application in the indoor environment. The Pierce Two Node Model considers a human as two concentric thermal cylinders, a core cylinder and a thin skin cylinder surrounding it. Clothing and sweat are assumed to be evenly distributed over the skin surface. It then determines the heat flow between the environment, skin and core body areas, using the same thermoregulatory system and controls as described by

---

<sup>1</sup> As wind speed varies, the probability of exceedance is usually specified. 20% probability of exceedance means that an activity is “comfortable” if it stays for 80% of the time or more within the wind speed range stated.

Stolwijk and Hardy (1966). In cold environments, thermal comfort sensation is mainly determined by skin temperature, while in warm environment, skin wettedness is a better indicator. It also considers transient conditions and thus allows the changes in body temperature with exposure time to be evaluated. Therefore, it would be more appropriate to use the Pierce Two Node Model than PMV for outdoor thermal comfort assessment. Though so, many standards for the outdoor environment applied by cities have relied heavily on human responses in indoor settings (ASCE, 2004). There are also other indices developed which combine only climatic components into a single number. For example, operative temperature ( $T_{op}$ ) combines only combines air temperature, mean radiant temperature while new effective temperature ( $ET^*$ ) combines into a single number the effects of air temperature, mean radiant temperature, humidity, and air velocity.

Since all these models were developed based on indoor conditions and simple energy balance models, American Society of Civil Engineers (ASCE) (2004), Arens (1986), Arens, Zhang and Huizenga (2006a, 2006b), Hoppe (2002), Huizenga, Zhang, Arens, and Wang, (2004), Zhang, Huizenga, Nikolopoulou and Steemer (2003), Nikolopoulou, Baker and Steemer (2001), Zacharias, Stathopoulos and Wu (2001, 2004), Scudo (2002) and many have tried to develop more representative models and methodologies which potentially could be used for assessing thermal comfort in outdoor environments.

Huizenga et al. (2001, 2004) focused on modifying algorithms for existing models to better representing the effects of transient state, non-uniform environment and the asymmetrical thermal sensation of the human body. They have developed a model which assesses thermal comfort of 19 parts of the body to determine the overall thermal comfort of an individual. Since thermal comfort is based on thermal comfort of body parts, thermal properties of objects that are in touch with the body, like seating, could be specified. The model also concerns blood flow between body parts as thermal sensation on one body part could affect another. With all the fine details taken into account, the model represents thermal comfort state very close to that of a real person. The draw back is that it is more appropriate to represent a particular individual and not the general response of mass population.

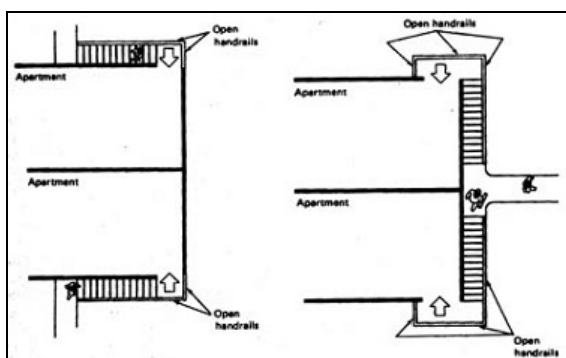
Arens (1986) and ASCE (2004), on the other hand, emphasize on the methodology itself. Besides using the Pierce Two Node Model, attention was also paid to expanding the consideration of other physical factors that would affect comfort. Arens (1989) added wind force at pedestrian level to be assessed in parallel with thermal comfort in the evaluation of outdoor thermal comfort. ASCE (2004) extended the method to include also wind chill in addition to thermal comfort in the evaluation. Meanwhile, thermal comforts for different basic activities (sitting, standing and walking) are assessed separately. Places are categorized into suitable for sitting, standing or walking based on the thermal comfort so assessed.

Though so, all these are based only on measurable, quantifiable physical components. Psychological effects are not taken into account. Thorsson, Lindqvist, and Lindqvist (2004), Nikolopoulou (2001, 2005), Zacharias et al. (2001) and many other have proved

differences between calculated PMV and Actual Sensation Vote (ASV) of users in urban open spaces. Nikolopoulou, and Lykoudis (In press) summarized the difference as due to available choice, environmental stimulation, thermal history, memory effect and expectations. Though so, studies on scientific assessment quantifying the differences could not be found. In fact, Nikolopoulou (2001, 2002) and Zacharias et al. (2001) tried to derive simple equations from multiple regressions obtained from field studies to account for the differences between PMV and ASV.

## 2.4 Design evaluation of and environment - behavior

The built environment is designed for human activities. Steinfield (1992) stated that a successful human response is the essence of successful design and it defines the meaning and value of built form. The satisfaction and well-being of the occupants are critical for the moral justification of the profession of designers. Designers therefore would like to obtain feedback directly or indirectly from users. However, it is not always easy for non-professionals to express specific comments on design. Besides direct comments from users, human spatial behavior could sometimes be a more powerful indirect evaluator of the performance of the designed environment. How people use and behave in the spaces and whether or not a design can meet the needs of the occupants reflect to a great extent the functional quality of design, which is one of the three basic elements of Vitruvius' definition of architecture - *utilitas, venustas, firmitas* (function, form, and structure). Deasy and Lasswell (1985) provided a case study of how architectural design affect users' behavior and why the behavior patterns become a major concern in the design. Figure 2.2 shows two floor plans. On the left, the stairs isolate adjacent tenants while on the right, the stairs bring adjacent tenants together for social interaction. As can be seen, the arrangement of the stairs could promote or discourage social interaction. Designers should therefore make careful adjustment on the design based on tenants' different needs for social interaction.



**Figure 2.2 Left: Centrifugal effect. Adjacent tenants are isolated by the stair locations. Right: Centripetal effect. Adjacent tenants are brought into contact by the stair locations.**

As human spatial behavior could reveal the performance of the designed environment, it is always desirable to accompany evaluation of human spatial behavior with the preliminary design studies. However, human spatial behavior is probably the most difficult aspect of design performance to evaluate and predict before construction. Even the nature of spatial behavior has been widely debated. For example, Skinner (1953) considered human behavior was entirely determined by the environment. Earlier behaviorist Adams Lewin (Lewin, Adams et al., 1935; Lewin, 1936) considered an individual's behavior within a particular setting is determined by continual interaction of inner and outer forces, such as personal needs, values, and attitudes, as well as environmental conditions. Many other behaviorists agreed that cognitive processes are significant in determining the relationships between environment and behavior (Bandura, 1969; Rotter, 1954). Nahemow and Lawton (1973) regarded behavior as a function of the personal elements, environmental elements and the interaction between personal competencies and environmental press. Kaplan and Kaplan (1982) argued that environmental behavior is a function of the actions a person is trying to carry out, the informational patterns of the environment, the person's perception and knowledge of the situation, and internal reflection (Moore, 1987). In brief, human spatial behavior is considered as a complex reveal of an individual's physiological, psychological, physical and social status, and the environment's physical, social and cultural environment. For this reason, the methods designers used so far to evaluate the performance of design in terms of spatial behavior, whether manual or computational, have strict limitations. We will discuss in the following sections the current evaluation methods, their advantages, and their drawbacks at three levels: (a) general design evaluation methods, (b) environmental simulation methods, and (c) more specifically, computer simulations of human environmental behavior, which are directly related to our work.

#### **2.4.1 General design evaluation methods for environmental behavior**

Kalay (2004) categorized the generally used environmental design evaluation in terms of human spatial behavior as follows:

- Norms and regulations
- Case studies and precedents
- Post occupancy evaluation (POE)
- Direct experience behavior simulation
- Indirect experience behavior simulation

### **a. Norms and regulations**

Norms and regulations, in the form of design guidelines and codes, are a convenient way to encapsulate knowledge about human factors in architecture and apply it to new design situations. This approach is relatively easy to implement at an atomic level. However, the need to make tradeoffs between competing factors and the large number of norms that may come into play in any design project makes building evaluation for code compliance a lengthy and difficult process. The generalized nature of rules and regulations can sometimes be misleading because their applicability in the context of a specific design situation depends on the evaluator's interpretation and judgment (e.g. the building inspector). Meanwhile, this kind of normative approach is only effective for improving design quality if the knowledge base used to generate them is accurate and complete. In the case of human spatial behavior, serious questions can be raised about the extent and accuracy of our knowledge (Kalay, 2004).

### **b. Case studies and precedents**

As norms and regulations, case studies and precedents are convenient to use. They provide a rich, empirically validated, anecdotal basis for evaluating human factors that they serve as architecture's most useful sources of design information. Designers can project expected behavioral patterns by comparing the emerging design to similar buildings in similar contexts. However, cases may or may not exist. Even if case exists, the context of case study might differ from the current design physically, socially or cultural, which would provide misleading information. Also, there might be more applicable cases that are outside the designer's sphere of knowledge. Computational case-based reasoning systems were developed to overcome this very deficiency (Zimring et al., 1995).

### **c. Post occupancy evaluation (POE)**

Post occupancy evaluation (POE) is an evaluation of the built environment based on the accumulated experience of occupants who already live, work, play, or study in the environment. It is done by asking the occupants to comment on the design of the environments, or by observations and others research methods. It is therefore the most accurate method of design evaluation as the data collected reflects the real behavioral patterns of the occupants. However, POE is costly in many ways, including legal exposure, client disruption, time and expense (White, 1991). Meanwhile, considered the data comes from built environment, it is often too late and costly for any retrofit design. Therefore, instead of improving the current project, it is more often used to serve as a case base that can be consulted by future projects.

#### **d. Direct experience behavior simulation**

Direct experience behavior simulation employs human beings as a testing apparatus to evaluate the impact of an environment on its inhabitants. Full-scale mock-ups, prototypes or virtual representations (like Virtual Reality) of designs are used so that human subjects could interact with them on a somewhat realistic basis.

This kind of design evaluation is commonly used in cars, model homes, toys, human-computer interfaces, and many other artifacts. The built environment, in most cases, cannot justify full-scale modeling because it often produces one-of-a-kind artifacts whose failure from a human factors point of view may be regrettable but not outright dangerous. Virtual representation like Virtual Reality is also the most difficult approach to evaluate human factors, because it implies the ability to create realistic mockups that encourage suspension of disbelief on the part of the human testers: they must behave as if the environment they visit is the 'real' one (Kalay, 2004).

#### **e. Indirect experience behavior simulation**

Indirect experience behavior simulation involves simulating modeled users in modeled environments. It has advantage over direct experience behavior simulation in the sense that *average* users' response to the environment is provided. Direct experience usually involves only a limited number of people as testers which is hard to avoid personal preferences and judgment. In indirect experience, computer programs are designed to simulate the average users' response based on the general perception and cognitive processes used by humans when confronted by an environment, as well as the judgmental processes they employ (Kalay, 2004).

### **2.4.2 Simulation of environmental behavior**

Environmental behavior simulation can be used in (a) training of environmental design students and professionals, (b) assessment of people's environmental preferences and behavioral patterns, when exposed to alternative environmental configurations, (c) the visualization of complex settings prior to their construction, and (d) the incorporation of simulated settings into the planning and design of new environments or the renovation of existing ones (Stokols, 1993). Whether it is direct or indirect behavior simulation, it involves using models or representations of built environments or events that occur in the environment to assess the level of satisfaction of prospective users of the environments. Such environmental modeling includes the presentation of sketches, scale models, photographs, video and computer-aided presentations, and full-scale mock-ups of planned environments. Among all, computer simulation has proven to be an effective

method in environmental design and evaluation in terms of time, cost and feedback cycles. In the next section, we will focus on computer simulation of environmental behavior as this is the general direction of the study.

## **2.5 Computer simulation of environmental behavior**

Computer simulation can be applied on real-world situations as well as hypothetical situations. It can simulate system performance under all conceivable conditions, It can also study the effect on the process simulated by controlling different parameters. In return, it provides artificial, yet realistic data quickly and in large quantities without having to implement the costly and sometimes not feasible real-world application before the actual construction.

Computer simulation is the most feasible technique to analyze and evaluate a process due to the inappropriateness of laboratory or field test experimentation (Shannon, 1975).

Most current environment computer simulations pay more attention to the visual qualities or physical qualities of built environments, such as lighting, energy use, and thermal comfort, than to human spatial behavior. Human spatial behavior simulations that exist are often limited to some well-defined areas of human activities where there has been considerable empirical research that can help develop the requisite cognitive models (Kalay, 2004). Archea (1977), Glaser and Cavallin-Calanche (1999), and Kaplan & Kaplan (1982), etc, developed general human spatial behavior model using discrete event simulation methods, geometry-based approaches (Glaser and Cavallin-Calanche, 1999), or neural-nets (O'Neill, 1992). Here, we will discuss the approach used in various domains.

### **2.5.1 Pedestrian simulation**

Pedestrian simulation is probably the most common environmental behavior simulation, along with fire egress simulation. Recent pedestrian behavior modeling employs agent-based models, which is based on modeling individual objects, agents, and particles. Some agent-based models are driven by goals, engaging in obstacle avoidance and interaction with other agents. The agents have plans or schedules giving distinct purpose to their trips that drive them to complete some tasks, such as shopping (Haklay, O'Sullivan et al. 2001; Kerridge, Hine et al., 2001). Some other models are derived from various analogies in fluid dynamics and particle systems and also embracing key ideas from the theory of self-organization. All models emphasize the way pedestrians interact with one another and with the environment that they walk in. For example Helbing, Schweitzer et al.



(1997) developed an active walker model, which responds to the environment as it moves around and also alters that same environment as it moves. The general rules these models use are walking rules for interpersonal and obstacle avoidance and shortest path. For example, Helbing, Molnar et al. (2001) used rules of shortest path, an individual desired speed, and keeping certain distance from other pedestrians and borders (Batty, 2001).

### **2.5.2 Crowd and fire egress simulation**

Stahl (1982) and Ozel (1993) developed fire egress models, simulating the behavior in emergency. Ozel' model uses actions (such as "go to exit") and goal modifiers (such as "alarm sounds") libraries to define the behavior rules. These libraries, in turn, use the fire event, the building configuration, and the characteristics of the people as the determinants of their rules. As in pedestrian simulation, crowd and fire egress simulation aims at testing level of services like if there is sufficient passage width for pedestrian movement, or if particular signs are effective in the way finding process etc.

### **2.5.3 Urban microclimate simulation**

All of the studies mentioned did not take into account the consideration of microclimatic factors. In fact, it is possible to predict human behavior with microclimate. Bruse (2002, 2003, 2005a, 2005b) designed a system using virtual users to assess the urban microclimate. With changes in the urban environment, like changes in building height and density, the microclimatic environment is changed and users will show different behavior. For example, people would choose paths where they could avoid strong airflow. The embedded hypothesis is that users will find a thermally comfortable path or a thermally comfortable place to stay. The densities of agents in different areas then reveal the quality of the microclimatic environment. Since the focus lied in microclimate assessment, the algorithm of agent movement is based on resistance which walkable areas and thermal states closer to the comfortable state would have lower resistance. The predicted behavior is totally driven by the resistance accounted by the individual. Since the composition of resistance is very simple and does not take into account the interactions between agents and the environment and between individual agents, it is difficult to represent the reality. Though so, the concept of quantitatively representing the impact of microclimatic factors worths notice.

## **2.5.4 Urban space simulation**

Based on Steinfeld (1992) and Irazábal (1994)'s proposals toward an artificial or virtual user, Yan (2005) developed an urban computational model that simulates a built environment, its occupants and their behavior. It consists of a usability-based building model and an agent-based user model. The building model is a computer model that represents the building objects. Usability –attributes that can support the inference of human spatial behavior are embedded in the building model. The agent-based user model is autonomous model. It applies behavioral rules to each individual to simulate both individual and group pattern of user behavior including encountering, congregating, avoiding, interacting, etc. The behavioral rules are derived from literature of human spatial behavior, field study, and Artificial Life research. By comparing the simulation results with the field data collected, the simulation emulates fairly well the interactions between individual users, groups of users and the environment. For example, there are reasonable interpersonal distances between individual users, users in a group would move together and have focal point during meeting, users would use shortcuts, make use of architectural features as seating, etc.

## **2.6 Influences of the studies on the research**

### **2.6.1 Criteria employed – independent variables**

Different microclimatic factors affect human behavior in an indirect way. They first affect individuals' comfort state which people would react to it in terms of behavior. Also, combinations of different microclimatic conditions might induce same or different comfort state. Therefore, it is essential to include both individual microclimatic factors and comfort state in the simulation process to complete the model. In general, the comfort state can be derived from thermal comfort which is determined by microclimatic conditions, clothing and activity of the user.

Since the simulation is to target outdoor urban spaces, it is essential that the comfort model used to be appropriate for outdoor application. The model that raised by Arens (1986) and ASCE (2004) would be a suitable one. It assesses the outdoor comfort by three major factors, the Pierce Two Node Model, wind force at pedestrian level and wind chill. Also, thermal comforts for different basic activities (sitting, standing and walking) are assessed separately. In this case, a simple, yet representative reference would help formulate the behavior of the agents.

## 2.6.2 Criteria employed – dependent variables

Based on study of Zacharias, Stathopoulos and Wu (2001, 2004), Thorsson, Lindqvist, and Lindqvist (2004), Knez and Thorsson (2006), Bruse (2002, 2003, 2005a, 2005b) and Katzschner (2003) microclimate has three major impacts on the use of urban plazas:

- Presence level, i.e. number of users
- Location or path preference
- Duration of activity

### a. Presence level

Warm and sunny conditions are important factors in the use of urban spaces (Whyte 1980). Thorsson (2004) measured the absolute number of people present in the urban space studied along with mean radiant temperature ( $T_{MRT}$ ). Even though large variations existed, an increase in the number of people was observed with increasing  $T_{MRT}$ .

Zacharias, Stathopoulos and Wu (2001) had a similar conclusion. Microclimatic factors, with temperature being the most important, affects strongly in the daily, free use of downtown public spaces. Also, there was lower and upper bounds on presence level as a function of temperature. Although rising temperature had a positive effect on presence, such presence peaked at a moderately warm temperature, thereafter decreased significantly.

### b. Location or path preference

A thermally comfortable location is preferred for those intended to expose in urban spaces for a period of time. Microclimatic conditions could have great variations across different areas of urban spaces (ASCE, 2004). A standing position is likely to be more exposed to the cooling effect of wind, whereas seating may be designed to be a suntrap, both of which may compensate for the cooling effects of low temperatures and wind. Different activities generate different amount of energy as well. Standing generates more energy than sitting, so that one feels warmer when the ambient temperature is well below body temperature. Combining with different dressing, there could be great variation in thermal comfort across urban spaces for different activities (Katzschner, Lutz; Bosch, Ulrike; Rottgen, Mathias, 2002). Therefore, under different microclimatic conditions, there could be great variations in users' location and path preferences. Whyte (1980) showed concentration of users under sunlight in New York in May. Zacharias, Stathopoulos and Wu (2001)'s study showed that there is a tendency for people to move into the shade, or out of direct sunlight at higher temperature ( $>20^{\circ}\text{C}$ ). Thorsson,

Lindqvist, and Lindqvist (2004) had a similar study which the presence of sunlight contributes to the flight of people from public spaces at higher temperatures.

### **c. Duration of activity**

When the thermal environment becomes too hot or too cold for comfort, people improve their level of comfort, either consciously or unconsciously, by modifying their clothing. Another way to avoid discomfort is to change patterns of behavior by choosing the most supportive thermal environment opportunities available within the area. The duration for one activity is then associated with rate of change of thermal comfort level and the deviation from the expected thermal range of the user. For example, one might expect to feel warm when exposed to the sun. There is a range of warmth which the subject would tolerate. When the exposure time is long enough, the thermal comfort level would exceed the expected range of the user, i.e. becoming too hot. The faster the rate of getting warmer and the narrower expected thermal comfort range the shorter the duration of the activity.

### **2.6.3 Criteria employed - behavior**

According to Gehl (1996), activities in city plazas can be classified into three types:

1. Necessary activities: going to school or work.
2. Optional activities: resting, enjoying, these activities are especially dependent on physical configuration of environments.
3. Social activities.

These activities could be classified by goals (Yan 2005) which can be categorized into 4 groups:

1. To rest: sunbathing, eating and people watching etc.
2. To play: performing, dancing and gaming etc.
3. To gather: waiting and talking
4. To pass by: going to other places

To further characterize different types of activities, activities could be considered as composing of various primary activities. Primary activities are activities associated with individual which could be identified visually. Also, they do not associate with any social or cultural meanings. Sitting, standing, walking, running, lying down and cycling are

examples of primary activities. Two people chatting on a bench are considered as two sitting activities in close distance. The social component chatting is represented by distance between the two individuals. A person going to rest in a plaza can be expressed as a series of primary activities in the sequence of walking, sitting and walking. The association of various types of activities with primary activities is described as below:

- Sunbathing: standing, sitting, lying down
- Eating: standing, sitting
- People watching: standing, sitting
- Performing: standing, sitting
- Gaming: standing, walking
- Waiting: standing, sitting
- Talking: standing, sitting, walking
- Passing by: walking, running, cycling

Based on the study of Gehl (1996), Whyte (1980), Yan (2005), sitting, standing and walking are dominant primary activities found in urban plazas. Therefore, in this study, these three types of primary activities would be the main focus, particularly in defining rules governing different types of activities.

#### **2.6.4 Simulation approach**

To simulate effects of microclimate on human behavior in urban spaces, one possible approach is to modify appropriate existing simulation models. A model as such involves lots of components, like environment modeling, microclimatic assessment, behavioral modeling, simulation engine, and visualization engines etc. Making use of existing models would be more economical and sensible in terms of time and resources than starting from scratch. Also, validated models have the advantage of reducing possible flaws in the development process. In this case, the Bruse model and the Yan model would serve as a good base to start.

Bruse' model relies on resistance instead of having a well developed set of behavioral rules in terms of algorithm. The resistance does not take into account social factors which

agents' behaviors would deviate from reality. For example, there is no group behavior and the agents would generally pick the close and thermally comfortable seats which in reality people might look for a people watching spot or a place good for chatting (Gehl, 1987). Meanwhile, Bruse used PMV model to derive the thermal condition. As mentioned, PMV employs a steady state heat transfer model which is more appropriate to use in indoor environment than outdoor environment. Therefore, in using Bruse' model, not only the resistance algorithm, but also the thermal comfort model have to be modified.

Yan's model basically determines behavior based on the qualitative aspects of a designed environment. It uses well studied behavioral rules as algorithms for human behavior in the urban environment, but it has no time and microclimatic components. That is, the behavioral pattern would only change with changes in the building model, not with time or other factors. Therefore, an environmental component has to be included. It should be able to incorporate microclimatic and thermal information, and provide quantitative measures of microclimatic impacts on human behavior. It is also essential to include time and seasonal factors to determine the qualitative changes in behavior. For example,

- Transition in a day would have different number of users; hence induce different usage patterns, including pedestrian traffic, route preferences, seating preferences and standing preferences.
- Seasonal changes including temperature, sun/ shade provision and clothing level will affect users' seating choices and activity preferences.

To assess the impacts of time and seasonal factors, it is then possible to use multiple regression and correlation to find out the impact for each microclimatic factor, as in Zacharias et al. (2001, 2004) and Thorsson's (2006) study. In this case, a thorough model which could demonstrate moving behavior, social behavior and microclimatic influence is resulted which could be used to simulate human behavior in urban spaces.

In this study, Yan's model will be modified as it is more comprehensive, comparing with Bruse's model. The methods of this simulation are described in the following chapters.

## Chapter 3

# Urban Spatial Behavior

To establish causal relationship between microclimate and behavior, and to ensure correspondence of the simulation to reality, the simulation is based on a large amount of quantitative, real-world behavioral data. The real-world behavioral data was collected to obtain important statistical measurements about behavioral patterns in urban spaces. The relationship between microclimatic conditions and human presence and activity is investigated. Aggregate behaviors in public open spaces are related to measured local climatic conditions. Public space users are mapped with their respective locations and activities in the open space. These measurements can be used generally to evaluate existing microclimatic environments in terms of human spatial behavior, and specifically, to model the behavior of our virtual users. The data is also served for validation purpose.

### 3.1 Urban setting – the Sproul Plaza

To study the impact of microclimate on human behavior, the Sproul Plaza in the campus of the University of California at Berkeley is used for a few reasons:

It has basic design elements as described in the research of William Whyte's *Social Life in Small Urban Space* (Whyte, 1980) and Jan Gehl's *Life between Buildings* (Gehl, 1987). It has primary seating (benches) and secondary seating (steps), water, sun, vending, trees and surrounding buildings to support various kinds of urban spatial behaviors.

The users' composition is simple. Most users are students aged between eighteen to thirty (Marcus and Wischemann, 1990). The majority of presence is associated with the campus environment. This simplifies the simulation.

It has been studied intensively by researchers, such as Marcus and Wischemann (1990), and through graduate student projects in classes (e.g. Environmental Research Methods and Computer Vision).

The simulation model uses Yan's model as a base. Yan used the Sproul Plaza in his simulation model and the model has been validated. This will simplify the work as

further calibration and validation would only concern the introduced environmental model.

### **3.1.1 The physical environment**

Sproul Plaza is a major student activity location at the University of California, Berkeley. It is divided into the upper Sproul and lower Sproul. They are separated by a set of stairs. In this study, we will mainly focus the center of the upper Sproul Plaza. For easy communication, it is referred to as Sproul Plaza later in the writing.

The upper Sproul Plaza is characterized by a fountain in the center (Figure 3.1). It is one of the major landmarks in the campus. It is also a popular meeting place in the campus for its prominent location and form.



**Figure 3.1 The upper Sproul Plaza in the morning.**

On the east of the upper Sproul Plaza is the Sproul Hall, which was formerly the campus administration office, and is today the student and admission services. Sproul Hall is situated on a rise above upper Sproul Plaza and features a broad, terraced stairway leading to the entrance, with lawns located on the sides. The terraced stairway and the ready audience make the upper Sproul Plaza a popular location for student protest. Sometimes, different interest groups in Berkeley will also perform at the stairway. The lawns are also popular staying area for users in the Plaza.

To the north is Sather Gate, which leads into the central campus. The Golden Bear café at the Cesar Chavez Student Center is next to the Sather Gate and attracts lots of people, particularly around lunch period.



To the south is Telegraph Avenue where there are lots of commercial activities and bus lines. During the day, large numbers of students walk through the Plaza on the way to class or on the way to Telegraph Avenue. The Martin Luther King Student Union on the South Campus area has board stairs and columns on its ground level which make it a popular sitting and meeting place. The ground floor of the Student Union hosts the Cal Bookstore run by the Associated Students of UC Berkeley (ASUC). Therefore, the Student Union is also referred to as ASUC later in the writing.

The Plaza also features a double row of the pollarded London Plane trees on the south and on the north which is characteristic to the Berkeley campus. In the day time, numerous student groups set up tables along the tree rows to recruit and advertise other students.

### 3.1.2 The microclimatic environment

Generally, Berkeley has a cool-summer Mediterranean climate. It is like spring all year round. With the cool breeze from the Pacific, summer day is usually around 20 °C (Figure 3.2). In a year, the temperature would be over 30 °C for only about a week when there is strong wind from the inland. It has apparent diurnal change, ranges from 6 to more than 15 °C. The dry period of May to October is mild to warm, with average high temperatures of 18 - 22 °C and lows of 11- 13 °C. The rainy period of November to April is cool with high temperatures of 13 - 18 °C and lows of 7 - 9 °C. In general, The most precipitation on average occurs in January (Figure 3.3). Snow is extraordinarily rare. Humidity is mild throughout the year, and it is with relatively more humid in summer (Figure 3.4).

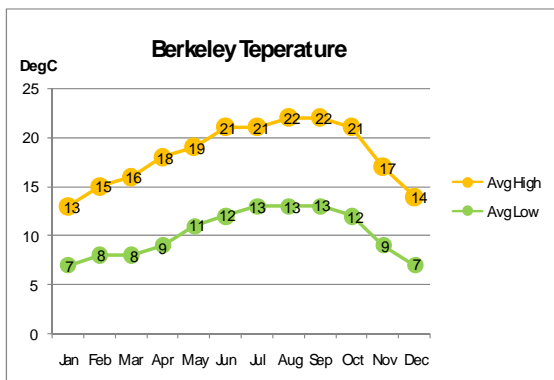


Figure 3.2 Berkeley temperature<sup>2</sup>

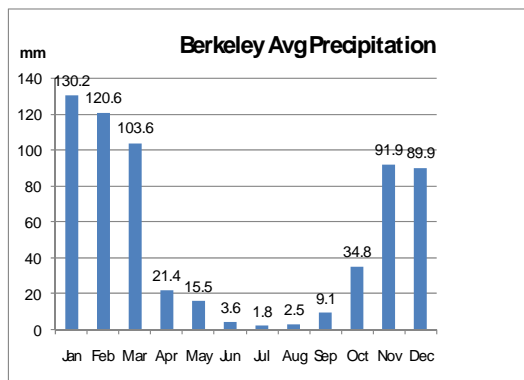
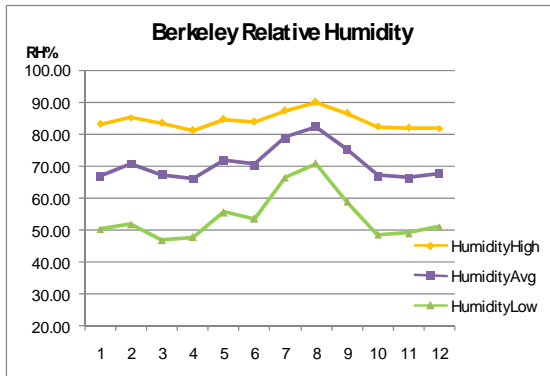


Figure 3.3 Berkeley precipitation<sup>3</sup>

<sup>2</sup> From <http://www.weather.com>

<sup>3</sup> From <http://www.weather.com>



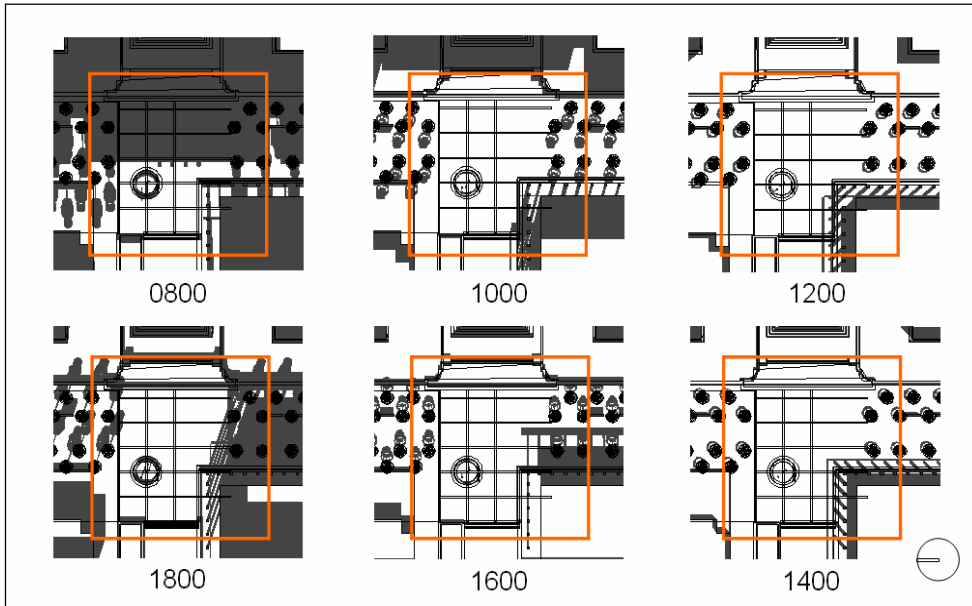
**Figure 3.4 Berkeley relative humidity<sup>4</sup>.**

The effect of overshadowing on the Sproul Plaza is mainly affected by the Sproul Hall on the east and the ASUC on the southwest. In the morning, the Plaza is shaded by the Sproul Hall. It gets more exposed to the sun approaching to noon. While the shading effect of Sproul Hall is reducing later in the day, the shadow of the ASUC is gaining influence of on the Plaza. The impact of the building shadows depends on the sun angle of the day.

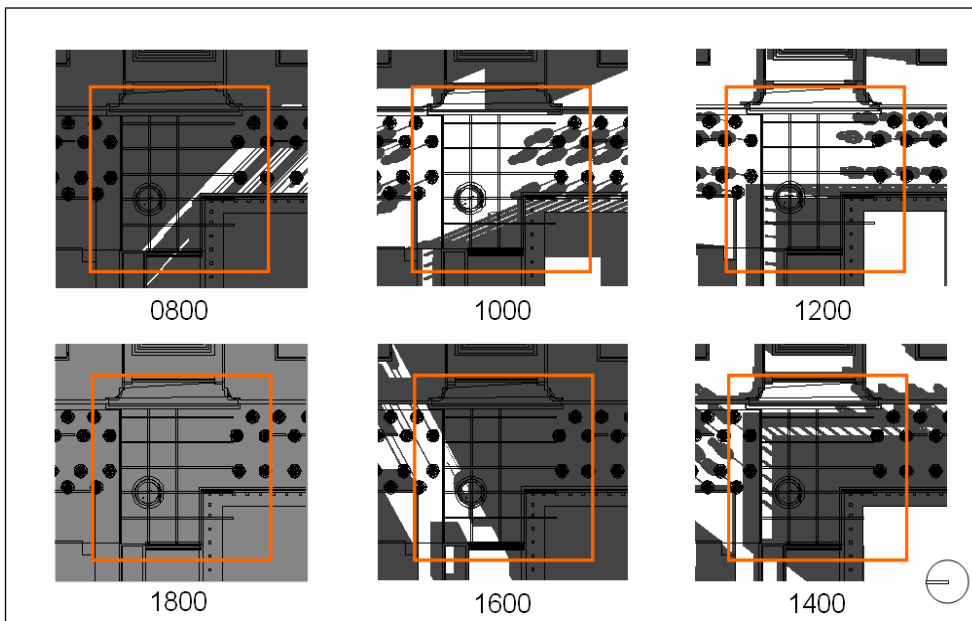
On summer solstice when daylight is the longest (Figure 3.5), the Plaza is not shaded much throughout the day, except in the morning. Most of the seating is exposed to the sun in day time. The solar hour at the center of the Plaza can be up to 9 hours. The east stairs on the ground floor of the ASUC and the areas under the trees are the major shaded areas in the Plaza in the afternoon. On winter solstice (Figure 3.6), with the much lower sun angle, the Plaza has much different shading condition throughout the day. The Sproul Hall shadow does not leave the Plaza fully exposed until around 9:30 in the morning. Not long after the shading effect of the Sproul Hall is disappearing, the shadow of the ASUC starts influencing the Plaza. This Plaza is never fully exposed to the sun on this day. It is fully shaded by the MLK Student Union at around 2 o'clock in the afternoon, though its effect gradually reduced with time. At the center of the Plaza, the solar hour could be as little as 2.5 hours.

---

<sup>4</sup> From <http://www.wunderground.com>



**Figure 3.5 Overshadowing at Jun 21 (Summer Solstice)**



**Figure 3.6 Overshadowing at Dec 21 (Winter Solstice)**

From the wind rose at the San Francisco Airport (SFO) (Figure 3.7), it can be seen that the prevailing wind direction is west-northwest. Stronger winds always come from this direction. Weaker winds have more varied directions. In general, the west-northwest prevailing wind direction is more apparent in spring and summer. In autumn and winter, more wind come from the mainland which make the effect less apparent.

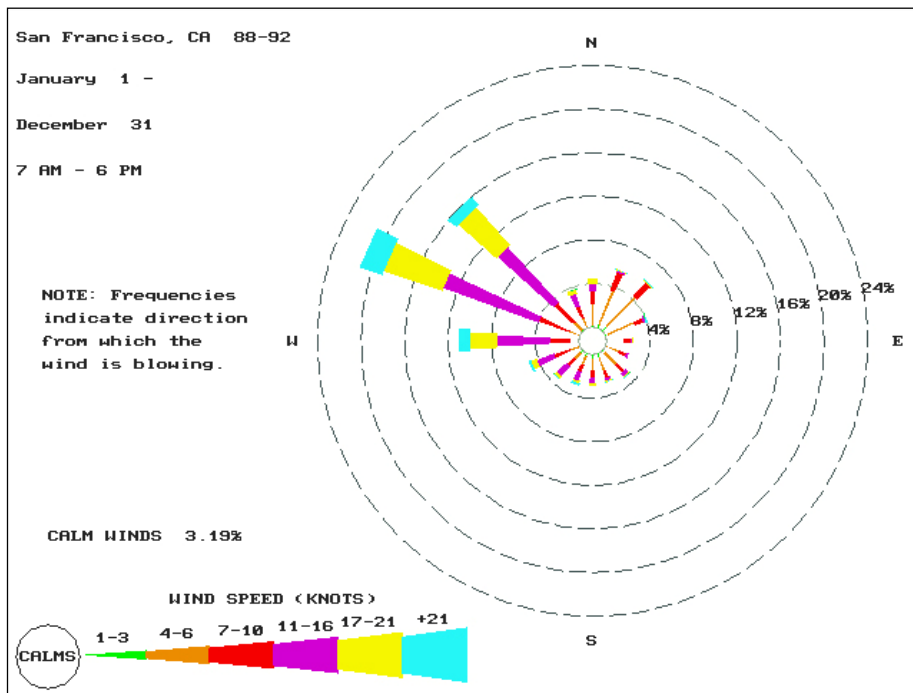


Figure 3.7 Wind rose at SFO, prepared by Pacific Environmental Services, Inc.

In Berkeley, the wind direction is mainly from the west (the sea side) through March to November while wind direction is more varied in other months (Figure 3.8). During May to October when there is steadier sea breeze, wind speed is steadier and is around 4.47m/s (10 mph). In other months, there is greater variation in wind speed, from 0 to 11.18 m/s (0-25 mph).

At the Sproul Plaza, the wind environment is generally calm at the pedestrian level, usually within 2 to 3 m/s. No extreme wind condition was identified at the Plaza area. This is probably due to the uphill topography of the campus and the configuration of the campus buildings which wind environment at the pedestrian level is protected.

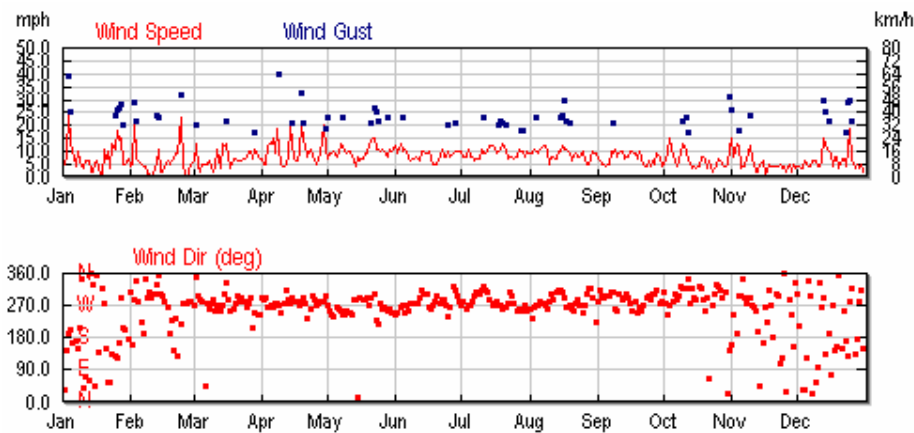


Figure 3.8 Wind speed and wind direction at Berkeley. (Source: [www.wunderground.com](http://www.wunderground.com))

## **3.2 Field study**

To obtain people's spatial preferences with respect to the microclimatic conditions, a field study, including video recording and questionnaire, was carried out at the Sproul Plaza in a year round period. The video recording was to construct behavioral mapping of the Plaza. The long term study will provide adequate observations to reveal significant information about people's spatial preferences (Miles et al., 1978). The questionnaire was to obtain the usage preference and the thermal sensation of the users in the public space under the microclimatic conditions so exposed.

### **3.2.1 Questionnaire**

The questionnaire is to obtain the usage preference and the asked sensation votes of the users in the public space under the microclimatic conditions so exposed. For this reason, in parallel to the questionnaire, meteorological data was recorded. A handheld Hobo data logger recorded temperature and relative humidity; and a wind speed meter recorded wind speed at the location of the interviewee. Whether the interviewee was exposed to the sun or shade of any kind is also recorded. A sample of the questionnaire is attached in Appendix 1.

### **3.2.2 Video recording**

The video recording was taken from the Office of Grad Div-Communications & Events which is located at the 325 Sproul Hall. Alongside with the video record, meteorological data was also recorded. A handheld Hobo data logger recorded temperature and relative humidity at 1-minute intervals (Figure 3.9). Wind speed and direction were obtained from the weather station situated on the top of 2111 Bancroft Street in Downtown Berkeley. Data was collected at 15-minute, 60 minute, and 24-hour intervals.



**Figure 3.9 Recording setup.** A digital video camera is connected to a laptop and a Hobo data logger (at the window) collects temperature and relative humidity.

In the study, it is intended to get the number of different types of users and the distribution of users under different time of the day and different microclimatic conditions. The measurements help us get a quantitative assessment of many generally believed qualitative design rules. The major measurements interested in are listed below:

How many people in the Plaza at different time of the day? This is an indicator of the level of service of the Plaza – how many people were using the space.

What is the probability that a user who entered the Plaza would sit, stand, walk through it or do other things under different microclimatic conditions? At different time of the day, the different locations have different microclimatic conditions, like shaded or exposed to the sun, with mild or no wind. A user's objective and preference would be his/ her property of the user model that will affect a user's decision of what to do in the Plaza.

How many people came to sit by the plaza fountain, on the steps, or on the benches, respectively, under different microclimatic conditions? The spatial distribution would indicate which area or type of place would be more preferred by users. Hence, help architects to evaluate the success of the design.

How long did each person sit in a place and what is the distribution of their time of stay? In general, it is assumed that under good weather, more people would prolong the time of stay to get more pleasure.

### **3.2.3 Surveyed dates**

The plaza was surveyed systematically from morning (before 9am) till evening (around 5:30pm). Each survey session consists of two week days during the months with academic schedules. Records on rainy days were discarded as the data might be misleading, for example, the umbrellas used might affect the head count of the record. The survey days chosen were either Tuesday or Thursday as class schedules on these two days were generally based on 1.5 hour multiples, with morning classes start on 8:00am.

Class schedules on Mondays, Wednesdays and Fridays had much variance in class schedules which would increase the complexity of the data. The survey days were selected so as to represent samples over a temperature range and sky condition representing the academic period. The surveyed dates were Sept 4, Sept 9, Oct 9, Oct 14, Oct 16, Nov 18, Nov 20 in 2008; and Feb 3, Feb 5, Apr 28, Apr 30 in 2009. Due to the weather issue and sky coverage, not all data from the survey days were used. The major data used were from Sept 4, Sept 9, Oct 9, Oct 14, Nov 18, Nov 20 in 2008; and Feb 3, Apr 28, Apr 30 in 2009. The relationship of the sun paths of these surveyed dates with the sky coverage of the academic period of 2008-09 is illustrated in Figure 3.10.

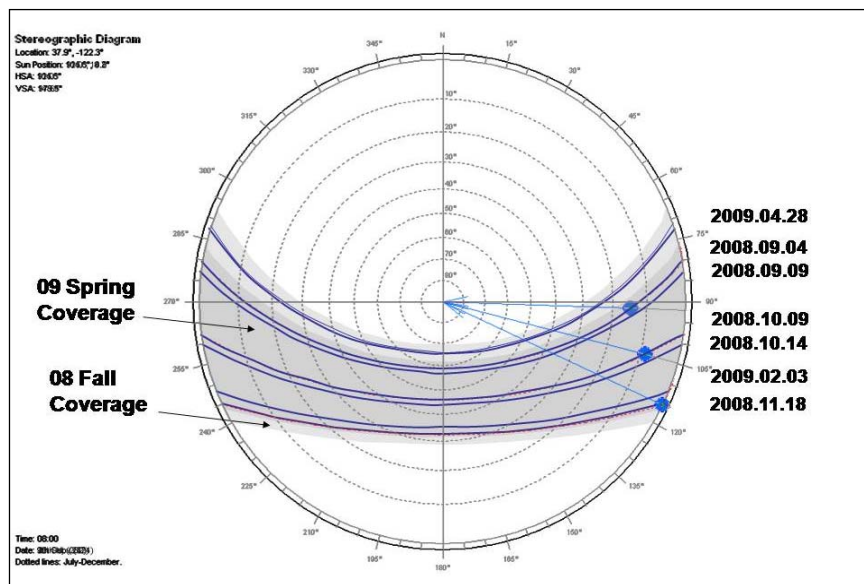
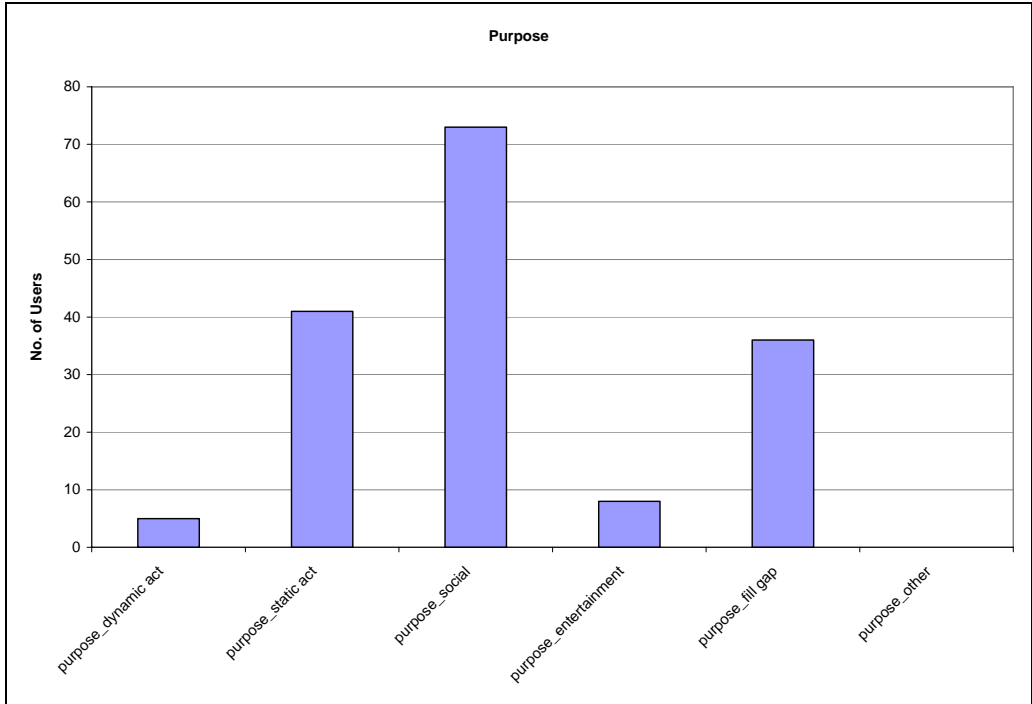


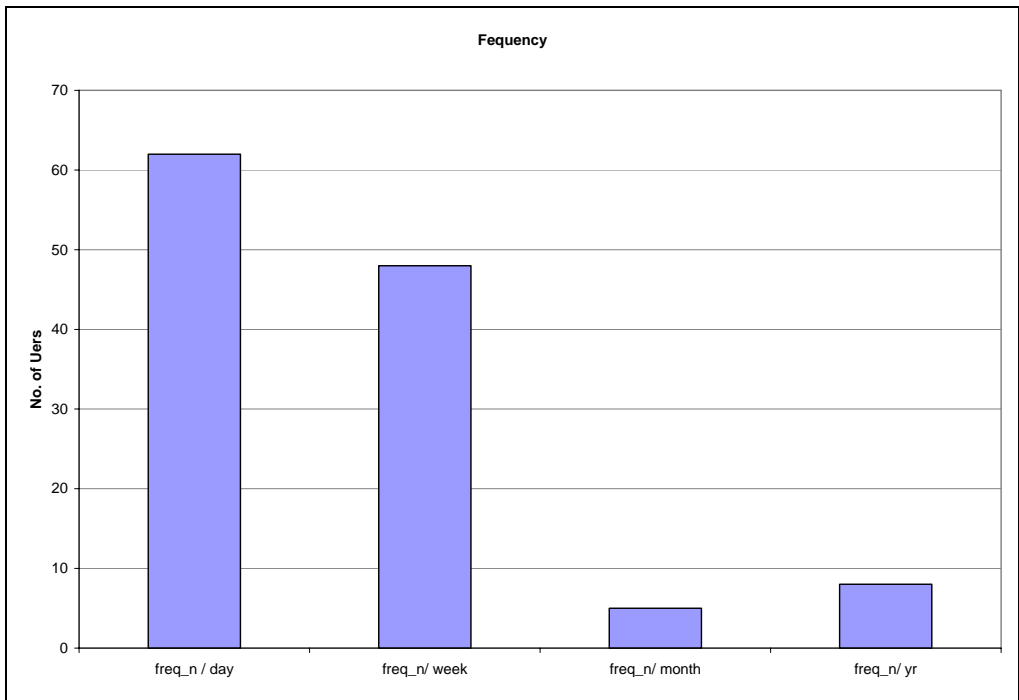
Figure 3.10 Sun paths of the survey days (lines) in the academic period (shaded area).

### 3.3 The usage pattern

The Plaza is a linear design creating promenade for students who walk between the south side of campus, where most dormitories and other student housing is located, and the heart of campus which hosts the libraries and classroom buildings. It makes many people think it is simply a pedestrian thoroughfare, except when some events happen occasionally and turn the plaza into a crowd-gathering place. In fact, it is quite different from what many people think about the plaza. Figure 3.11 shows that most of the users use the Plaza as a social place. Static activities and filling gap are also common purposes for users while dynamic activities and entertainment are less common purposes. Meanwhile, it is used on a daily or weekly basis by many people (Figure 3.12). This suggests the plaza is, indeed, a good public space, and attracts many people to come, stop, sit and look around.



**Figure 3.11 Purpose of usage from questionnaire.**

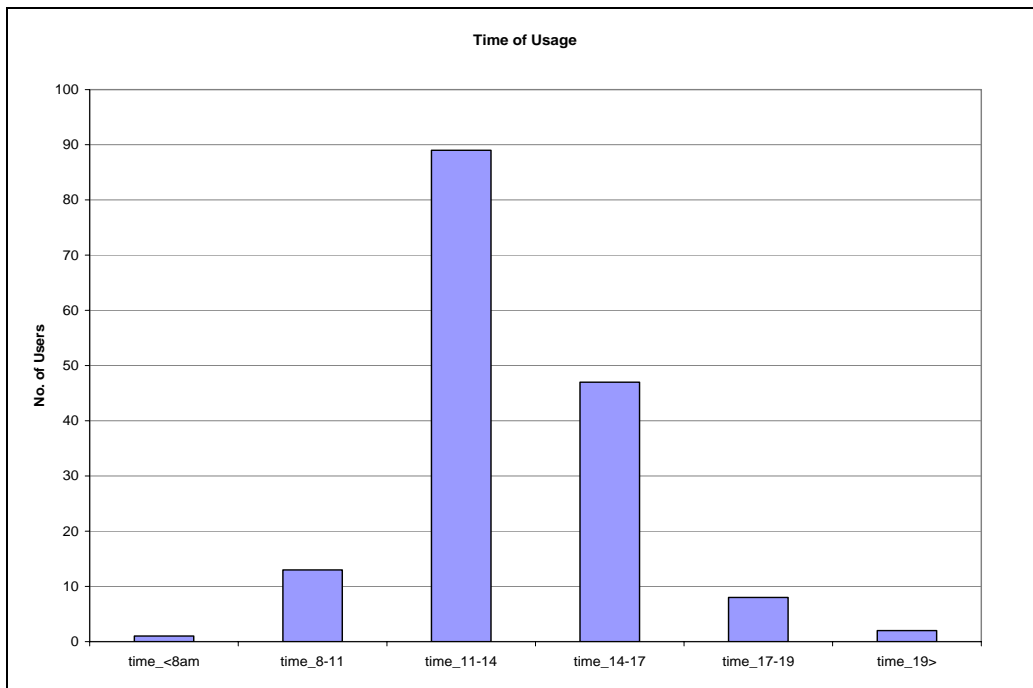


**Figure 3.12 Frequency of usage of interviewees.**



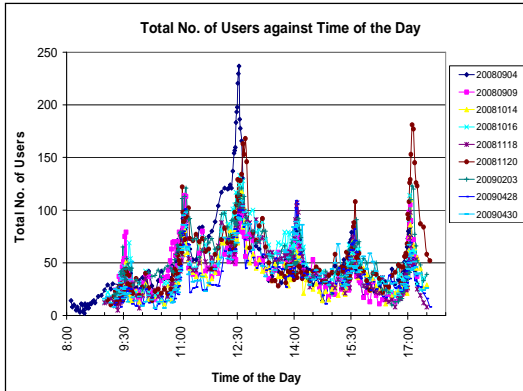
### 3.3.1 Number of users and time of usage

From the questionnaire, majority of the users use the Plaza around lunch period and early afternoon (Figure 3.13). Much fewer users use the Plaza in the morning and late afternoon. Limited number of users would use the Plaza in the early morning and in the evening. This matches with the results from the video record.

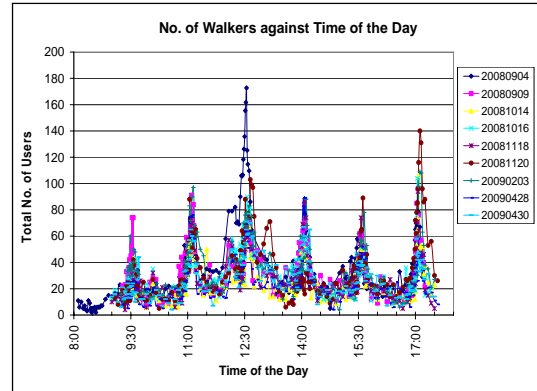


**Figure 3.13 Time of usage from questionnaire.**

Figure 3.14 to Figure 3.17 show the number of various types of users at different time of the day from the video record. The number of users rose up and down throughout the day (Figure 3.14). In a day, though not very apparent, it can be seen that there were peaks around the class time. The peaks at class time were more apparent when the different survey day data were overlaid. The peak was highest at around 12:30, then 17:00, then 11:00. 14:00 and 15:30 had closer peaks and the peak at 9:30 was the lowest.



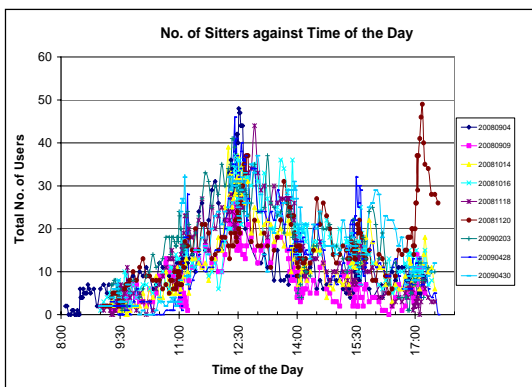
**Figure 3.14** Number of users on the surveyed days.



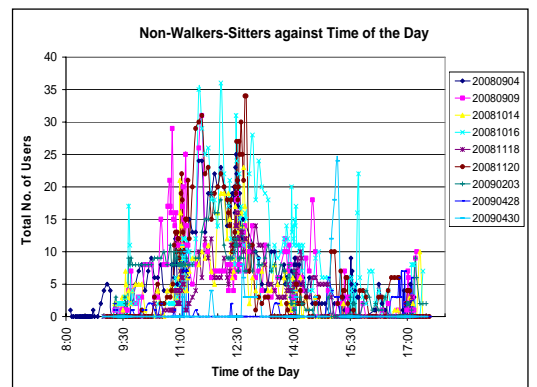
**Figure 3.15** Number of walkers on the surveyed days.

The number of walkers shares similar pattern as that of the total number of users, as the majority of users was walkers (Figure 3.15). Most of the walkers were students going to classes or finishing classes which caused the peaks at the class times. The peak at 12:30 pm was highest as there were also a lot of people going through the Plaza for lunch. The peak at 5:00 pm was mainly caused by students leaving the campus as most of the users captured were approaching the Telegraph Avenue. Note that the peaks in fact occurred slightly after the class times as students left and traveled for the next class.

The number of sitters throughout the day did not have multiple peaks as that for walkers. The number of sitters was low in the morning and generally rose up to peak at around 12:30 pm when there was a lot of people having lunch and meeting in the plaza (Figure 3.16). The number of sitters decreased gradually in the afternoon when there were more students meeting in the Plaza between classes. The abnormal peak at 5:00 pm on Nov 20, 2009 was due to an evening event (a speech) in the Plaza.



**Figure 3.16** Number of sitters on the surveyed days.



**Figure 3.17** Number of non-walkers-sitters on the surveyed days.

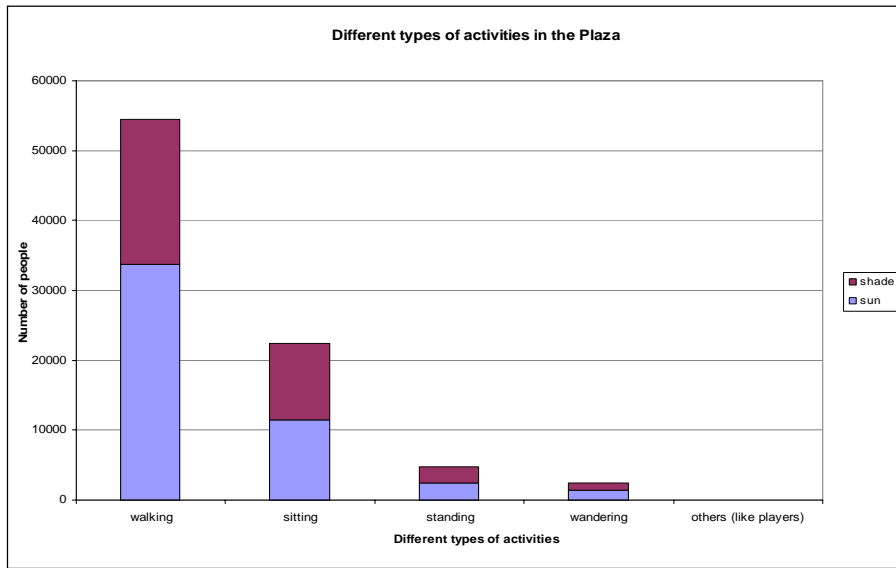
Non-walkers-sitters include those who stood, wandered, cycled or played in the Plaza (Figure 3.17). The number of standers was generally greater when there were more people in the Plaza. People stood when there were fewer places to sit, met others on their ways or talked to seated people which standing would provide better face to face communication. Wanderers were mainly student groups working at promotion counters in the Plaza. They walked around in the Plaza to give out flyers or did other promotional work. They were usually active around lunch hours when there were more people. There were less people as the semester approaching to the end. People cycled usually do not stay in the Plaza for long. Some might stopped in front of the cafeteria, but most of them were just passing-by. There were not many players in the Plaza during the observed period. The only players observed were few people playing skateboards and balls in the afternoon when there were fewer people in the Plaza. The Plaza was more spacious in this period where players could have greater enjoyment and less impact to other users in the Plaza.

For these reasons, the number of non-walkers-sitters through time does not have clear pattern as those for walkers and sitters. Roughly, it can be seen that there was a peak around 12:00 noon when there were more people in the Plaza.

### **3.3.2 Activity types of users**

Types of activities of users were simply differentiated into primary activities of walking, sitting, standing and wandering. There were also a small proportion of users cycling, running or playing in the Plaza.

The majority of activity was walking, around 65% (Figure 3.18). This is probably because the Plaza is a main entry to the campus and it connects various academic and administrative buildings, canteens and some other campus facilities. It is therefore a major passage for many users leaving or entering the Campus. Around 27% of users were sitters. The Plaza has many features, like fountain, stairs with wide treads, lawn and seats, which provide good sitting places for users. Sometimes, there could be so many users that one might not be able to find a seat in the Plaza. People standing, wandering or having other activities in the Plaza accounts for less than 10%. As mentioned, there were more people standing and wandering when there were more users in the Plaza. Only an insignificant proportion of users would carry out other types of activities.

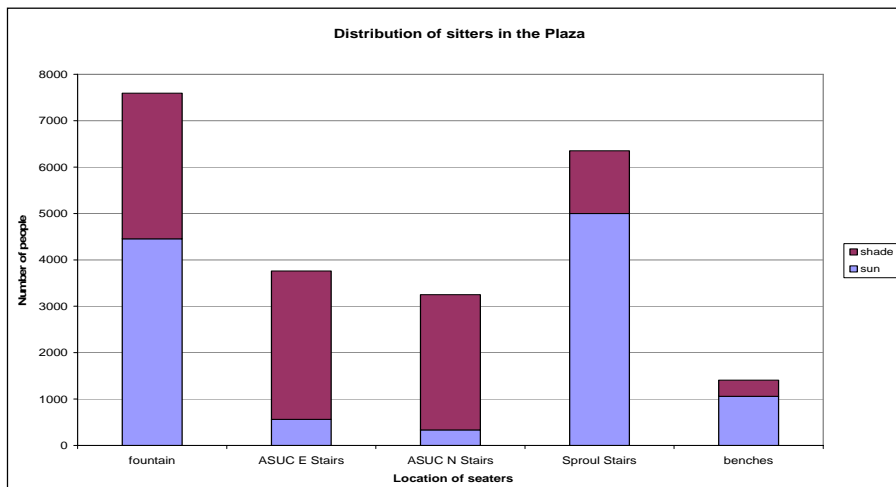


**Figure 3.18** Number of users of different types of activity in the Plaza.

### 3.3.3 Distribution of users

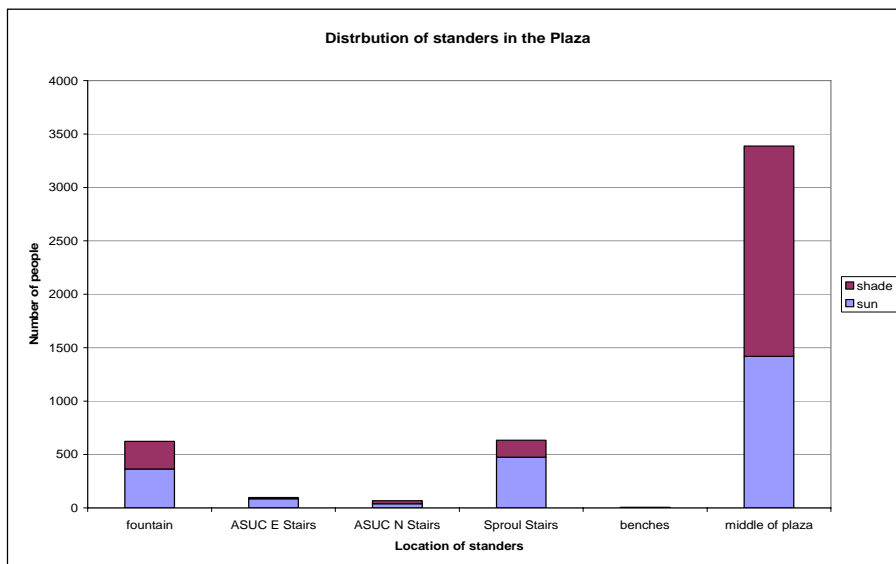
Distribution of walkers is more depending on time. In the morning, more walkers traveled from south to different buildings in the north. This was reversed in the late afternoon when people left the campus. In the afternoon, the distribution of walkers was more even from every direction. People traveled through the Plaza to different parts of the campus as well as outside the campus. That is, the distribution was mainly due to the distribution of facilities around the Plaza.

Consider people sitting (Figure 3.19), the majority of people preferred sitting at the fountain and the stairs in front of the Sproul Hall and the ASUC. Comparatively, much fewer people sat at the benches. The secondary seating, particularly the fountain, is more attractive to people who want to sit. It attracts people to linger in the Plaza space and encourages social interaction. This might be because the visual and aural attraction of moving water in the fountain. The acoustic effect of the fountain located close to seating may successfully screen out surrounding traffic noises, help immeasurably in creating pleasant ambience and producing stress-reducing effects (Marcus and Wischemann, 1990).



**Figure 3.19 Distribution of sitters.**

The majority of standers preferred standing in the middle of the Plaza (Figure 3.20). This might seem contradicting with most of the urban space studies which people prefer standing by some kind of boundaries (Whyte, 1980; Gehl, 1996). Note had to be taken that the building boundaries (Sproul Hall and the ASUC) provided more opportunities for sitting than standing. Most of the people stood at those areas were mainly associated with people sat at those areas. With many people sitting at those areas, there was limited space available for other people to stand. At the same time, the middle of the Plaza was a convenient place for short and non-purposeful meeting which occurred very often in the Plaza, like those met each other on the way to school. These caused more people standing to stay in the middle of the Plaza instead of staying at the boundaries in the Plaza.



**Figure 3.20 Distribution of standers.**

### 3.3.4 Duration of usage

Duration of users indicate how long people would stay in the Plaza. This excluded those passed through the Plaza as they did not really spend time in the Plaza. Over 75% of the users would stay for less than 10 minutes (Figure 3.21). The mean staying time is 440 seconds. The longest staying time was 4433 seconds while the shortest was just about few seconds. The short duration time accounted for people meeting friends and left and those managing their bags and clothes. The number of users decreased significantly with longer staying time. In general, the duration time is more wide spread for those staying at the Sproul stairs. Though more people staying at the ASUC and the fountain, they generally stayed for a shorter period of time.

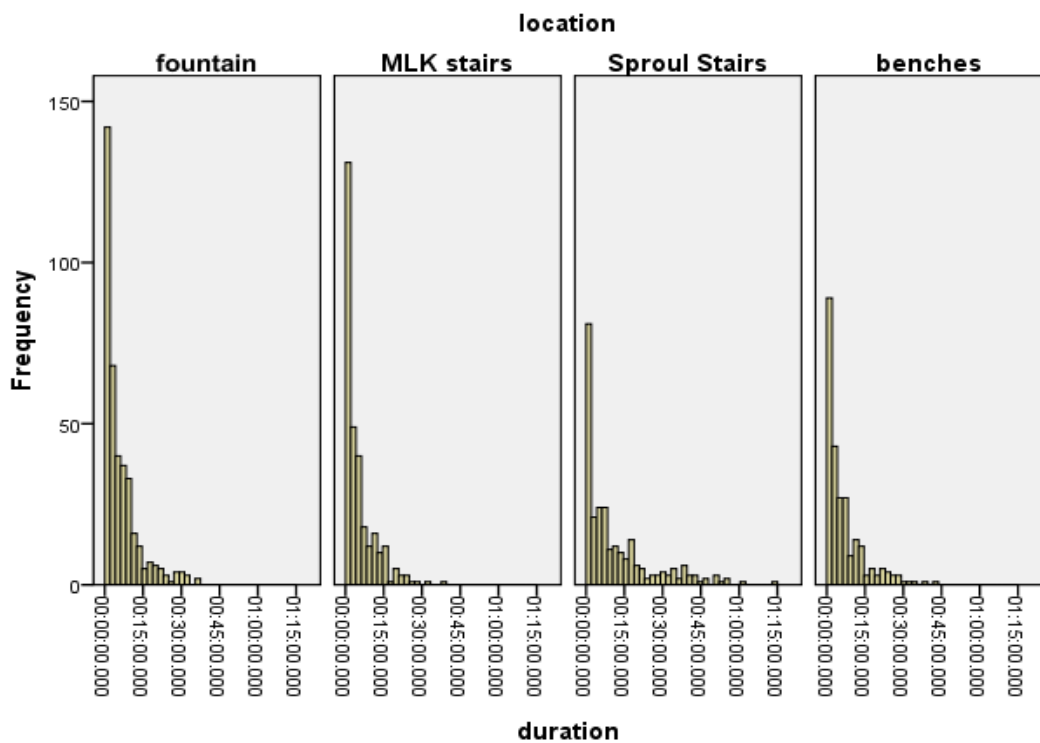
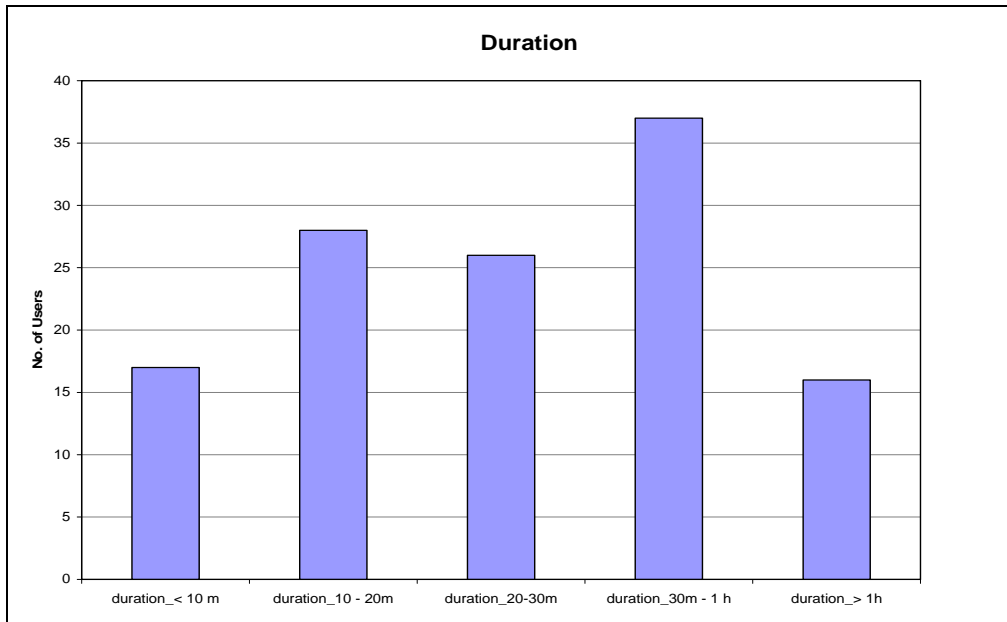


Figure 3.21 Distribution of duration of users, excluding walkers.

The questionnaire shows a quite different duration pattern (Figure 3.22). Interviewees expressed a more generous duration. Most of the users would stay for 30 minutes to 1 hour. A lot of people would stay from 10 to 30 minutes. Relatively few people would stay for less than 10 minutes or more than an hour. This is probably due to the fact that people stayed in the Plaza longer were more likely to be captured for interview.



**Figure 3.22 Duration of usage from questionnaire.**

### **3.4 Effects of microclimate**

#### **3.4.1 Influence of individual microclimatic factor**

From the graphs above, it could be easily seen that more people preferred to stay in sun. Over half of the walkers preferred to stay in sun. Sitters at the fountain, the Sproul stairs and benches tended to sit under sun. The stairs at the ASUC were mostly under shade, so were the people sat there. Except people standing in the middle of the Plaza, most of the people preferred standing in the sun. In winter, the middle of the Plaza was under shade for most of the time which caused people stood there to be under shade. In fact, those stay longer in the Plaza were those staying in sun.

For other microclimatic factors, here I will explain with the results of the questionnaire and those from the video record.

### 3.4.1.1 Influence of individual microclimatic factor from questionnaire

In the questionnaire, interviewees were asked for their sensation vote. The corresponding calculated thermal sensation (TSENS) was also calculated<sup>5</sup> to see if there are any discrepancies. Results show that the asked sensation vote (ASV) deviates greatly from the calculated thermal sensation (Figure 3.23). Below 1.0 calculated TSENS, ASV is generally greater than TSENS, while above 1.0 calculated TSENS, ASV is generally lower than TSENS. This was probably due to difference in thermal preferences, thermal adaptation and previous thermal experience. Different people have different ranges of thermal preference which a larger sample might lead to a more coherent result. The consumption of food and drinks and clothing level would also affect the thermal sensation. Also, the previous thermal experience would impact the thermal sensation if the interviewees had not spent enough time in the Plaza. Over half of the interviewees were in non-ventilated environment or exercised before entering the Plaza (Figure 3.24). They might feel warmer and had higher ASV while those stayed in air-conditioned environment might feel cooler and had lower ASV. Since there is difference between the ASV and the calculated TSENS, both values are included in the following discussion.

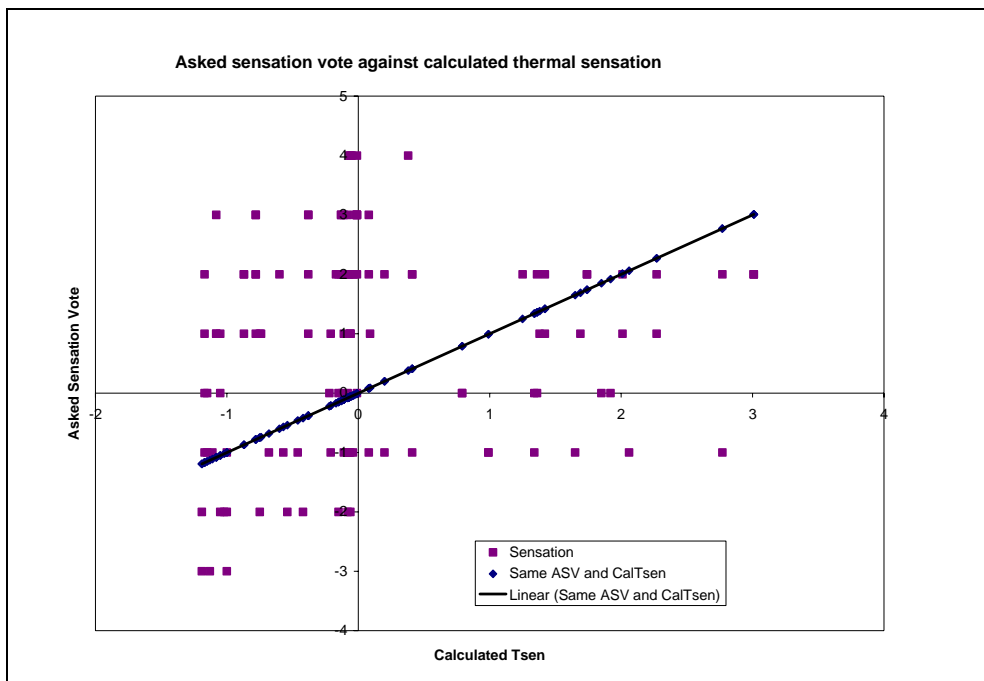
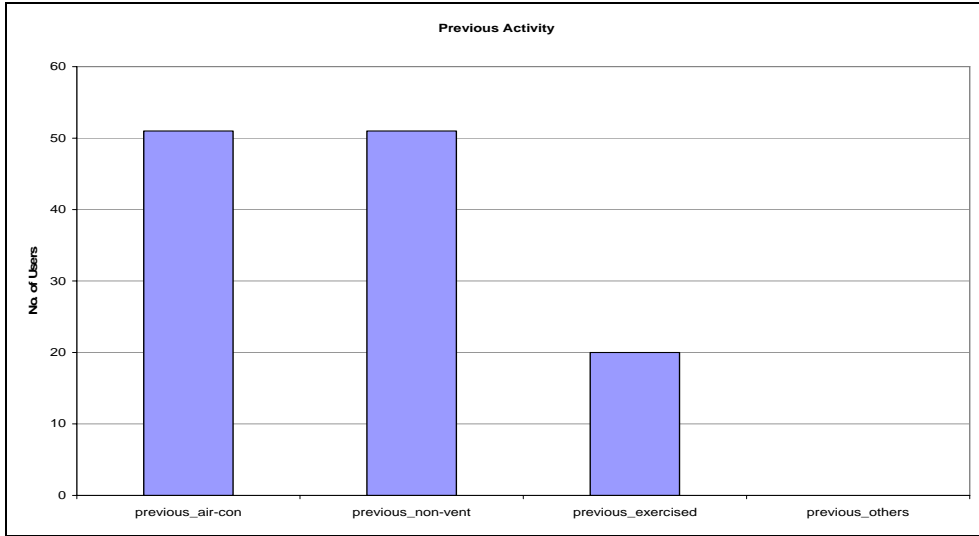


Figure 3.23 Difference between the asked sensation vote and the calculated thermal sensation.

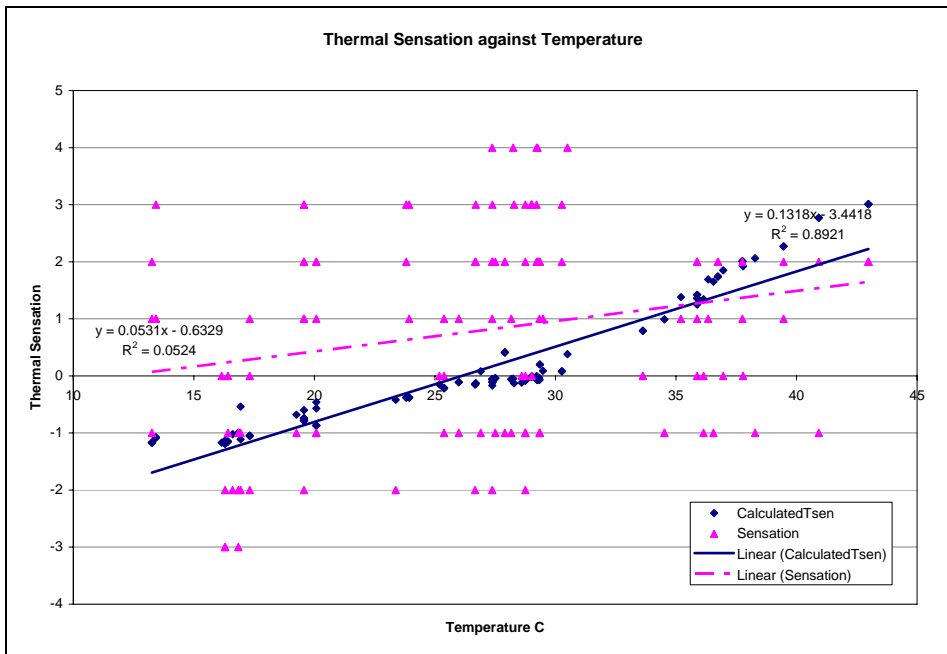
<sup>5</sup> The clothing level is assumed to be appropriate to the climate even in reality there is great variance in the clothing level.





**Figure 3.24 Previous activities of interviewees before entering the Plaza.**

In terms of temperature, both ASV and the calculated TSENS rise with increasing temperature (Figure 3.25). Since ASV had much variance, the rise of ASV with temperature is less apparent. Meanwhile, the ASV distribution does not show a clear range of temperature fulfilling thermal comfort (thermal sensation -1 to +1). The calculated TSENS distribution, on the other hand, shows comfortable temperature to be between 20°C to 35°C.



**Figure 3.25 Temperature with thermal sensation from questionnaire.**

Wind speed and relative humidity, on the other hand, show opposite trends (Figure 3.26 and Figure 3.27). Both ASV and calculated TSENS decrease with increasing wind speed and relative humidity. The changes with relative humidity are greater than those with wind speed. Meanwhile, the distributions do not have any indication on the range of wind speed or relative humidity which thermal comfort is attained.

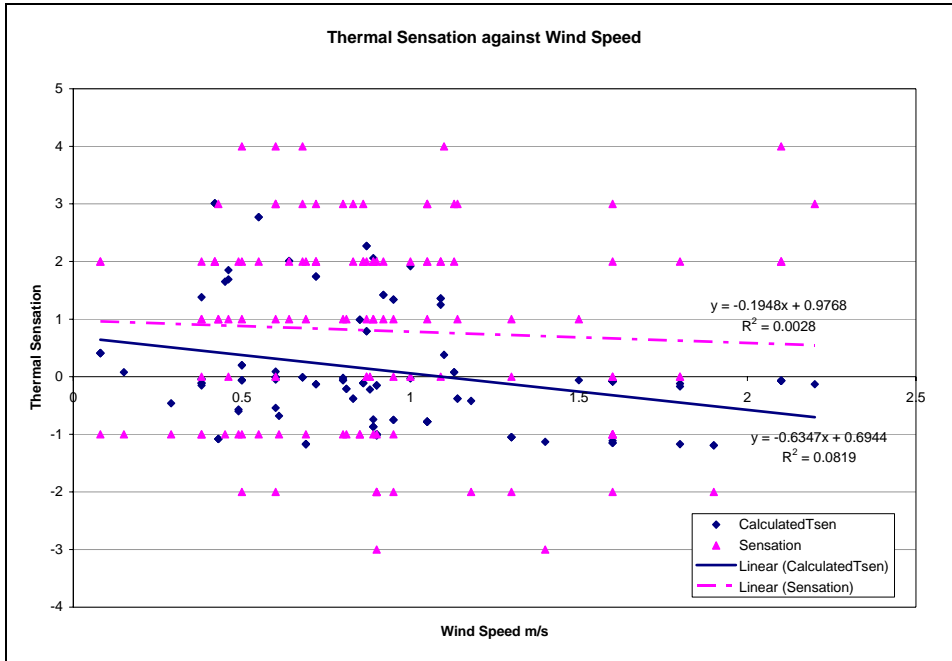


Figure 3.26 Thermal Sensation against wind speed from questionnaire.

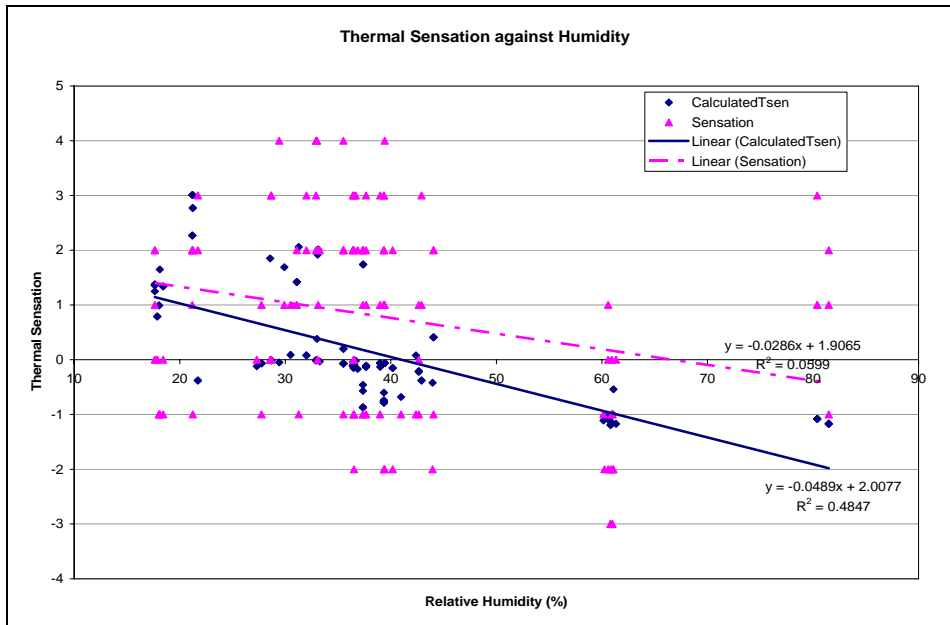


Figure 3.27 Thermal Sensation against relative humidity from questionnaire.

Next, we will see the influence of individual microclimatic factors on thermal, sun, shading and wind speed preferences.

Figure 3.28 shows the warmth, sun, shade and wind preferences against temperature. For convenience, ASV is also included. The trend lines show that users prefer cooler, less sun and more wind when the temperature gets higher, though the change is very little. The shading preference does not seem to have apparent variation with the change in temperature.

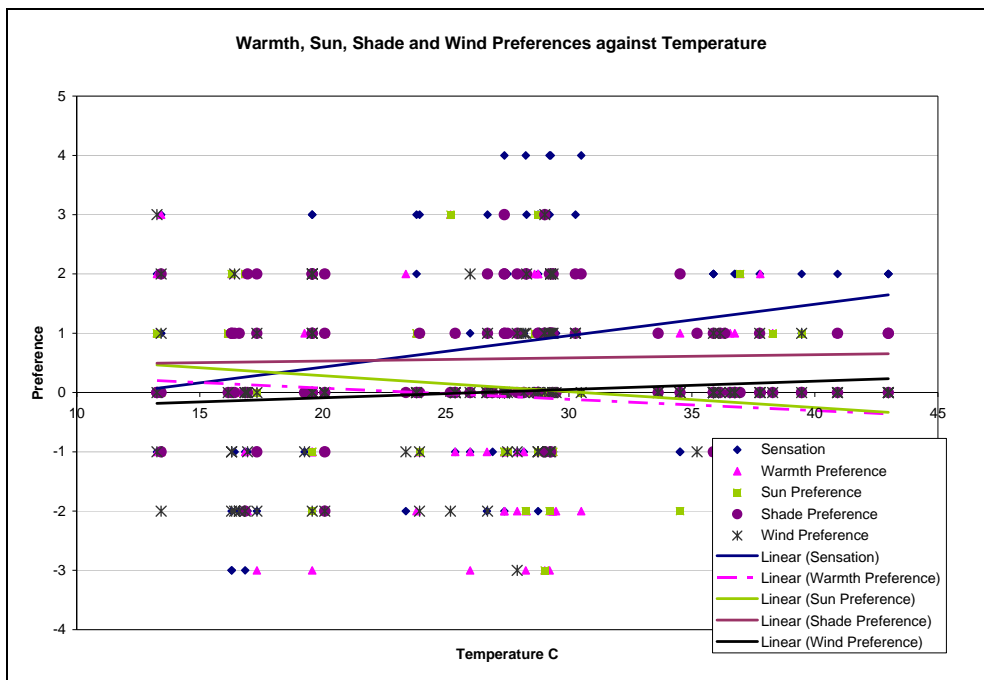


Figure 3.28 Warmth, sun, shade and wind preferences against temperature.

When the wind speed increases, users are thermally more comfortable. The trend lines show that users prefer warmer, more sun and even more wind (Figure 3.29). The preference to more wind with increasing wind speed might be due to the fact that people prefer more continuous air flow rather than instantaneous flow. The preference to shading has insignificant change. However, as the preference votes are widely spread, statistically, the effect of wind speed is not significant enough to establish a casual relationship.

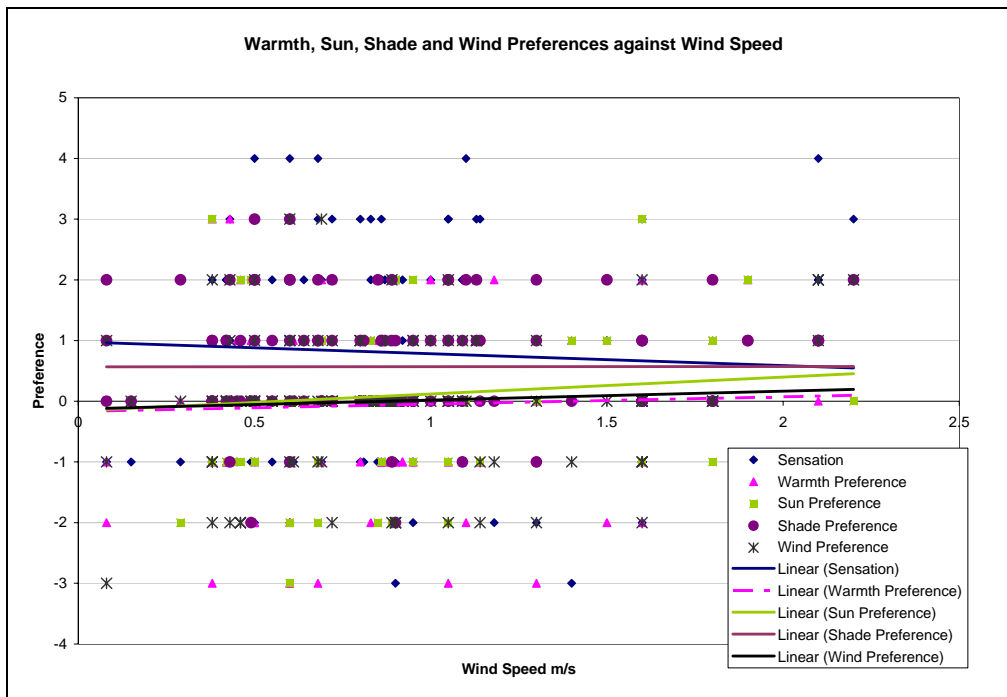


Figure 3.29 Warmth, sun, shade and wind preferences against wind speed.

When the relative humidity increases, ASV decreases. The trend lines show that users prefer warmer, more sun and less wind (Figure 3.30). This might be due to the fact that the higher humidity compensates the cooling effect of wind that people prefer warmer, more sun and less wind. The preference to shading has insignificant change. Again, the preference votes are widely spread, that statistically the effect of relative humidity is not significant enough to establish a casual relationship.

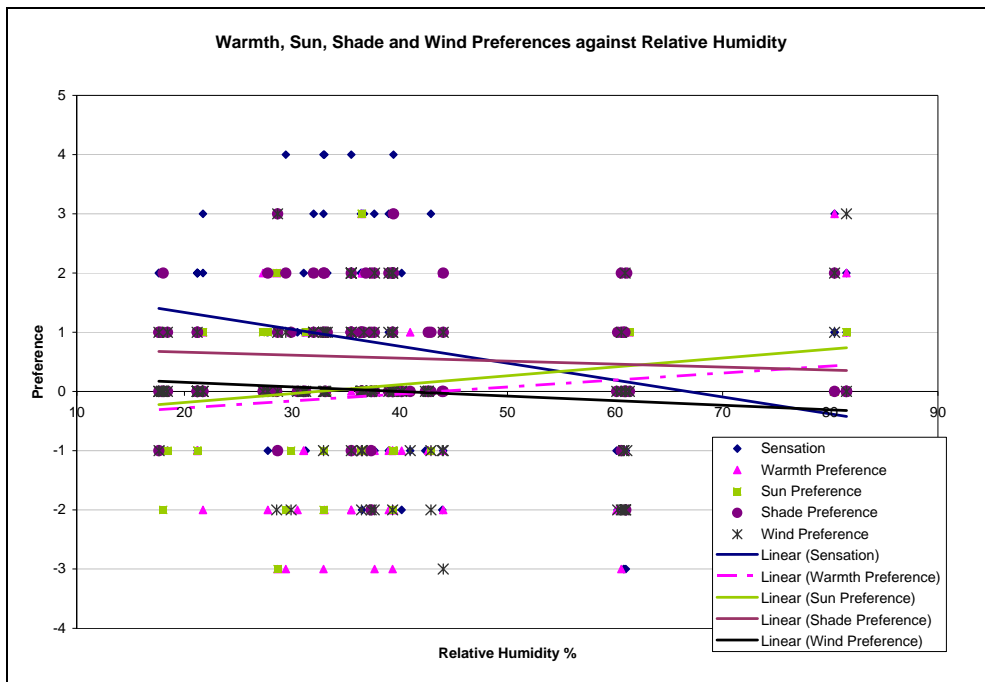


Figure 3.30 Warmth, sun, shade and wind preferences against relative humidity.

People generally feel more comfortable when they are in sun (Figure 3.31). However, the preferences to warmth, sun, shade and wind speed are indifferent. This might hint that people chose to be in sun or in shade to fulfill their preferences

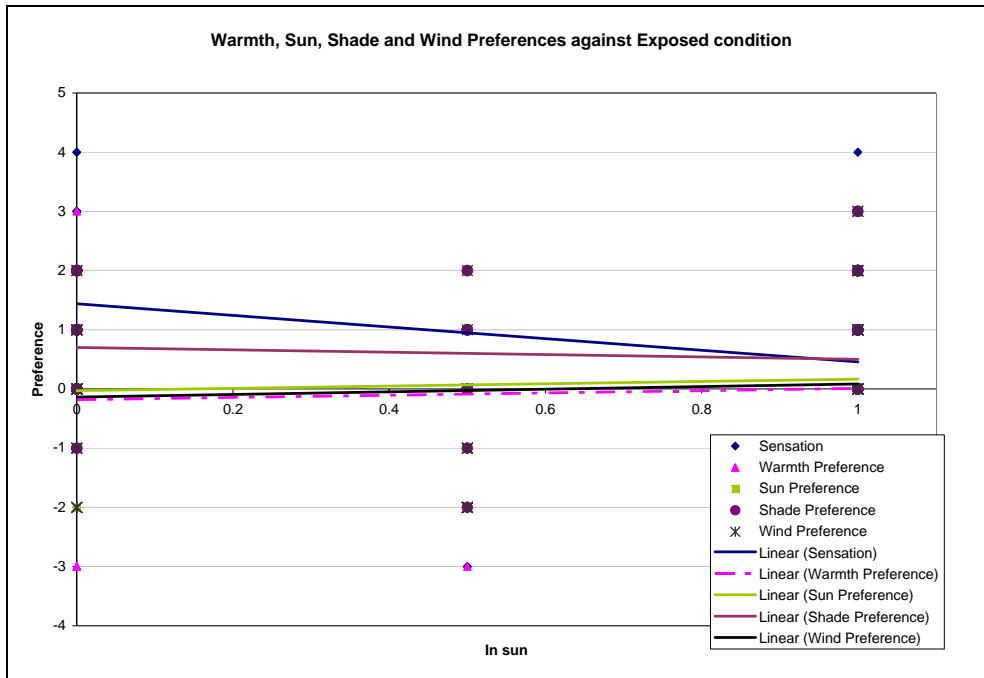


Figure 3.31 Warmth, sun, shade and wind preferences against exposed condition.

### 3.4.1.2 Influence of individual microclimatic factor from video record

Regarding the video record, I will explain with the number of sitters from the video record. It has more apparent pattern than other types of activities, though they share similar characteristic.

There was no clear activity pattern with temperature. In a day, there was more usage with higher temperature and the usage decreased upon a certain temperature (Figure 3.32). When normalized the daily temperature (i.e. assign the mean day temperature as 0 and distribute the day's temperatures according to its number of standard deviations from the mean day temperature) (Figure 3.33), it can be seen that there was a clear rise in usage with the increase in temperature to a slightly warmer temperature and decreased thereafter. This indicated that the normalized temperature has a curvilinear effect on the usage and people preferred a slightly warmer thermal environment. This also matched with the survey results that people preferred a slightly warmer thermal environment. Also, as users would modify their own outdoor thermal comfort by means of clothing,

consumption of food or other means throughout the year, the patterns were very similar in the year round period.

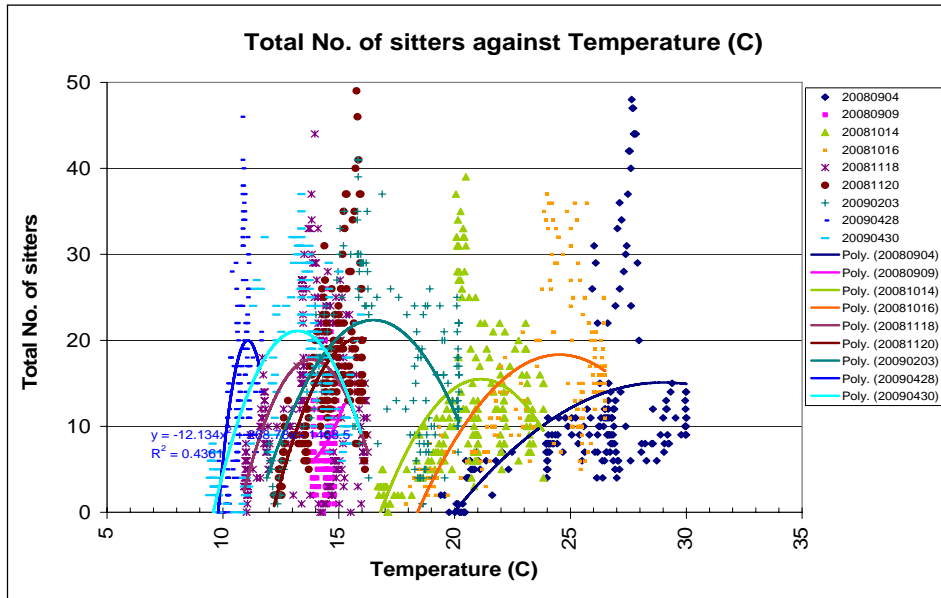


Figure 3.32 Number of sitters against the surveyed days' temperatures.

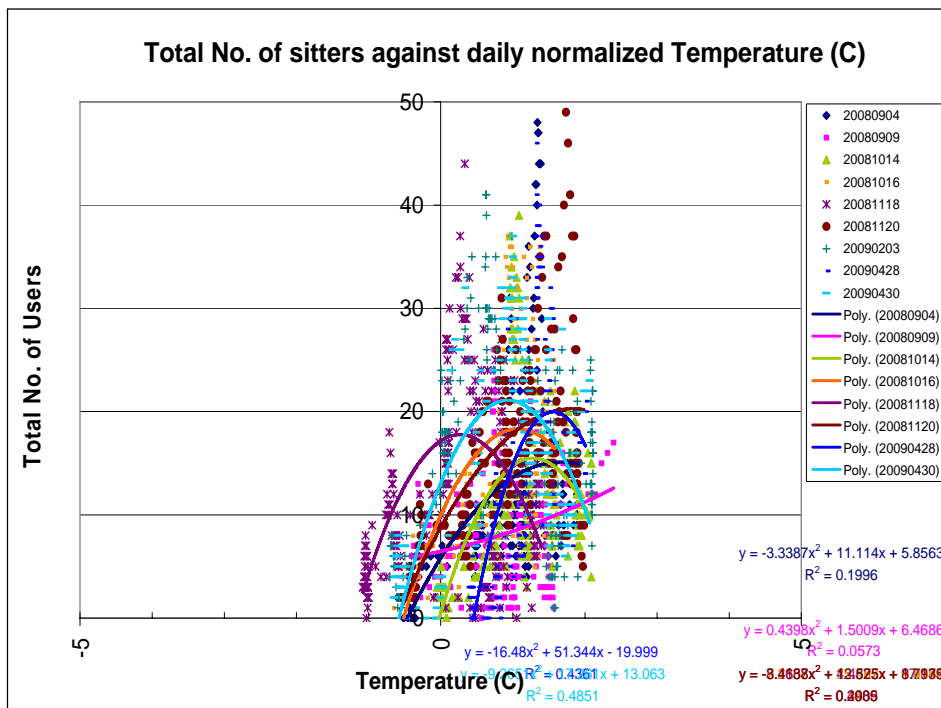


Figure 3.33 Number of sitters against the normalized temperature.

However, the same did not apply to other factors recorded. Figure 3.34 to Figure 3.36 indicate the total number of sitters against wind speed, relative humidity and the proportion of exposed area (proportion of area under sun). They did not reflect a clear pattern of usage with the change of the recorded factors. As can be seen from the trend lines, there was neither apparent linear, curvilinear, logarithm nor exponential movement as shown in the case of temperature. This means that individually, these factors did not have evident influence on the usage. They might, however, to a certain extent, influence the spatial usage pattern in a less apparent manner. As can be seen from Figure 3.37, there was a concentration of usage around the normalized sitting comfort. This indicated that individual microclimatic factors might not have evident impact, the collective effect, comfort, did.

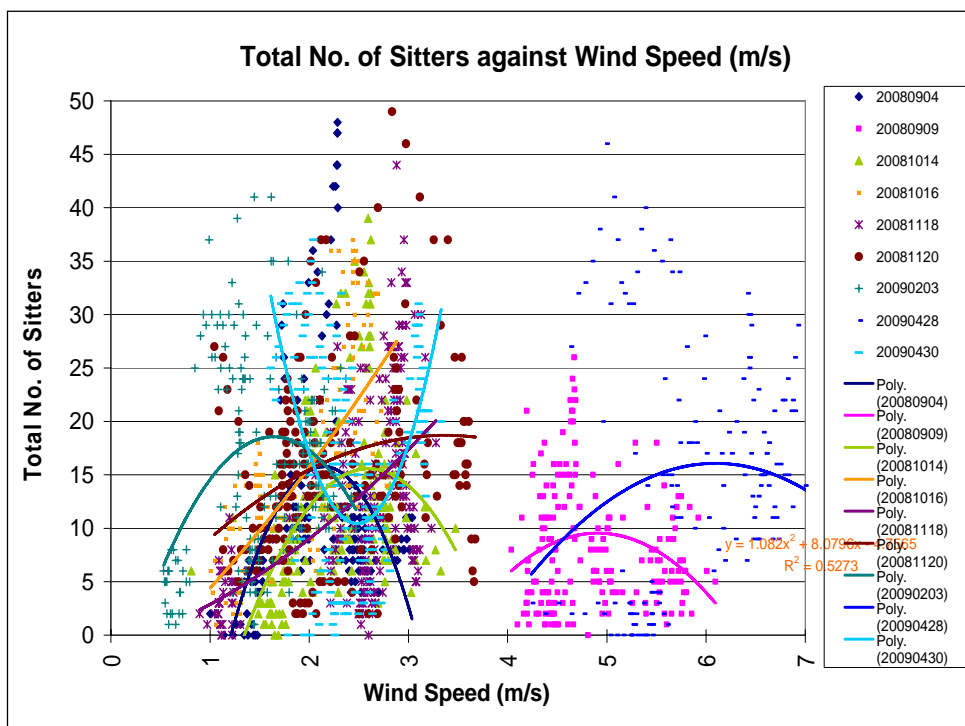


Figure 3.34 Number of sitters against wind speed.



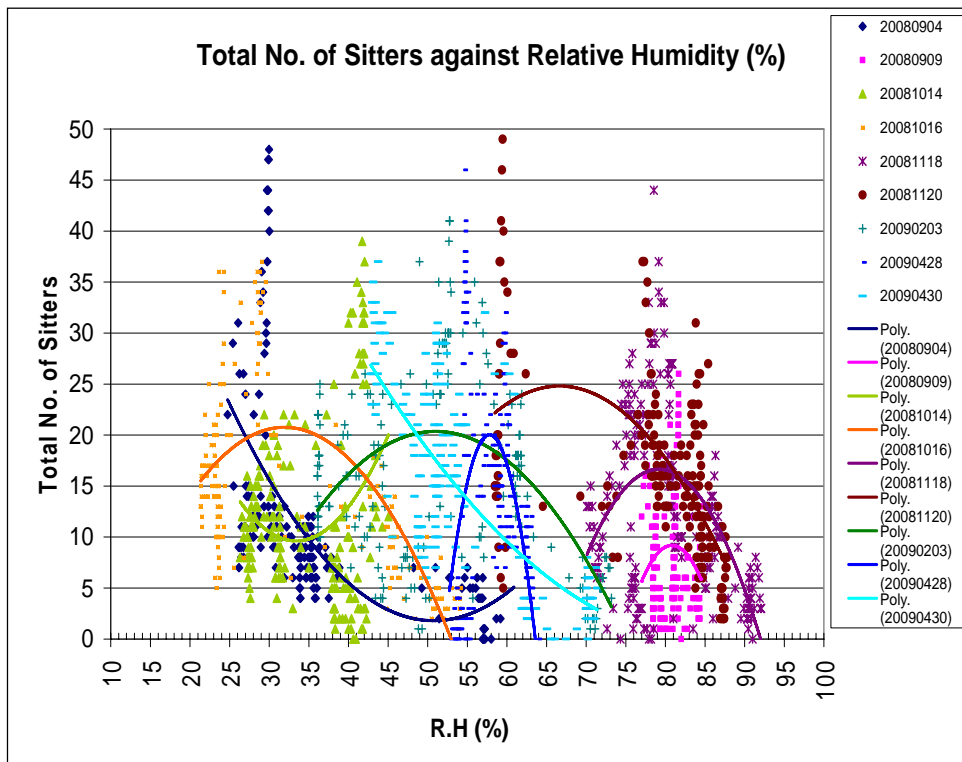


Figure 3.35 Number of sitters against relative humidity.

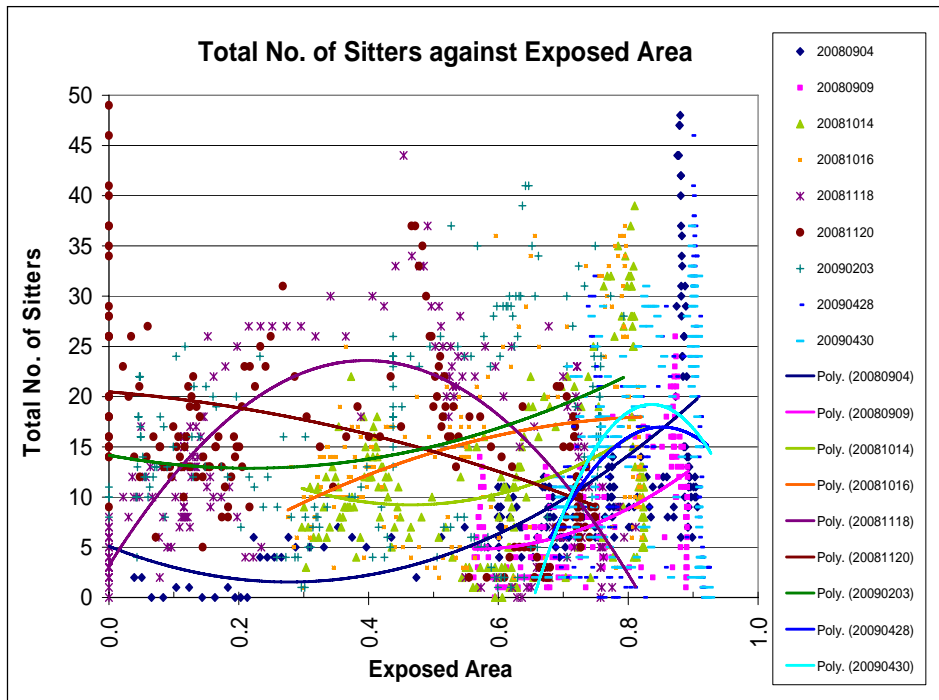


Figure 3.36 Number of sitters against the proportion of exposed area.

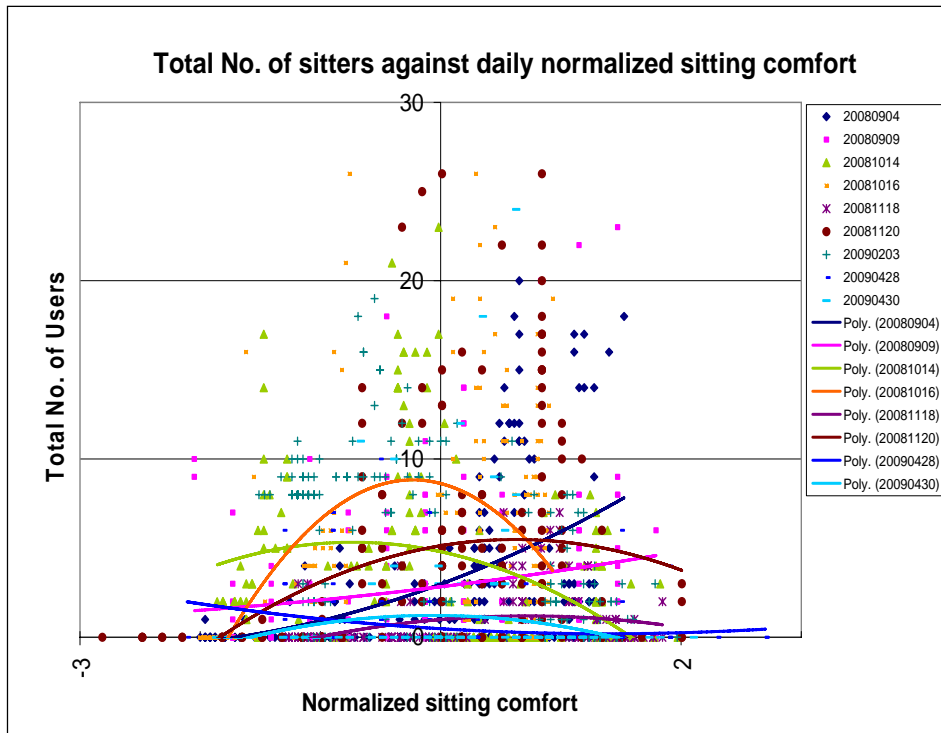


Figure 3.37 Number of sitters against normalized sitting comfort.

### 3.4.2 Collective effects of microclimatic factors

To study the collective effects of microclimate, multiple regression analyses were used. This is because microclimate consists of different factors and the various combinations could produce the same or different thermal sensation. Meanwhile, according to ASCE (2004), thermal sensation, wind chill, and wind force have to be considered together in determining outdoor comfort. By using multiple regressions, the effects of different microclimatic factors could be determined together based on the corresponding correlations. That is, how much the factor is affecting the spatial behavior could be determined. Multiple regressions also helps to derive simple regression equation based on the correlation of the various factors and the inter-correlation between the involving factors. It is then easy to use the regression equation in the prediction model with considerable reliability.

In the study, temperature, relative humidity, wind speed, activity type and clothing are the major factors in concern. Some factors, like temperature, would have curvilinear effect. That is, the impact would increase with the increasing temperature and decrease after temperature reached a certain point. Also, the normalized values might have significant impact. Therefore, both the power terms and the normalized values were also included as independent variables to explore the curvilinear effects. Besides these factors,

the presence of sun and the proportion of area in sun were also included to have a more comprehensive picture of the influence of microclimate.

To more closely reflect the change in the usage pattern, factors other than microclimatic ones were also included in the multiple regression analyses. Those included were the day and percentage of the school in the semester, the week and percentage of the school in the semester, the time of the day, and the minutes to or from class peaks. This was because from the field survey, it could be seen that the number of users decreased as the semester approached to an end. Also, there were apparent peaks which they should be taken care of.

The statistical analyses were carried for the number of users, activity type of users, the spatial distribution, and the duration of usage. The correlation is used as an indicator of the degree of relationship between two variables. The greater the correlation value, the greater the relationship, regardless of the sign. The sign only indicates the positive or negative relationship between the two variables.

**Table 3.1 Correlation of various factors with total number of users.**

<u>Studied Factors</u>	<u>Correlations</u>
schDay_n	-0.0990
schDay_p	-0.0959
SchWk_n	-0.1018
schWk_p	-0.0984
daySession	0.1852
minToFromClass	-0.3116
minToFromClassSq	-0.2751
TempC	0.1768
WindSpeed_ms	-0.0436
RH_p	-0.1220
exposed_p	0.1046
sunPresence	-0.0289
clothing	-0.1780
Comfort_Walker	0.1831
Comfort_Stander	0.1521
Comfort_Seater	0.1506
N_temp	0.2774
N_tempSq	-0.3788
N_windSpeed	0.1650
N_windSpeedSq	-0.1901
N_RH	-0.2505
N_RHSq	-0.2325
N_exposed	0.2672
<u>N_exposedSq</u>	<u>-0.0249</u>

Table 3.1 shows the correlation of different factors with the total number of users. It could be seen that the relationship of individual microclimatic factors with the usage is very weak. Comparatively, comfort of different types of users and the normalized values of the microclimatic factors have much stronger relationship with usage. Meanwhile, the time to class peaks and the session of the day (morning, afternoon or evening) also have relatively strong relationship with the usage.

Concerning the different types of activities (Table 3.2), it is interesting to note that the day of school has opposite impact to walking and sitting activities. Walking activity is decreasing as the school proceeds while sitting activity is increasing. This indicates that as the semester proceeds, less people trespass the Plaza while more people stay to study, to meet, to enjoy or for other reasons. Also, time to class peaks has much more relationship with walking activities than any other types of activities. This is probably due to the fact that people staying in the Plaza are not necessarily people rush for classes. Their activities then have weaker relationship with class peaks.

Microclimatic factors and the associated normalized values, on the other hand, have much stronger relationship on sitting, standing and wandering than walking. This is probably due to the fact that people tend to stay in the Plaza cares more about their

comfort than passers-by. Also, as in the case of the level of usage, individual microclimatic factors tend to have much weaker relationship than their associated normalized values.

**Table 3.2 Correlation of various factors with different types of activities.**

	<b>Walking</b>	<b>Sitting</b>	<b>Standing</b>	<b>Wandering</b>
schDay_n	-0.1198	0.1166	-0.2335	-0.1432
schDay_p	-0.1185	0.1159	-0.2268	-0.1294
SchWk_n	-0.1218	0.1131	-0.2358	-0.1420
schWk_p	-0.1204	0.1116	-0.2281	-0.1251
daySession	0.2314	0.1568	-0.0923	-0.1563
minToFromClass	-0.4346	-0.0275	0.0191	0.0399
minToFromClassSq	-0.3813	-0.0309	0.0178	0.0385
TempC	0.1290	0.0945	0.2309	0.1863
WindSpeed_ms	-0.0050	-0.0243	-0.1865	-0.0279
RH_p	-0.0715	-0.1826	-0.1267	0.0755
exposed_p	0.0502	0.0658	0.2046	0.1584
sunPresence	-0.0423	0.0198	-0.0241	-0.0132
clothing	-0.1300	-0.0966	-0.2302	-0.1845
N_temp	0.1870	0.3816	0.0369	0.1684
N_tempSq	-0.2607	-0.4209	-0.2452	-0.2027
N_windSpeed	0.1347	0.2249	-0.0174	-0.0010
N_windSpeedSq	-0.1381	-0.1476	-0.1707	-0.1795
N_RH	-0.2051	-0.2889	0.0196	-0.1554
N_RHSq	-0.1497	-0.2528	-0.1809	-0.1684
N_exposed	0.1567	0.1967	0.3676	0.3539
N_exposedSq	-0.0010	-0.0927	0.0192	0.0240
Comfort_Walker	0.1427	0.0696	0.2492	0.2025
Comfort_Stander	0.1019	0.0702	0.2600	0.1634
Comfort_Sitter	0.1072	0.0650	0.2335	0.1691

Regarding the spatial distribution (Table 3.3), temperature and the associated normalized values show relatively higher relationship with the usage at the fountain, ASUC and the Sproul stairs, but not at the benches. Other microclimatic factors and comforts generally have greater relationship with the usage at the ASUC than that at the fountain and the Sproul stairs. Clothing has the greatest association with the usage at the ASUC, than Sproul stairs, benches and the fountain. This also holds for wind speed. Though there is no other evidence, it seems that places more susceptible to downdrafts would have greater association with clothing.

**Table 3.3 Correlation of various factors with distribution.**

	<b>fountain_n</b>	<b>ASUC_n</b>	<b>SpStair_n</b>	<b>bench_n</b>
schDay_n	0.1552	-0.1813	0.1669	0.0426
schDay_p	0.1563	-0.1709	0.1569	0.0450
SchWk_n	0.1543	-0.1852	0.1640	0.0416
schWk_p	0.1550	-0.1724	0.1513	0.0441
daySession	0.1480	0.0434	0.1124	-0.0692
minToFromClass	-0.1107	0.0070	0.0451	-0.0358

minToFromClassSq	-0.1108	0.0015	0.0437	-0.0452
TempC	-0.0151	0.4699	-0.1266	-0.1132
WindSpeed_ms	0.0040	-0.1164	0.0286	-0.0808
RH_p	-0.1060	-0.2771	-0.0521	0.1340
exposed_p	0.0364	0.1816	0.0176	-0.1416
sunPresence	-0.0115	0.0043	0.0268	0.0079
clothing	0.0136	-0.4700	0.1242	0.1127
N_temp	0.2411	0.3138	0.2549	0.0386
N_tempSq	-0.2860	-0.2863	-0.3505	0.0275
N_windSpeed	0.1568	0.1486	0.1437	-0.0617
N_windSpeedSq	-0.1200	-0.2140	-0.0432	0.0773
N_RH	-0.1887	-0.2773	-0.1544	-0.0653
N_RHSq	-0.1642	-0.2059	-0.1892	0.0171
N_exposed	0.1367	0.3527	0.0527	-0.0318
N_exposedSq	-0.0971	0.0311	-0.0565	-0.0951
Comfort_Walker	-0.0508	0.4278	-0.1005	-0.0443
Comfort_Stander	-0.0174	0.4075	-0.1239	-0.0678
Comfort_Sitter	-0.0395	0.4492	-0.1462	-0.1026

Day and week of school have comparatively much weaker relationship with the usage at benches. In fact, all the factors studied basically have very weak association with the usage at the benches. This is also reflected in the correlation coefficient which shows the relationship of all the factors studied with the usage at the bench. Table 3.4 shows the correlation coefficients of usage at the four major locations. It shows that the factors studied have greatest association with the usage at the ASUC, than the Sproul stairs and the fountain, with that at the benches the weakest.

**Table 3.4 Correlation coefficients of usage at the fountain, ASUC, Sproul stairs and the benches.**

<b>fountain_n</b>	<b>ASUC_n</b>	<b>SpStair_n</b>	<b>bench_n</b>
0.564672	0.690946	0.609214	0.380135

**Table 3.5 Correlations of various factors with duration of usage.**

Studied Factors	Correlation
startTime	-0.1007
sun	0.0792
schDay_n	0.0151
schDay_p	0.0132
SchWk_n	0.0166
schWk_p	0.0166
aroundPeak	-0.0954
minToPeak	0.1086
minToPeakSq	0.1037
TempC	-0.1295
Wind_ms	-0.0177
RH_p	0.0676
exposed_p	0.0322
clothing	0.1274
Comfort	-0.1133
N_temp	-0.0596
N_tempSq	-0.0975
N_windSpeed	-0.0323
N_windSpeedSq	-0.0617
N_RH	-0.0424
N_RHSq	0.0317
N_exposed	0.1029
N_exposedSq	0.0243
location	0.1092

Table 3.5 shows the correlations of various factors with the duration of usage. It could be seen that though temperature and clothing have the greatest association with the duration of usage, the correlation values are indeed very low. In fact, the correlation coefficient (with all the factors studied) is 0.314 which the square of the correlation coefficient (coefficient of determination) is 0.0988. That is, less than 10% of the duration of the usage could be explained even with the many factors included. The time spent in the Plaza, based on the questionnaire result, was more based on the time available and the objective of usage, like attending events or filling time gaps.

It can then be concluded that the studied factors mainly associate with the number of users, types of activities and the spatial distribution, but not the time spent in the Plaza. Therefore, regression equations so generation could be applied in the number and activity types of users, and the corresponding spatial distribution. It is not suitable to use it in the prediction of the duration of usage in the Plaza. The application of the regression equation in the prediction is described more in detail in the following session.

### 3.5 Prediction of spatial behavior

Along with the correlation and coefficient of determination studies, multiple regression studies also enable coefficient information which is useful in the prediction of spatial behavior. The multiple regression equation takes the form  $y = b_1x_1 + b_2x_2 + \dots + b_nx_n + c$ . The b's are the regression coefficients, representing the amount the dependent variable y changes when the corresponding independent variable changes 1 unit. The c is the constant, where the regression line intercepts the y axis, representing the amount the dependent y will be when all the independent variables are 0.

As in the previous studies, factors used include day and time of school, clothing level, the comfort of different types of activities, microclimatic factors and the associated normalized values. The major difference is that the analyses are to be separated in sessions based on the class peaks. There were several class peaks in a day which could

not be handled easily by simple multiple regression studies. Again, the class peaks were 9:30am, 11:00am, 12:30pm, 2:00pm, 3:30pm and 5:00pm. The analyses were also separated into sessions by the type of activities and the proportion in sun or in shade as these should always be identified separately. Also, by separating the analyses in sessions, higher *coefficient of determination, R-square*, could be obtained. Coefficient of determination is basically the square of the sample correlation coefficient between the outcomes and their predicted values. The values vary from 0 to 1. It indicates the percent of variance in the dependent variable which could be explained collectively by all of the independent variables. Hence, the greater the value, the more reliable the prediction. Without separating the analyses into sessions, the R-squared value generated from the multiple regression could be as low as 0.2. That is, the factors would have low correlation with the outcome and it would not be reliable to use the results from the regression analyses for future prediction purpose. In fact, the R-squared value obtained with the sessions could be as high as 0.9319 (the percentage of walkers in sun at 14:00) and over 78% of data required for the prediction had coefficient of determination more than 50%.

With all these setups, the regression coefficients were generated and the coefficient could be substituted in the regression equation for prediction. For example, the number of walkers in shade at 2:00 pm was given by

-239.53		
-2.36	*	<i>schDay_p</i>
2.37	*	<i>schWk_p</i>
7.55	*	<i>daySession</i>
-0.44	*	<i>minToFromClass</i>
0.01	*	<i>minToFromClassSq</i>
6.90	*	<i>TempC</i>
-6.53	*	<i>WindSpeed_ms</i>
-22.59	*	<i>RH_p</i>
-0.68	*	<i>exposed_p</i>
-3.10	*	<i>sunPresence</i>
175.03	*	<i>clothing</i>
-0.75	*	<i>N_temp</i>
0.74	*	<i>N_tempSq</i>
2.57	*	<i>N_windSpeed</i>
1.29	*	<i>N_windSpeedSq</i>
-2.63	*	<i>N_RH</i>
-4.79	*	<i>N_RHSq</i>
19.34	*	<i>N_exposed</i>
4.33	*	<i>N_exposedSq</i>
-53.16	*	<i>Comfort_Walker</i>
-58.48	*	<i>Comfort_Stander</i>
20.82	*	<i>Comfort_Sitter</i>

At the same time, to achieve higher confidence in the prediction, not all data required was directly derived from the statistical analyses. This is because not all the spatial usage data had high R-squared values. That is, not all data were reliable enough. An abstract of the R-squares recorded for the number of walkers is illustrated in Table 3.6. In the table,

some of the R-squares are bolded and some are in italics. The bolded R-squares are those with higher values. They can be used to determine others which have lower R-squared values, as displayed in italics. For example, in the 9:30 am column, the number and percentage of walkers in shade have higher R-squared values. These can then used to determine the number of walkers and the number of walkers in sun which have lower R-square values. In this case, we can obtain spatial usage data with higher confidence by indirectly using the regression results.

**Table 3.6 R-squared for numbers of walkers at different class peaks.**

walker	9:30:00	11:00:00	12:30:00	14:00:00	15:30:00	17:00:00
subtotal	<i>0.376</i>	<i>0.648</i>	<i>0.585</i>	<i>0.555</i>	<i>0.376</i>	<i>0.579</i>
sun	<i>0.584</i>	<i>0.693</i>	<i>0.715</i>	<b>0.7246</b>	<b>0.7246</b>	<b>0.6573</b>
shade	<b>0.6846</b>	<b>0.6939</b>	<b>0.7782</b>	<i>0.539</i>	<i>0.604</i>	<i>0.602</i>
sun%	<i>0.887</i>	<i>0.893</i>	<i>0.907</i>	<b>0.9319</b>	<i>0.876</i>	<b>0.9171</b>
shade%	<b>0.8870</b>	<b>0.8934</b>	<b>0.9075</b>	<i>0.931</i>	<b>0.8762</b>	<i>0.917</i>

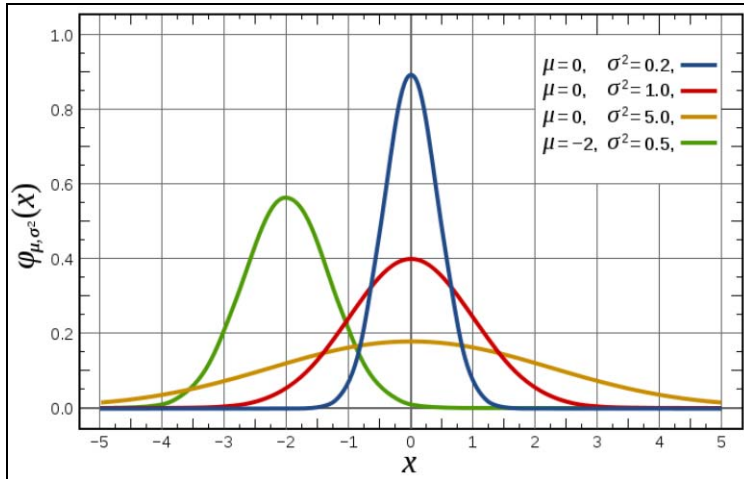
Similar procedure was carried out to obtain the distribution of users at different locations. For example, the ratio of people sit at the fountain in sun at 2:00pm was given by

2.5935		
0.0016	*	<i>schDay_p</i>
-0.0012	*	<i>schWk_p</i>
-0.0167	*	<i>daySession</i>
0.0019	*	<i>minToFromClass</i>
0.0000	*	<i>minToFromClassSq</i>
-0.0671	*	<i>TempC</i>
0.0409	*	<i>WindSpeed_ms</i>
-0.2252	*	<i>RH_p</i>
0.0013	*	<i>exposed_p</i>
0.0011	*	<i>sunPresence</i>
-1.3484	*	<i>clothing</i>
-0.0154	*	<i>N_temp</i>
0.0118	*	<i>N_tempSq</i>
0.0020	*	<i>N_windSpeed</i>
0.0046	*	<i>N_windSpeedSq</i>
0.0060	*	<i>N_RH</i>
0.0042	*	<i>N_RHSq</i>
-0.0683	*	<i>N_exposed</i>
-0.0084	*	<i>N_exposedSq</i>
0.1969	*	<i>Comfort_Walker</i>
0.0963	*	<i>Comfort_Stander</i>
0.2179	*	<i>Comfort_Sitter</i>

Comparatively, prediction of duration is more simple. The statistical studies showed that duration had insignificant association with microclimatic factors nor other factors like the day and the week of the school. It can then be assumed that the duration at the four locations followed the pattern as shown in Figure 3.21. It is then possible to use the normal distribution to derive the duration of a large number of individual users. The



normal distribution is often used to describe, at least approximately, any variable that tends to cluster around the mean. Figure 3.38 shows a probability density function with different means and standard deviation. Using the means and standard deviations of duration at different locations from the survey, it is then potential to generate the duration time of individuals with confidence.

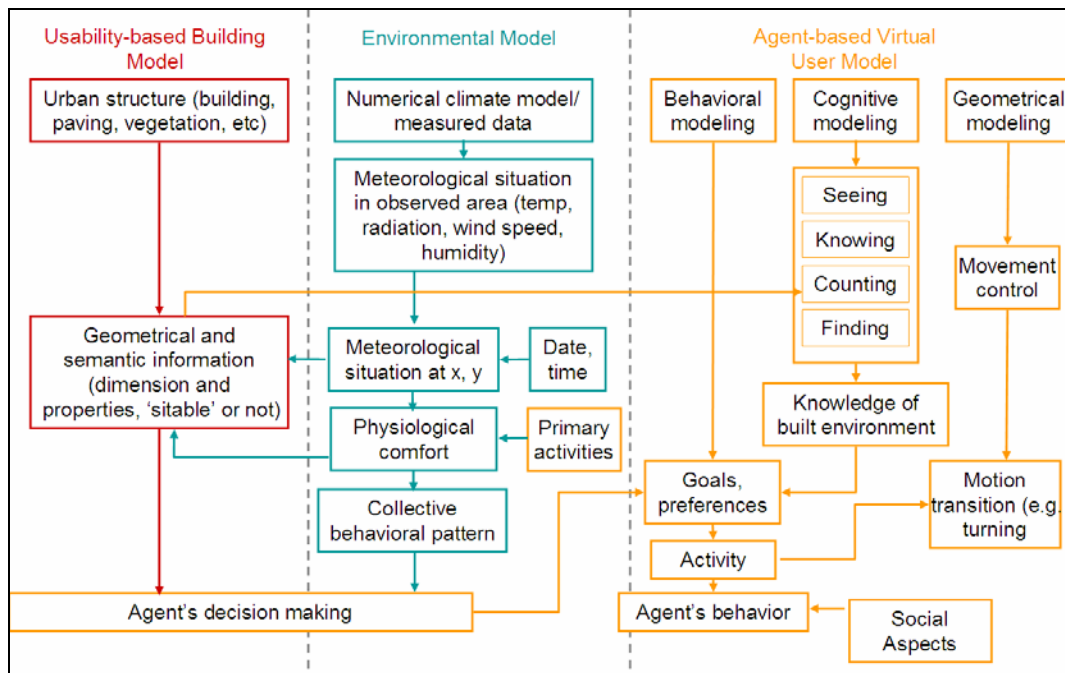


**Figure 3.38 Probability density function.**

## Chapter 4

# The Simulation Model Structure

The simulation model consists of three major components, the usability-based building model, the environmental model and the agent-based virtual user model. The usability-based building model contains geometrical and usability information of the urban structure. The agent-based virtual user model holds the cognitive model which acquires knowledge about the built environment, and a behavioral model which controls the behavior based on the environment, personal needs and preferences of individuals. The environmental model contains mainly intangible information, including date, time, microclimate and general comfort information of the virtual users and the environment. It also holds the environmental control which information influenced by microclimate is processed. For example, sun position and shading. The modeling structure and the relationship of the three components are shown in Figure 4.1.



**Figure 4.1** The modeling structure of the simulation.

The usability-based building model and the agent-based virtual user model were basically developed by Yan. In this study, works have been focused on the development of the environmental model, the association of the environmental model with the other two

models, and the development in the original models to support the virtual user responses to the intangible environmental impact. The designs of the three components are described in the following sessions.

#### **4.1 The usability-based building model**

The built environment consists of a large number of design elements, such as floors, stairs, walls, windows, vegetation, lawns, fountain and benches etc. These elements have their own properties which human can perceive, understand and act on them appropriately. This is a very important characteristic in human spatial behavior simulation which makes it different from those found in Artificial Life simulations. In Artificial Life simulations, like Boids simulation (Reynolds, 1987) and the Artificial Fish (Tu, 1996), the simulations were focused on the interaction between the autonomous life-like agents and avoiding obstacles. In these simulations, objects perceived in the environment were considered as obstacles which agents have to avoid. In human behavior simulation, agents might have to interact with the objects encountered rather than just avoiding them. They have to *perceive* and *understand* the nature of the elements in the environment properly before they could behave accordingly. For example, when an agent encounters an object, he has to understand if it could be seated before he sits on it. For this reason, the model of the built environment has to reflect not only the geometry of the design elements, but also the embedded meaning of the design objects, i.e. the types and usability information of the design elements, to the agents who inhabit in the environment.

Conventionally, architectural CAD models are commonly used in the Architecture/Engineering/ Construction (A/E/C) practice. Computer-based 2D drawings and 3D models are used in all design phases for communication, presentation, and evaluation in terms of energy, lighting, acoustics, and aesthetics, etc. The models contain very rich graphical information of the geometry and some textual information about design elements' types which lies in the layer names in layer-based models. However, CAD models are not immediately applicable in the simulation as they lack of usability information. For example, a flat surface can either be the top of a bench that users could sit on or the ground that could be only walked on. Without a name, it would be difficult to communicate between humans, not to mention virtual users. Even with a name, say, 'bench', it is still not clear to virtual users how many people can sit on it, whether it is movable, whether it is occupied by a user, and so forth.

In the original simulation model, Yan developed a model which contains both graphical information derived from CAD models and non-graphical information of properties of usability in the Scalable Vector Graphics (SVG)/ Extendable Modeling Language (XML) format. CAD models are rich in graphical information and widely used in the design practice. It makes the simulation practical and eventually applicable to everyday design

practice, which is an objective of this research. As CAD models contain only limited textual information, SVG/ XML technology was employed to supplement the limited textual ability of CAD models. XML was designed to transport and store data in a text format. SVG is a family of specifications of an XML-based file format for describing two-dimensional vector graphics. As such, SVG images and their behaviors could be searched, indexed, scripted and, if required, compressed. SVG/ XML is semantically rich in nature which makes it an appropriate tool to store complicated non-graphical information. Also, it is text-based which virtual users could easily retrieve and process the stored data so as to understand the type and properties of each design element.

#### **4.1.1 Geometrical model**

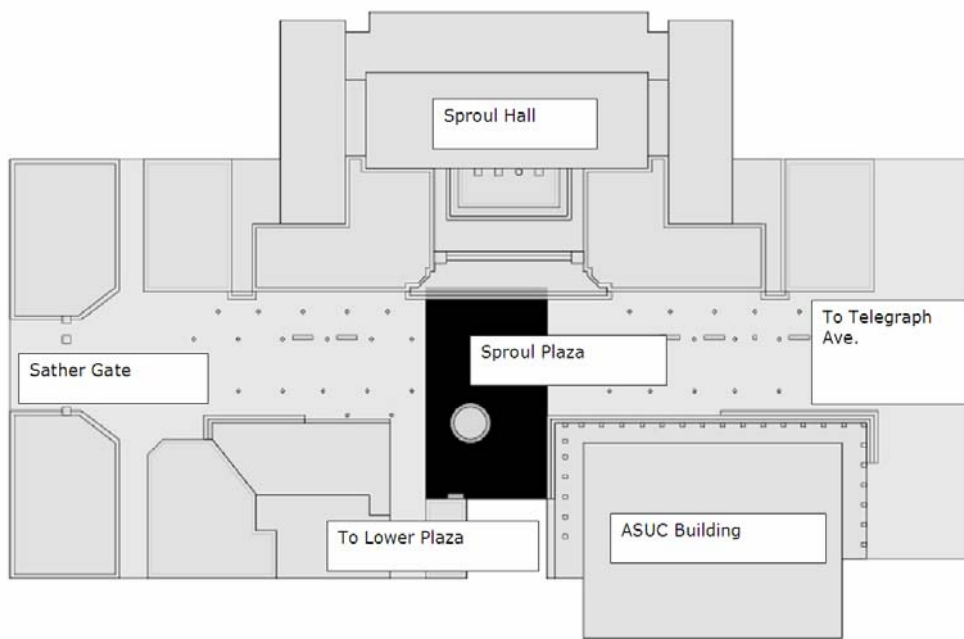
The usability-based building model is built based on the popularly used layer-based DXF format. The layers in the CAD model are named with meanings of the geometries and geometries are placed in the appropriate layer. The naming convention is standardized to ease the conversion to the usability-based model. For example, Step-SproulHallLevel1.1 is the name of a design component of type Step, and its ID is Step-SproulHallLevel1.1, meaning it is a step in front of the Sproul Hall and is the first step of the first stair. Also, as the model is two dimensional, the z-depths of the components are also recorded according to their actual spatial relationships, e.g. Step-SproulHallLevel1.1 is on top of the ground.

#### **4.1.2 Usability-based model**

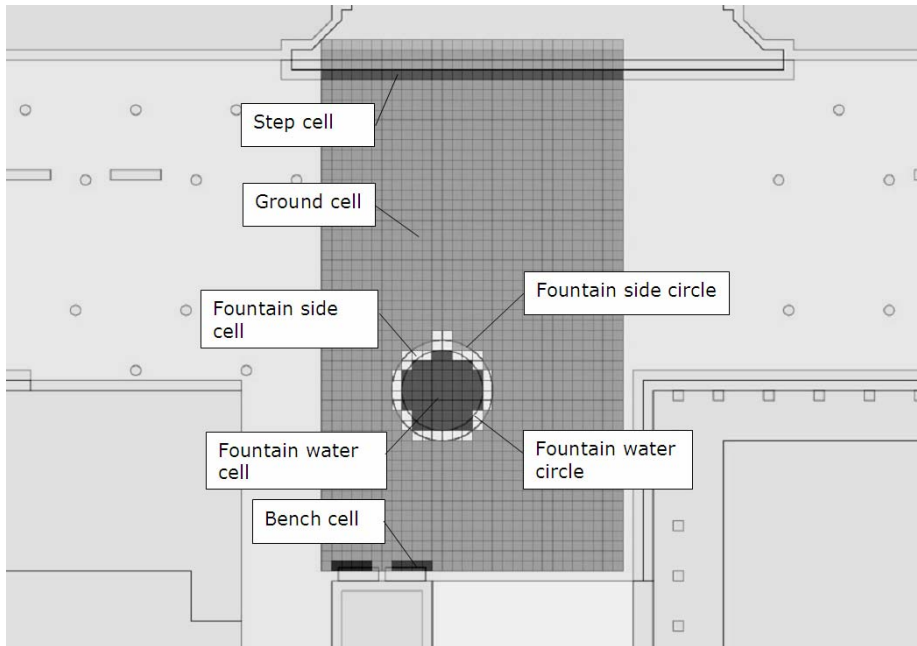
The DXF model is a text file which contains all the information about the geometries and their associated layer names. It is then parsed which the layer names and geometry information such as location and coordinates are converted into SVG elements. In SVG, attributes are added to the data structure of the elements. Meanwhile, the model is discretized into cells under the SVG structure. Each cell in the grid is an object that possesses several layers of properties. They include information such as location, usage properties (e.g. could be seated or not), environmental information (shading and wind speed information), and occupancy (i.e. occupied or not), etc. The information is accessible to the virtual users. Meanwhile, every virtual user can only occupy one cell based on its condition and his preference at a given time. That is, if a cell is being occupied, like being walked on it, it cannot be utilized by other users until the cell is free up. Since it might have more than one element exist in the same cell in the two-dimensional environment (e.g. a bench sits on the ground), cell properties are assigned based on the top most element, i.e. the one with the largest z-depths.

By now, the discrete space model becomes the usability-based building model. It is loaded with the required graphical and non-graphical information and is ready for further works.

As the SVG model is text-based, it requires a graphic formatter to present a graphical view to readers (Figure 4.2 and Figure 4.3). Also, for better visualization of the simulation result, a three dimensional model was created using the Virtual Reality Modeling Language (VRML) (Figure 4.4).



**Figure 4.2** Graphical view of the SVG model displayed in a SVG viewer (Yan 2005).



**Figure 4.3 Graphical view of the discrete space model - the fountain side, fountain water, benches, steps are all marked with different colors (Yan 2005).**



**Figure 4.4 The VRML model of the Sproul Plaza.**

## 4.2 The agent-based virtual user model

The agent-based virtual user model is responsible for geometrical modeling and motion control, perception modeling and behavioral modeling of virtual users. It models virtual users as autonomous agents who can perceive and understand the environment, and adjust their behavior to match it.

The simulation uses an object-oriented approach which virtual users are treated as objects who have certain properties and can execute some functions. Each virtual user has his own traits, goals, preferences and walking speed etc. They can walk to a location, avoid obstacles, calculate the shortest path and keep distance from strangers etc.

### 4.2.1 Geometrical modeling and motion control

#### 4.2.1.1 Geometrical modeling

Similar as the building model, virtual user is modeled in SVG format which includes both graphical and non-graphical information of virtual users. The SVG virtual user is basically two-dimensional (Figure 4.5). A VRML three-dimensional model is used for visualization purpose (Figure 4.6).

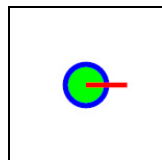


Figure 4.5 Two-dimensional model of an agent.



Figure 4.6 Three-dimensional model of an agent.

The graphical part of the SVG information includes only a circle and a short line indicating the facing direction of virtual user. This keeps the user modeling simple and focus could be made on the more significant properties, the non-graphical part of the user modeling. The non-graphical part of the user model defines the traits of the virtual users. The traits are defined based on the field study, which are expressed in terms of probabilities. For example, if the percentage of virtual users sitting in shade at the

fountain is 8.96% (hypothetical number), a virtual user has 8.96% of possibility sitting in shade at the fountain. The duration of stay of all the virtual users is assumed to follow a normal distribution which the mean and standard deviation were obtained from the field study.

The three dimensional VRML model presents virtual users as matchstick people who have arm and leg movements to depict basic user behaviors of sitting, standing and walking. These matchstick manikins have the advantage of simple geometry which utilizes low computational resources while maintaining efficient communication of how people use the public space. Meanwhile, the matchstick people have different colors to distinguish different virtual users.

#### **4.2.1.2 Motion control**

The VRML virtual user model has basic motion controls as start or stop walking, running, sitting down, sitting still, standing up, and standing still. During each step of the movement, each virtual user would occupy one cell in the discrete space model and have 8 degrees of freedom in directions of north, south, west, east, northeast, northwest, southeast, and southwest. A script is used to create a sequence of motions like walk to location *A*, sit for *n* minutes, then walk to another location *B*. Transitional movements such as sitting down and standing up and directional changes are inserted into motion sequence automatically.

#### **4.2.2 Perception modeling**

Perception modeling refers to the cognitive model of virtual users which acquires knowledge about the built environment and interprets it. It mainly consists of four components: knowing, finding, seeing and counting.

**Knowing** refers to the ability to identify natures of components in the built environment to help basic decision making of what to do and how to behave. The virtual users obtain their knowledge of the built environment from the usability based building model which they know location and orientation of all seats, all walkable areas and obstacles to avoid, shaded and non-shaded areas, windy and calm locations etc..

**Finding** refers to the ability to locate the most favorable path between the starting and the target points. People tend to use shortcuts (Gehl, 1987) and avoid unfavorable areas (like windy and shady areas in a cold environment). The virtual users are scripted to be able to locate the shortest path with most number of cells fall within the comfort zone. As the Plaza contains a relatively small area, the distance of the path is always in a higher priority. Give two paths with comparable distance, the virtual user would pick the one which has proportionally more comfortable cells along the route.



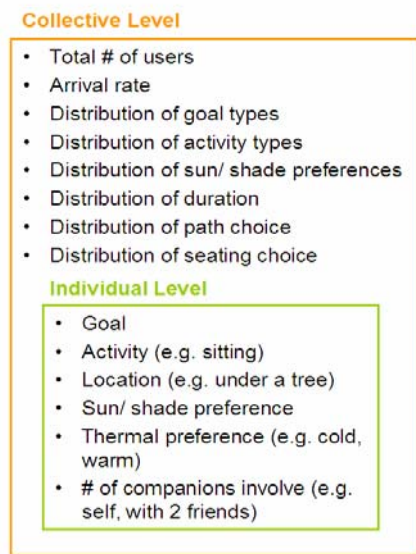
**Seeing** refers the ability to identify and react to unexpected objects within a circular area in front of a user in real-time. The unexpected objects are basically other virtual users whose presence in the proximity was not preconceived as other elements in the built environment in the beginning of the simulation. The virtual user would have to identify if it is an obstacle or an acquaintance. In case of the obstacle, he would have to modify the route to avoid hitting and keep reasonable inter-personal distance. In case of an acquaintance, a user would have to stop walking and stand for a while (to talk).

**Counting** refers to ability to identify duration fulfillment of a specific behavior. Every virtual user would follow the normal distribution curve of duration if he is to stay in the Plaza for a while. He would have to identify if he has stayed for a period long enough. If yes, he would leave and continue other motions in his sequence; if not, he would continue to stay in the Plaza.

### **4.2.3 Behavioral modeling**

Behavioral modeling concerns the way the simulation mimic human behavior in similar socio/spatial environments, given similar goals. In this study, an agent-based approach is used which the behavior of virtual users is determined through a hierarchical structure of behavioral rules. Behavioral rules provide sets of criteria and conditions which behavior would happen. For example, a walking person will avoid collision with a seat on the route. A person looking for a seat will look for something which could be seated on.

Based on the impact of microclimate on the usage of urban plazas, behavioral control is set at two levels, *collective level* and *individual level* (Figure 4.7).



**Figure 4.7 Behavioral control hierarchy.** specialized to each individual.

**Collective level** concerns what is happening in the global environment. Elements that are controlled in the collective level include total number of users, arrival rate, distributions of goals, activity types, sun/ shade preferences, duration, path choices and seating choices. These elements are controlled by the environmental model based on the microclimatic conditions and the physical environment of the urban space concerned. The mechanism is to use statistical information and probability distribution obtained in field survey.

**Individual level** concerns behavioral elements dedicated to each individual. Elements that are controlled in individual level include goal (activity), location, duration of activity, thermal and sun/ shade preferences, and number of companions involved. These elements are controlled by individual agents and are

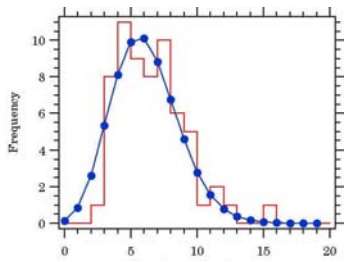
#### 4.2.3.1 Behavior in collective level

Collective level concerns mass behavioral pattern which defining with behavioral rules is not appropriate. Earlier in the sessions of statistical study and environmental model, we have described the application of multiple regression equations in the determination of distribution of activities, locations, sun/ shade preferences, path choices and seating preferences. Besides multiple regression equations, the simulation also employs different probability distributions to define behavior in collective level to add realism. These probability distributions are generated by statistics obtained from field measurements and observations on site.

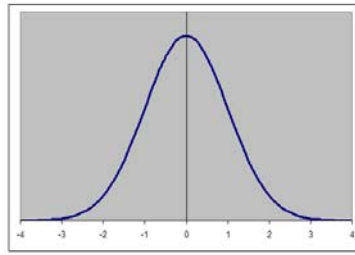
Poisson distribution (Figure 4.8) expresses the probability of a number of events occurring in a fixed period of time if these events occur with a known average rate, and are independent of the time since the last event. It is commonly used to model the number of random occurrences of some phenomenon in a specified unit of space or time. Therefore, it can be used to set up the rate that users enter the plaza.

Normal distribution (Figure 4.9) illustrates the quantitative phenomena in the natural and behavioral sciences. Therefore, it can be used to characterize elements like duration of stay.

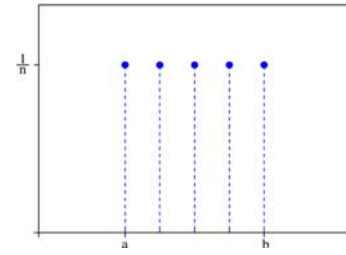
Uniform distribution (Figure 4.10) characterizes equal chance of occurrence of events. Therefore, it can be used to characterize events like meeting acquaintances.



**Figure 4.8** Poisson distribution for discrete probability process like arrival rate (Source: <http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg>).



**Figure 4.9** Normal distribution for distribution like duration (Source: <http://www.climateaudit.org/wp-content/uploads/2007/01/linsay7.jpg>)



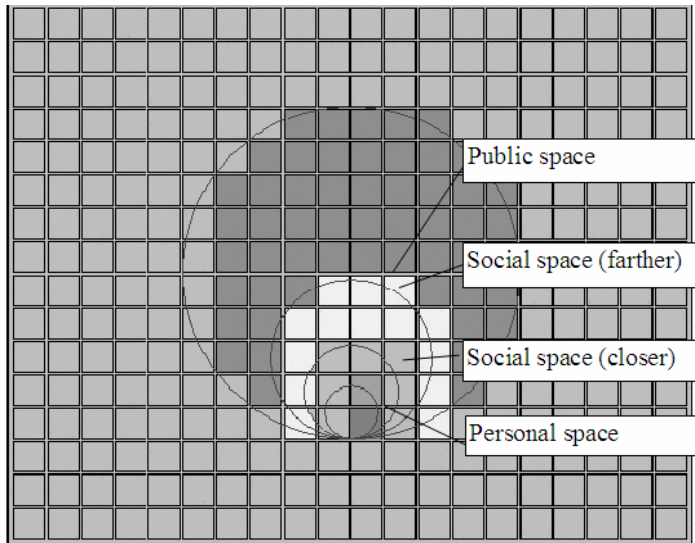
**Figure 4.10** Uniform distribution curves for distribution like meeting acquaintance (Source: [http://en.wikipedia.org/wiki/Uniform\\_distribution](http://en.wikipedia.org/wiki/Uniform_distribution))

#### 4.2.3.2 General rule

General rule govern spatial distances between users. Yan (2005) had defined the general rule of social spaces for the virtual users based on Hall's (1966) study on proxemics. Hall identified four categories of spatial territory which Yan used to determine the minimal distance between users. The four categories of social space are:

- Personal distance: 1200mm (4 feet)
- Social distance (close phase): 2100mm (7 feet)
- Social distance (farther phase): 3600mm (12 feet)
- Public distance: 7500mm (25 feet)

The four spaces of a virtual user are expressed as groups of cells in front of the user as shown in (Figure 4.11). The spaces would change with the change in the user's direction and movements. The spaces used that affect virtual users' movement are personal space, social space (closer), and social space (farther). Public distance is not affecting users' movement because other persons present can be seen only peripherally in this distance (Hall, 1966).



**Figure 4.11 Virtual users' social spaces (Yan 2005).**

#### **4.2.3.3 Detailed rules**

Apart from the general rule of social distances, detailed rules are required to govern individual's behavior. Whyte has identified seven elements for an urban space to be successful: seating, relationship with the street, sun and wind, water, trees, food and triangulation. By successful, it means that people are attracted to the urban space and are willing to spend time, carrying out various activities in the space. To characterize the impacts on the basic activities of walking, sitting and standing, Yan (2005) has grouped the influence of the seven elements into the following effects:

- Edge effect: affects walking, sitting and standing
- Attraction effect: affects walking, sitting and standing
- Distance effect: affects walking only
- Support effect: affects standing only
- Group effect: affects walking only
- Comfort effect: affects walking, sitting and standing
- SeatingPreferenceIndex: affects sitting only

## **Edge Effect**

People tend to walk along edges in large spaces, sit and stand along building facades which could provide sense of security and can have view to the outside. Edge effect is therefore a function of distance to boundaries of buildings or other architectural features like flower beds or fountains.

## **Attraction Effect**

People and human activities are the greatest object of attention and interest (Gehl 1987). High aesthetic quality architectural elements also attract users. Attraction is effect therefore the sum of the influence of surrounding effects, including the number of people involved and the distance between the event and the location of the user.

## **Distance Effect**

People tend to choose the shortest route instead of the safest one. People would cross the road on ground level even there are pedestrian flyovers. Paths on lawns also indicate shortcuts are preferred. Distance effect is therefore a function of distance.

## **Support Effect**

People tend to stand where supports are available and where there are irregular facades. It is therefore a function of availability of support.

## **Group Effect**

Three basic rules are defined based on Reynolds' Artificial Life's flocking algorithm. The three simple rules define the heading direction of a so-called Boid and result in a complex behavior pattern that mimics birds' flocking. The three rules are separations, alignment and cohesion.

**Separation** deals with minimal distances between users which characterize the spatial territory of users and is the same as what is used in the general rule.

**Alignment** concerns directional behavior of people walking in public spaces. Whyte pointed out that people walk at different speed, skip steps, weave in and out on crossing patterns, accelerate and retard to match the moves of the others.

**Cohesion** refers to the fact that people are bind together spatially by outside factors like existence of other people, their activities and events that happens in the public spaces

concerned (Whyte 1980). People try to stay in the main pedestrian flow or move into it (Whyte, 1980). They gather with and move about with others and seek to place themselves near others. New activities begin in the vicinity or events that are already in progress also tend to attract people to stay close.

### **Comfort Effect**

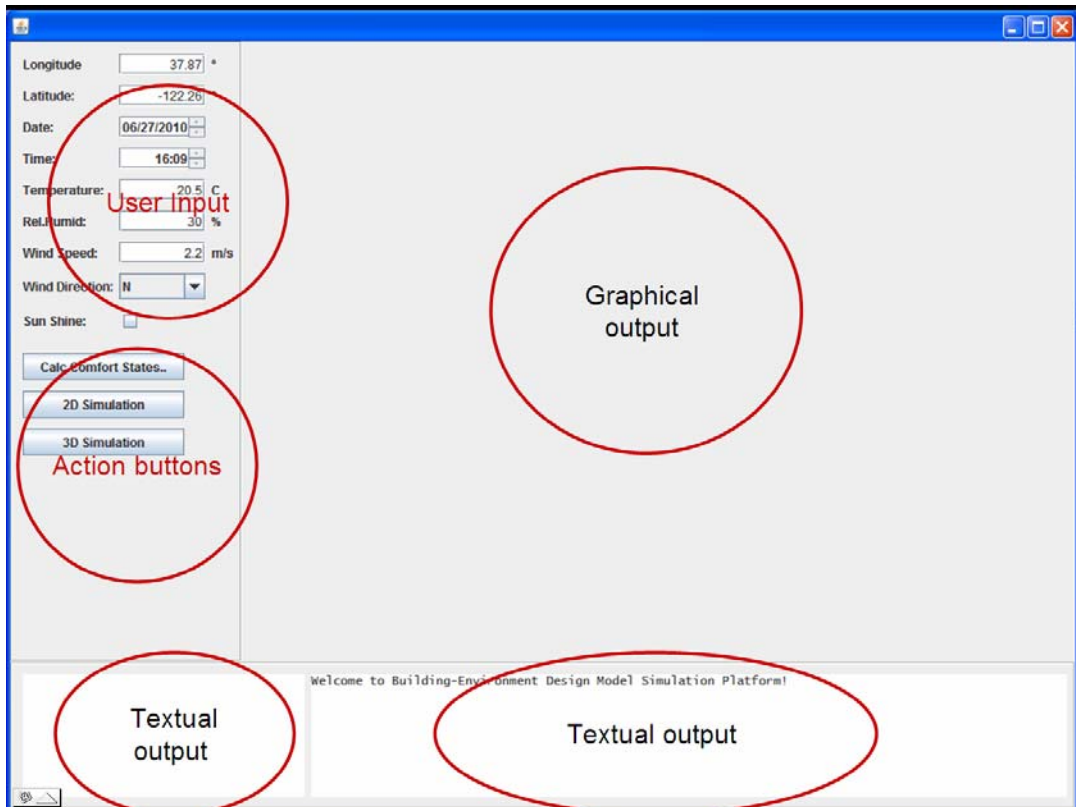
In Yan's model, comfort was considered as a function of shading provision and seating type. The effect of microclimate was not included. In this study, the comfort factor is modified. It is expressed as a function of *sunShade factor*, *thermal preference*, and *outdoor thermal comfort*. The comfort effect is translated to comfort maps, activity option maps and other information as described earlier in the session of environmental model.

### **SeatingPreferenceIndex**

A user intend to sit would find a seat where it is close, secure, have good views and comfortable. The choice is based on the seatingPreferenceIndex which is a function of closeness, security, points of interest and comfort. The higher the index, the more likely the seat is to be chosen by the user. As each user already has an activity option map of his own, he would make his choice based on the DistanceFactor, EdgeFactor and AttractionFactor within the available comfort cells in the option map.

## **4.3 The environmental model**

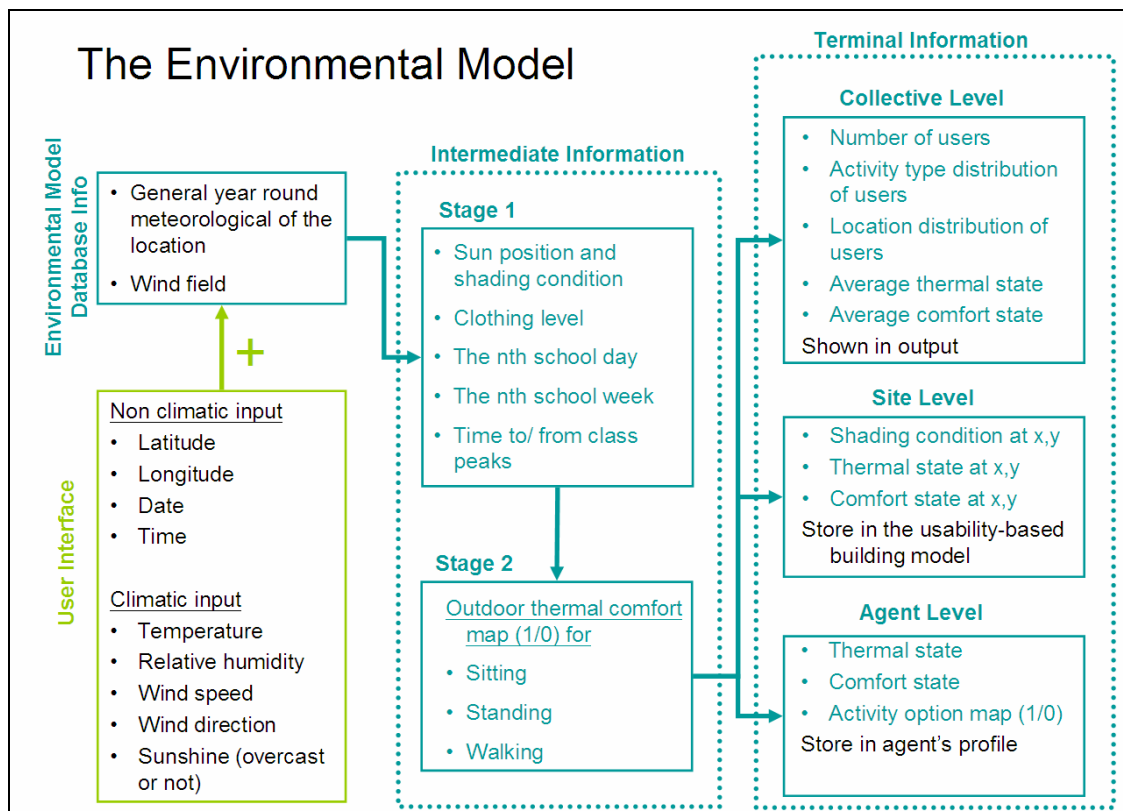
The environmental model manages intangible information which is influenced by microclimate. The information is based on inputs from the user interface (Figure 4.12) while the outputs are sent to the usability-based building model, the agent-based virtual user model and the output interface, depending on the type of information generated.



**Figure 4.12** User interface.

### 4.3.1 The structure

The environmental model collects non-climatic inputs of latitude, longitude, date and time of the simulation environment, and climatic inputs of local temperature, wind speed, wind direction, relative humidity and sunshine condition of the space in interest from the interface. After several stages of calculation, it generates collective simulation results as number, activity and location distribution of users, thermal and comfort states for various activities at the discretized cells, and comfort map, activity option map, thermal and comfort states of individual virtual users (Figure 4.13).



**Figure 4.13 Processes in the environmental model.**

### 4.3.2 The intermediate information

The non-climatic data input helps to define the sun position and corresponding shading condition of the environment which is saved as a separate information layer at the usability-based building model. It also helps to define the school day and the school week in the semester which was found to be statistically significant in defining the spatial usage in the Sproul Plaza which is a campus environment.

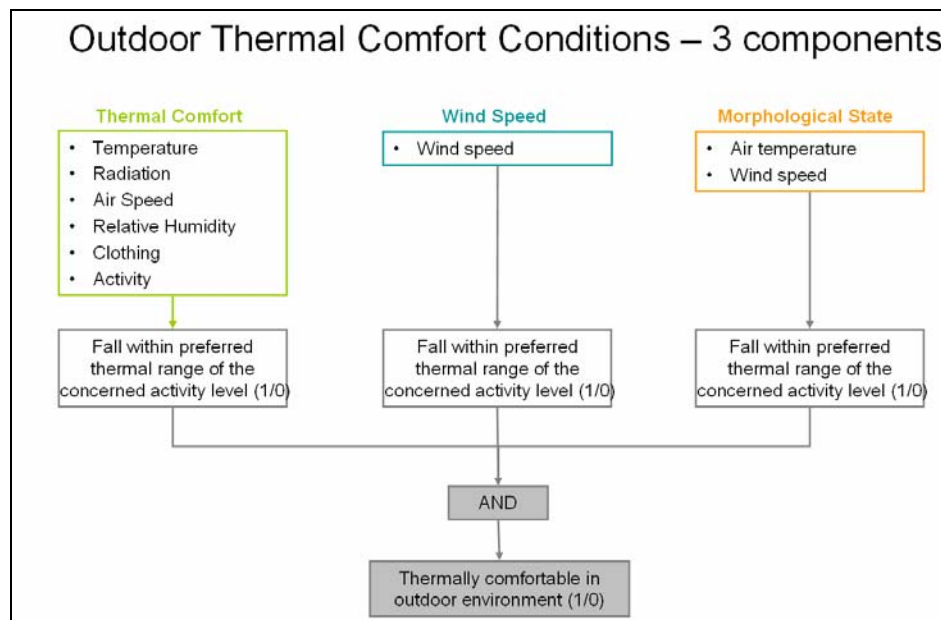
The climatic data input refers to local climatic data, which is equivalent to those being obtained from local weather station. The environmental model is responsible to generate microclimatic information based on the climatic data input. In this case, users are free to input any climatic data for hypothetical testing. Clothing level is virtual users is also determined by climatic input, temperature. It is assumed that all virtual users are clothed to the same level based on the temperature. Though, field study showed a great variance in the clothing level.

Meanwhile, it is not enough to generate all the required information with only the input data. Extra data is stored in the environmental model for further processes. This includes



the general year round meteorological record from the nearby weather station and the wind field of the local space in interest. For the prototype development, only data for the Sproul Plaza is available. In this study, the general meteorological record was obtained from the weather station situated on the top of 2111 Bancroft Street in Downtown Berkeley. It contains useful information like temperature, wind speed, wind direction and humidity at intervals. The station has full year meteorological data from year 2001 to 2009. The data was averaged to obtain a general year round data to help deriving spatial usage data in a collective level. The wind field is comparatively more complicated. It was based on airflow simulation from eight major directions (N, NE, E, SE, S, SW, W and NW) to support hypothetical case studies. The simulation was first calibrated using field measurement and meteorological records. It is then run several times to obtain wind fields from the eight directions. The wind field contains wind speeds at discretized cells at level 1.2m meter and 1.6 meter, which are about the head levels of people sitting and standing. The cells discretized in the airflow simulation are coherent with those used in the usability-based building model. As airflow simulation requires significant time and computing resources to obtain meaningful results, it was pre-calculated and the results were saved in text format for further processes. The air flow information is essential in deriving spatial usage in collective level as well as thermal state of individual users.

The second stage is to generate outdoor thermal comfort map for three common primary activities, sitting, standing and walking. The outdoor thermal comfort is assessed using the method described in ASCE (2004), which is based on thermal sensation, wind speed and wind chill. The three components are assessed individually as well as in combination to determine the overall level of comfort (Figure 4.14). In order to be considered as thermally comfortable in outdoor, all the three components have to fall within the comfort range.



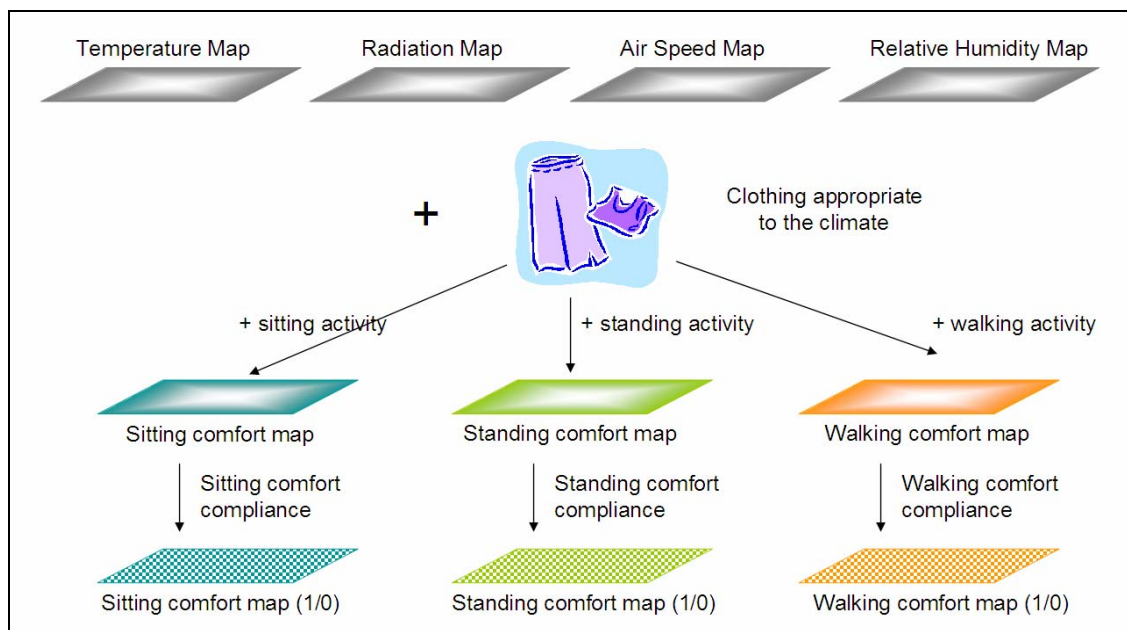
**Figure 4.14 Outdoor comfort determination procedure.**

The first step is to generate thermal sensation index (TSENS) map. TSENS is calculated using the Pierce Two-Node Model. It uses skin temperature as indicator for cold environment and skin wetness for hot environment. TSENS is calculated based on temperature, radiation, air speed, relative humidity at the discretized cells, together with the clothing level of virtual user, and the mentioned types of activities. The TSENS scale (Table 4.1) is used to represent the thermal comfort level. A typical comfort range is set from -1.0 to +1.0.

**Table 4.1 Thermal sensation (TSENS) scale**

-3	-2	-1	0	1	2	3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

The TSENS values at the cells are included in the usability-based building model. A comfort range is set from -1.0 to +1.0. In this case, all cells having TSENS value fall within the range is considered complying comfort of the corresponding activity (Figure 4.15). The thermal comfort fulfillment at cells then forms binary thermal comfort maps of activities. In parallel, comfort state at cells is also generated which positive values and negative values refer to comfortable and uncomfortable conditions respectively. The comfort states of activities are also included in the usability-based building model.



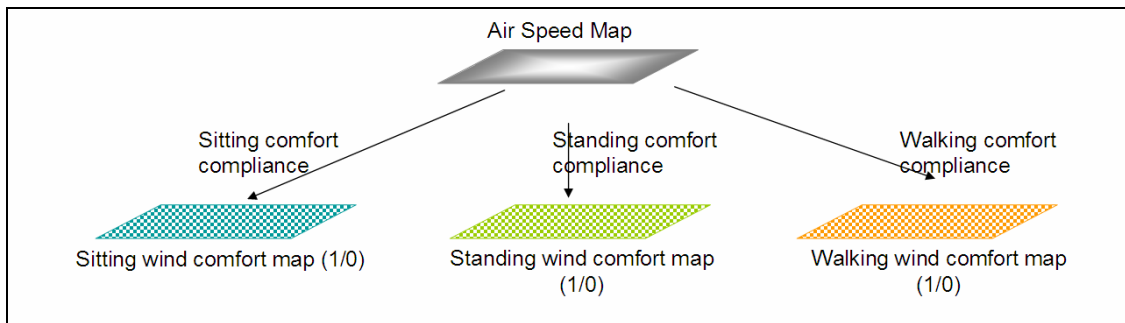
**Figure 4.15 The process of generating thermal comfort map.**

The next step is to generate wind comfort map for the three activities. Different activities have different comfortable range for wind speed. The acceptable ranges for three typical outdoor activities are shown in Table 4.2 (ASCE, 2004).

**Table 4.2 Wind speed ranges for activities, based on 20% probability of exceedance<sup>6</sup>**

Activity	Comfortable range for mean wind speed (m/s)
Uncomfortable for any activity	>5.4
Walking	0-5.4
Standing	0-3.9
Sitting	0-2.6

As in the thermal comfort map, the air speed map is checked with the compliance of the three activities to generate binary wind comfort maps. The maps show the cell is either fulfilling wind comfort of the corresponding activity or not.

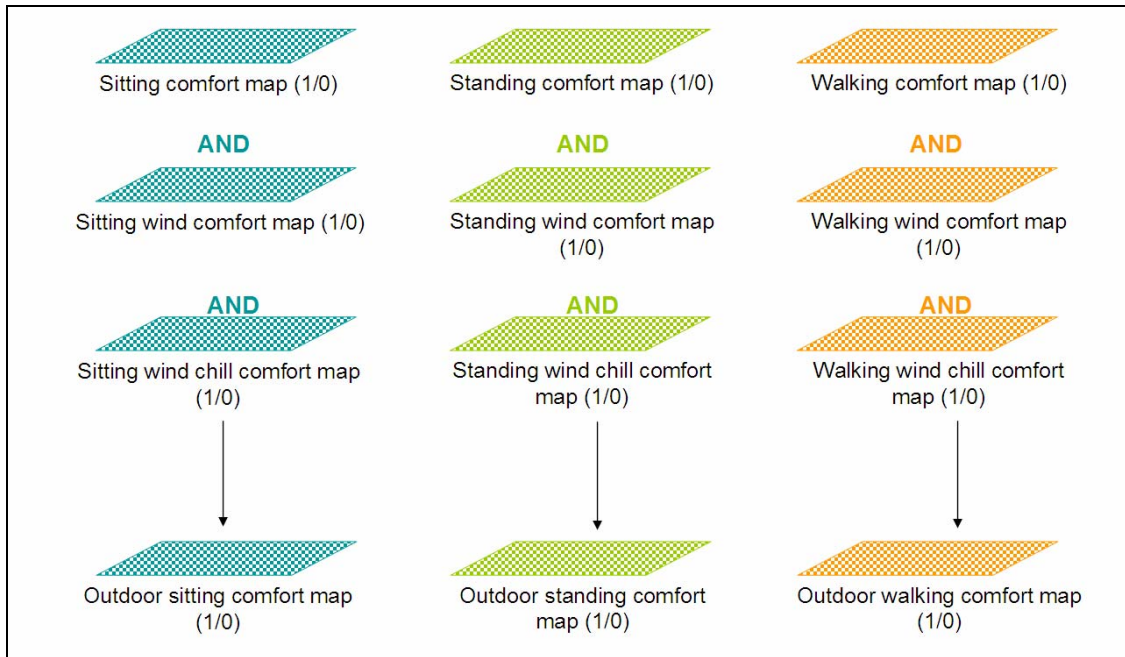


**Figure 4.16 The process of generating wind comfort map.**

The third step is to generate wind chill comfort map for the three activities. Wind chill combines wind speed and air temperature to determine chilling effect on the exposed skin. Wind chill effect is normally associated with cool climate, for example, it can be experienced during winter in many large North American cities when winds are channeled down the canyon-like streets (Aynsley, 1974). However, as suggested by Soligo et al (1997), only areas subject to seasonal temperatures less than 10°C should include a wind chill component when assessing pedestrian comfort (Soligo et al., 1997). In locations where this kind of low temperature condition rarely occurs even in the coolest January, the wind chill component could be neglected in the prediction of pedestrian comfort (Cheng and Ng 2006). The wind chill temperatures can be obtained by simple equation (Figure 4.17). An equivalent temperature of -20°C (-4F) is used as an onset of discomfort (ASCE, 2004).

<sup>6</sup> Since wind speed varies, the probability of exceedance is usually specified. 20% probability of exceedance means that an activity is “comfortable” if it stays for 80% of the time or more within the range stated.





**Figure 4.19 The process of generating outdoor thermal comfort.**

### 4.3.3 The terminal information

With the inputs and the intermediate information generated, we can then generate more meaningful information which is directly associated with the simulation of the spatial behavior of the virtual users.

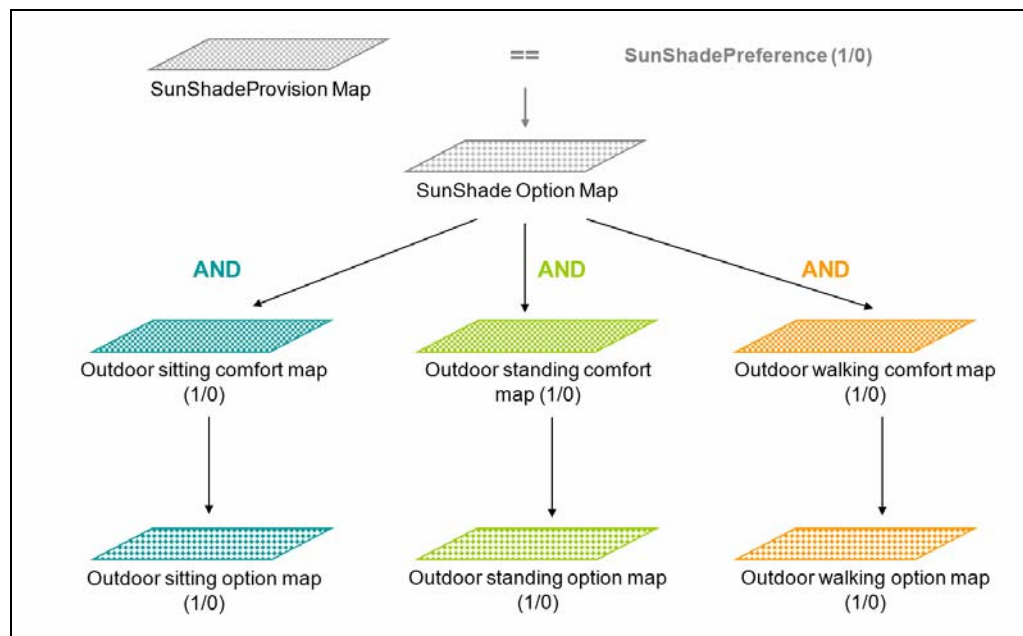
Firstly, we will generate information concerning the spatial usage pattern on a collective level. This includes the number of users, the activity type distribution of users, the location distribution of the users, average thermal state and average comfort state of the users. The duration of stay is not included as field study showed that it had little association with any factors studied. It is controlled at the agent level.

Except average thermal state and comfort state, the collective level information required is generated using regression equations derived from statistical studies. The statistical studies generated coefficients for factors affecting spatial behavior which could be applied in the regression equations. The factors being used in the regression equations are the day and the week for simulation in the semester, the time of usage, time to or from class peaks and the corresponding square values, temperature, wind speed, relative humidity, the proportion of Plaza exposed in sun, the presence of direct sunlight, clothing level, comfort of standers, sitters and walkers, normalized values of microclimatic data in a day and the corresponding square values. Not all the factors listed are directly input from the user interface. Some were derived or calculated in the earlier processes based on

the user inputs. For example, school day and week are derived based on the date input; normalized microclimatic data of the day is derived based on the year round meteorological record stored; clothing level and comfort values are intermediate results generated by the environmental model.

The average thermal and comfort states depend on the number of the users of each type of activities, as well as the location of people staying in the Plaza. The thermal and comfort states at locations are stored with other cell properties in the usability-based building model. As passers-by would not stay at a particular cell, the average thermal and comfort state of the passers-by are depending on the average values at the cells along the path. For virtual users who would stay at a particular cell, like those sitting, the values at the target occupied cells are averaged to obtain the required information. These values are reflected in the output interface.

At individual level, activity option map is to be generated for each virtual user. Each virtual user has his own shading preference. This preference is combined with the shading condition map to provide a binary sun/ shade option map. This map is combined with the outdoor thermal comfort map of the target activity of the virtual user. This map shows optimum location available for the target activity of individual virtual user (Figure 4.20). With all the options available on the map, the virtual users choose routes and destinations based on their needs, behavioral rules and preferences. If there is no option available, the virtual user would exclude the comfort consideration in the decision making process. Though so, the limited options reflect low comfort level which in turns affects overall spatial usage pattern.



**Figure 4.20** The process of generating activity option map.

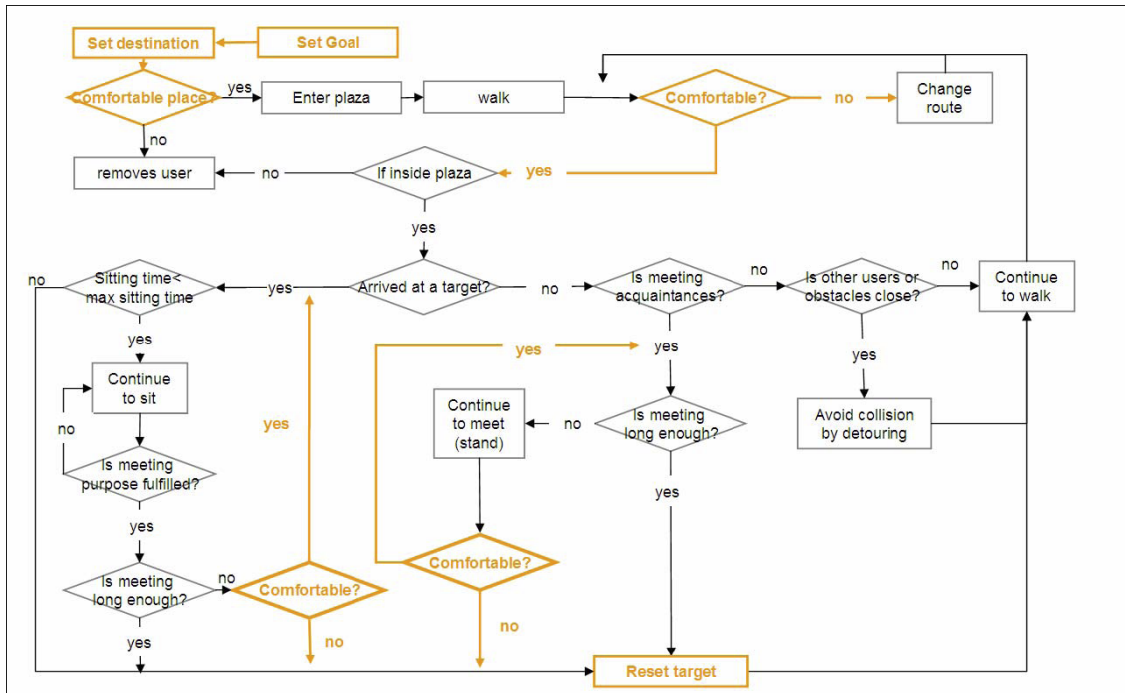
#### **4.4 The life of an agent**

In the beginning of the simulation, the properties of the whole environment are made known to the virtual users. That is, they know places that could be seated, shaded and exposed areas, windy and calm spots, etc. Each agent has preference and goal assigned within the bounds of the mass spatial behavioral pattern. The types of goals follow the definition of Yan (2005).

- To rest: sunbathing, eating and people watching etc.
- To play: performing, dancing and gaming etc.
- To gather: waiting and talking
- To pass by: going to other places

To goals are then considered as major primary activity to be carried out. Primary activities are those which could be identified visually and have no social or cultural meanings. In this study, we only focus on sitting, standing and walking as these are dominant primary activities found in urban plazas (Gehi, 1996; Whyte, 1980; Yan, 2005).

With the goal and preference defined, the agent would obtain his activity option map. He then needs to go through a series of processes to fulfill his journey in the Plaza. Consider an agent tends to sit in the Plaza for a while, his journey would follow the following structure (Figure 4.21).



**Figure 4.21 Model flow of an agent intended to sit.**

First, he would have to define his destination according to the location distribution pattern and his activity option map. If there is more than one option available in his activity option map, i.e. more than one favorable place, the agent will choose based on needs and behavioral rules, like availability, distance, seatingPreferenceIndex and number of users nearby. If there is no option available, i.e., everywhere in the Plaza is uncomfortable, virtual user would quest his goal of Plaza usage. If he needs to pass by or gather, he still has to fulfill his need and choose a destination based on the predefined behavioral rules, excluding comfort consideration. Otherwise, the system would remove the user.

Having the destination set, the agent then enters the Plaza and behaves according to the behavioral rules predefined. He would pick the shortest comfortable path and move forward while keeping reasonable interpersonal distance. He would detour in case of meeting obstacles, or stop and chat if he meets someone he knows until he gets to the target seat. At the seat, he would count if he has spent enough time. When he finishes, he would reset his target where he would leave the Plaza.

During the process, he would check if the places he stops at are comfortable cells as he knew of. If not, he would relocate himself to another location which companion might or might not follow. If the companion does not follow, they would simply depart and the user would continue to his target place. If the companion follows, they would move to a favorable location for both of them. As there are chances that the preferences of the users are opposite, like one prefers sun and one prefers shade, they would find places which have opposite properties next to each other.



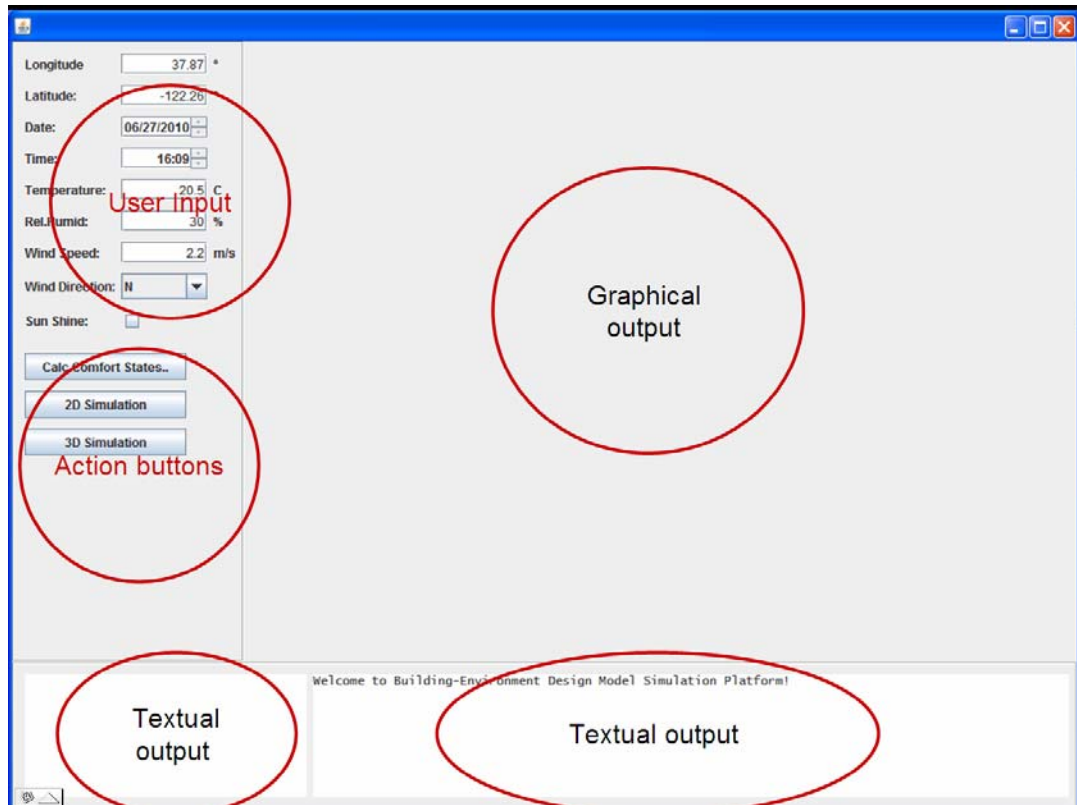
## Chapter 5

# Simulation and Visualization

In the previous chapter, we have described in details the properties and functions of the major components of the simulation model, the usability-based building model, the agent-based user model and the environmental model. In this chapter, we will describe how the three models are tied together in action to perform the simulation process.

### 5.1 The simulation process

The simulation starts with a window which contains a user input panel, a graphical output panel and a textual output panel (Figure 5.1). The user input panel offers input latitude, longitude, date, time, temperature, relative humidity, wind speed, wind direction, and the presence of direct sunlight. It also contains action buttons to proceed the simulation process. The graphical output hosts both outputs from the two-dimensional and three dimensional simulations. It is empty in the initial state. The textual output records collective usage information, including the estimated total number of users, the percentage distribution in terms of activity types, the average thermal and comfort states of users of different activities. The initial values are all 0.



**Figure 5.1 The simulation window.**

The simulation runs in two stages. In the first stage, the environmental model is in action which the input parameters are collected to determine the shading condition, air flow condition, outdoor thermal comfort maps of primary activities, as well as the collective behavioral information. The shading condition is handled by the internal engine. The air flow information is based on preloaded results from commercial simulation program, Fluent. The thermal and comfort information is calculated real-time using the Berkeley comfort evaluation program developed by Environmental Analytics (Berkeley, CA) for the American Society of Heating, Refrigeration, and Conditioning Engineers (ASHRAE) under RP-781. The collective behavioral information is based on field research. All the information is further processed to generate different sun/ shade option map and activity option maps for each agent (virtual user). During the process, the shading, wind speed, thermal state and comfort state distribution patterns are recorded with the building model. Individual thermal and comfort states, as well as the activity option map are recorded to the agent's profile. The collective usage information is to be combined with the building model and the user model for further simulation. Up to this point, textual information is ready for output.

In the second stage, the two-dimensional simulation renders the plaza usage scene based on the collective usage information, usability properties of the building environment and the behavioral rules of the users. The simulation engine first loads the SVG model which usability information is parsed. An agent path list is then created which a virtual user in

added upon entering the plaza and removed upon completion of journey. The list records all users' behavioral information associated with their paths, including the coordinates along paths, arrival time, motions, sitting directions, and duration of stay. The engine then runs the simulation at time steps (1 second per time steps). At each time step, each virtual user is moved by one step. They could be entering the plaza, move one step in the plaza or leaving the plaza, depending on the collective behavioral pattern generated. Upon each move, the agent path list is updated with the new coordinates of the virtual user if he is still in the plaza. Meanwhile, the virtual users move in the plaza according to the behavioral rules, their own activity option maps and the environmental properties perceived. The movements are displayed in the graphical output panel (Figure 5.2). At the same time, the agent path list is saved which could be viewed in the graphical output as a two-dimensional display (Figure 5.3) or use as a base for the three dimensional visualization.

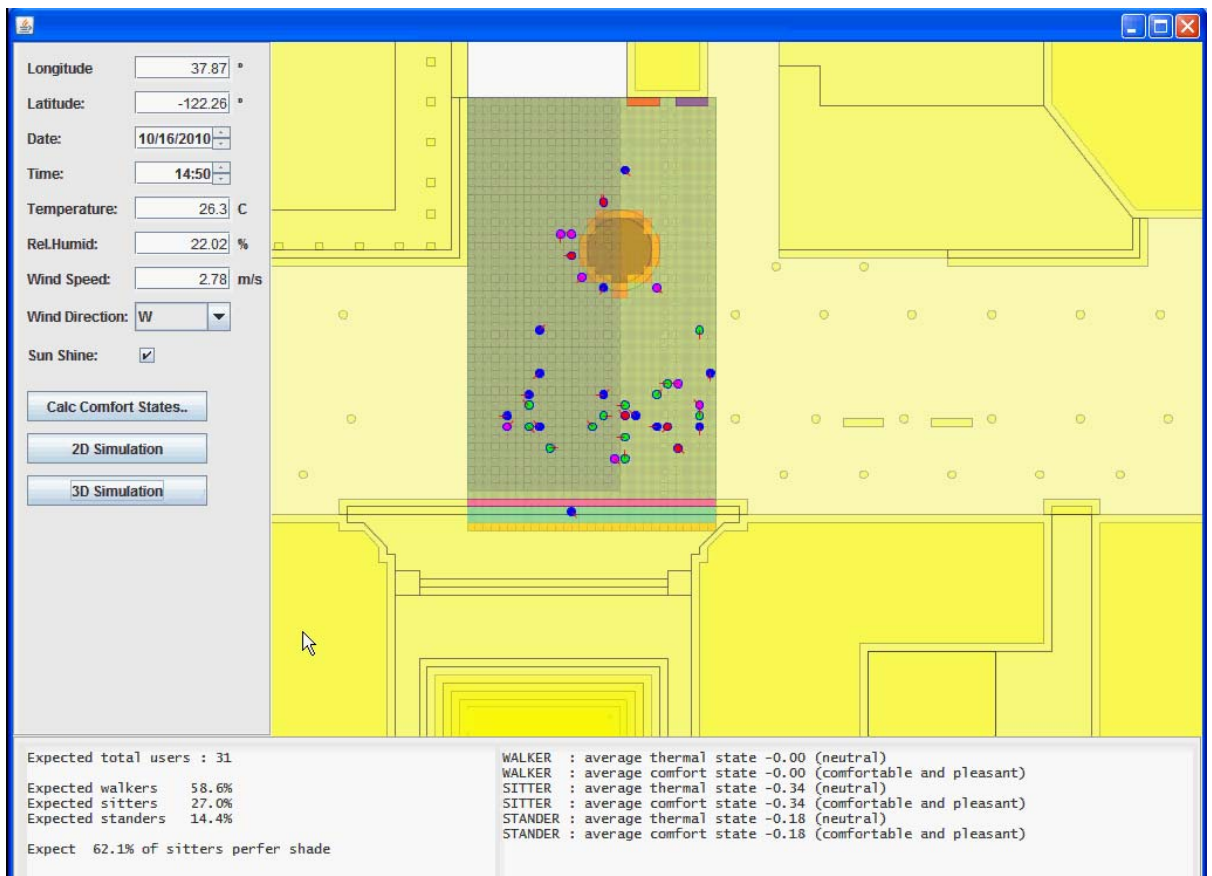


Figure 5.2 Two dimensional simulation with textual output.



**Figure 5.3 Two dimensional display of the path list.**

The three dimensional simulation renders the plaza usage scene in VRML based on information from the agent path list. That is, it is mainly used as a visualizing tool instead of a simulation engine which is run in the two dimensional simulation. A major reason is that even 3D simulation offers traits similar to those observed in reality, it is much less efficient and effective than 2D simulation. Also, as the plaza usage scene is designed to display usage for a period of time, the appealing animation might require significant resources in the simulation process which could be a tradeoff.

## **5.2 Validation**

Sample scenarios are run to compare with field records. Figure 5.4 shows a field record on 10/16 at 2:50pm. There were altogether 14 walkers, 9 sitters and 6 standers recorded. Majority of users at the fountain sat under shade. The temperature was 26.3°C; wind speed was 2.78 m/s; wind direction 267.2°; relative humidity was 22.02%. The same parameters were used to run the simulation.



**Figure 5.4** Photo of field survey show majority of sitters at the fountain were in shade.

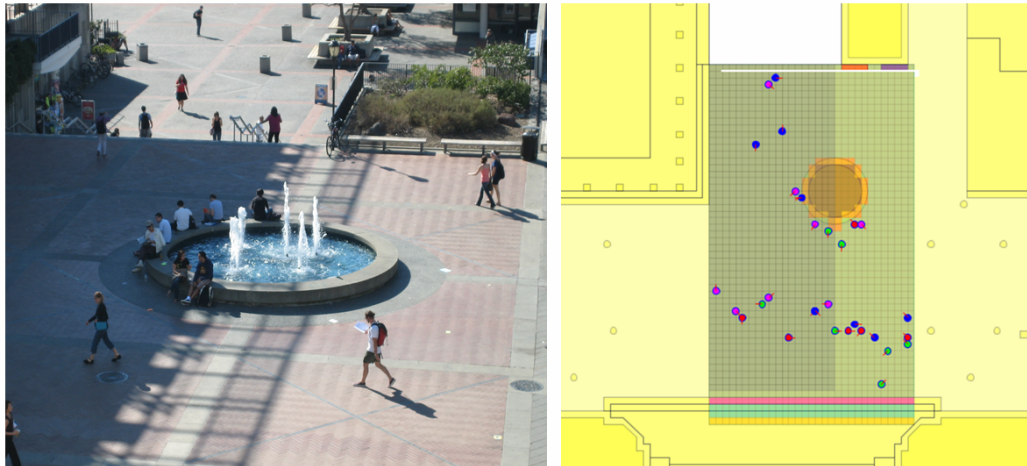
Figure 5.5 shows the simulated plaza using the same parameters. The simulation expects 31 users, with approximately 18 (58.6%) walkers, 8 (27.0%) sitters and 7 (14.4%) standers. 62.1% of sitters are expected to prefer shading condition (Table 5.1). These match with the field record. Figure 5.6 shows a comparison using the field photo and the two dimensional result where the gray grid indicates the shaded region. Majority of the sitters are found in the shaded portion of the fountain which is similar to the captured image.



**Figure 5.5** Plaza usage simulation using the same parameters as field record.

**Table 5.1 Comparison of sample scenario with simulation**

	Total	Walker	Sitter	Stander	Walker comfort	Sitter comfort	Stander comfort	% of Sitters prefer shade
<b>Field Data 1</b>	29	14	9	6	0.02	-0.32	-0.17	77.8%
<b>Simulation 1</b>	31	18	8	7	0	-0.34	-0.18	62.1%



**Figure 5.6 Simulation of the scenario with majority of fountain sitters at shade.**

Another scenario is run to compare with the field record. Figure 5.7 shows a cool and windy morning when there was limited number of users in the Plaza. It was 10am on 4/28. The temperature was 10°C; wind speed was 5.06 m/s; wind direction was 292.2°; relative humidity was 54.06%. Altogether, there were 9 walkers and 3 sitters recorded.



**Figure 5.7 Field record showing limited people using the Plaza.**

Simulating with the same parameters also produces a low usage scenario (Figure 5.8). The simulation yields 4 more walkers while the number of sitters and standers are the same (Table 5.2). The result is close to the field record. Figure 5.9 shows a side by side comparison for easy reference.



Figure 5.8 Simulation also shows low level of usage.

Table 5.2 Comparison of sample scenario with simulation

	Total	Walker	Sitter	Stander	Walker comfort	Sitter comfort	Stander comfort	% of Sitters prefer shade
Field Data 2	12	9	3	0	-0.54	-1.72	-1.75	0%
Simulation 2	16	13	3	0	-0.54	-1.72	-1.75	0%

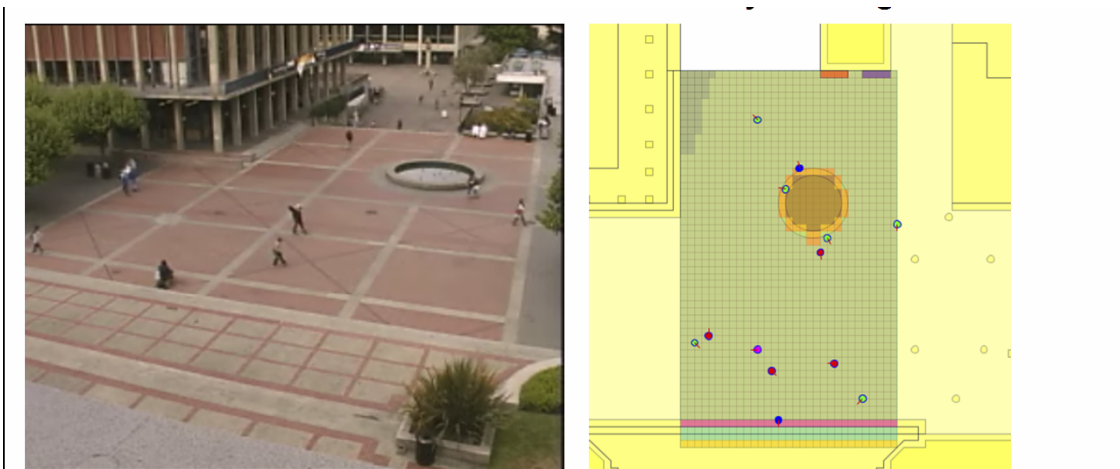


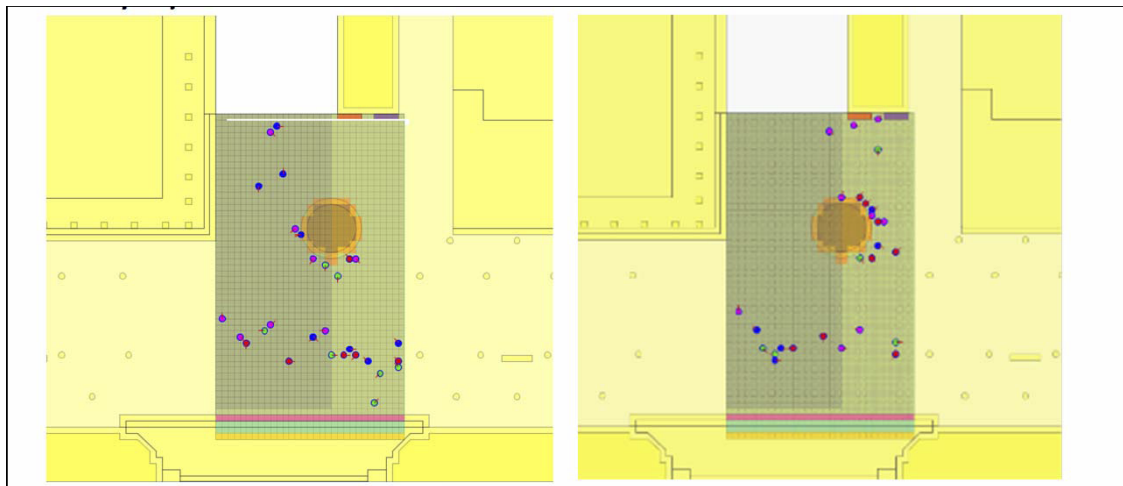
Figure 5.9 Comparison of a low usage scenario in a cool and windy morning.

### 5.3 Simulation for comparison of design alternatives

To experiment how microclimate affect users' behavior, we kept the previous simulation which more sitters clustered in shade as a control and ran another simulation with a

cooler temperature, 16.3°C. It is expected that people would run to the sunny side of the fountain to seek for a warmer environment.

Figure 5.10 shows a comparison of the two simulations. It could be seen that seated people cluster on the sunny side of the fountain at lower temperature. The testing case expects 27 users, with approximately 15 walkers, 9 sitters and 3 standers (Table 5.3). All of the users are expected to prefer sunny condition. Compare to the previous simulation, there are slightly fewer users and the activity distribution is similar. The main difference is the percentage of shading preference of sitters as well as the thermal and comfort states. The control simulation shows 62.1% of sitters prefer shading while the testing case shows no one prefer shading. The average thermal and comfort states in the control simulation are neutral, comfortable and pleasant for all of the activities. The testing case shows that average thermal and comfort states for sitters and standers are slightly cool, slightly uncomfortable but acceptable. Those values for walkers remain in the neutral and comfortable range.



**Figure 5.10** Left: simulation with 26.3 °C; right: simulation with a lower temperature, 16.3°C.

**Table 5.3** Comparison of sample scenario with different temperatures.

	Total	Walker	Sitter	Stander	Walker comfort	Sitter comfort	Stander comfort	% of Sitters prefer shade
<b>Control 1 (26.3°C)</b>	31	18	8	7	0	-0.34	-0.18	62.1%
<b>Case 1a (16.3°C)</b>	27	15	9	3	-0.21	-1.28	-1.04	0%

The second experiment uses the cool and windy morning as a control. We then run a few variations to see the impact of the change in environmental factors on human behavior.

First, we run a case with lower wind speed (from 5.06 m/s to 2.06 m/s) while keeping the temperature and relative humidity the same (10°C and 54.06%). We then run various cases with 5.0°C increment in temperature until 30°C.

Table 5.4 shows a comparison with all the cases listed. Case 2a, with lower wind speed, there is 1 more sitter expected while the number of walkers reduces from 13 to 8. The



comfort levels for all the three activities increase. Case 2b, with 5.0°C increase in temperature, the number of sitters return to 3 while the number of walkers increases from 12 to 20. The comfort levels for all the three activities continue to increase. Case 2c, temperature is increased to 20.0°C. There is 1 more walker and comfort levels for all the three activities increase. Other information remains the same. Case 2d, with temperature increased to 20.0°C, number of walkers decreases. Comfort levels for all the three activities continue to increase. Walker comfort becomes positive while comfort levels for the other two activities remain in the negative region. Case 2e, temperature is increased to 30.0°C. There is only 1 sitter left while the number of walkers increases to 50. Comfort levels for all the activities are now off the negative range.

**Table 5.4 Comparison of sample scenario with different temperatures.**

	Total	Walker	Sitter	Stander	Walker comfort	Sitter comfort	Stander comfort	% of Sitters prefer shade
<b>Control 2 (10°C, 5.06m/s)</b>	16	13	3	0	-0.54	-1.72	-1.75	0%
Case 2a (10°C, 2.06m/s)	12	8	4	0	-0.41	-1.57	-1.58	0%
Case 2b (15°C, 2.06m/s)	22	20	3	0	-0.2	-1.29	-1.03	0%
Case 2c (20°C, 2.06m/s)	23	21	3	0	-0.07	-0.86	-0.54	0%
Case 2d (25°C, 2.06m/s)	18	15	3	0	0.05	-0.33	-0.17	0%
Case 2e (30°C, 2.06m/s)	50	49	1	0	0.75	0	0.25	0%

From Case 2a through Case 2e, there are 5.0 °C increments in temperature, but the comfort levels increases only slightly. This is mainly because the clothing level is adjusted to accommodate the increasing temperature which compensates the original huge increase in comfort levels.

Meanwhile, Case 2e is an interesting case. Case 2d shows a drop in usage level. It is expected that the usage level would further decrease in Case 2e. Also, Case 2e shows only 1 sitter even with a comfortable sitting environment. This is probably because the simulation relies a great deal on field data while field data obtained does not include temperature as high as 30 °C. Therefore, hypothetical cases off the data range, like the one as in Case 2e, might not produce representative results.

## 5.4 Limitations

- The shading pattern could only be viewed in two dimensional simulation. In three dimensional simulation, VRML is used and it does not even cast shadows, because even this calculation would greatly slow down the rendering process. (Walsh and Bourges-Sévenier, 2001).
- Airflow distribution could not be viewed in both two dimensional and three dimensional simulations which evaluators could not have direct visual comparison between two different airflow conditions as in the comparison of

shading impacts. Airflow distribution information includes wind speed and wind direction. Wind speed is continuous data. It is often shown in color scale while wind direction is vector data which is often shown as arrows. In two dimensional simulation, the SVG viewer offers color differentiation for elements with different properties and transparency for the shading pattern. Including the airflow distribution information would complicate the scene and impairs the usage perception. VRML also cannot render airflow information.

- There are assumptions in the simulation setting which the simulation would not valid for all conditions. For example, there are only school periods and long holidays (summer and winter breaks). During the school period, there is no differentiation between weekdays and weekends. Also, the class schedule is assumed to be the same for every school day. Meanwhile, there is no daylight saving time throughout the year in the model.
- There is a range of input data for the simulation to have representative results. The statistics from field survey plays an important role in the simulation. Hypothetical cases that have great distinction from the realistic conditions might yield unrealistic number or distribution of users.
- There is also limitation for the comfort model used. The model works best for sedentary humans wearing light clothing and exposed to conditions near the middle of the ASHRAE comfort zone. The farther away you are from that type of condition, the more “error” there will be in the result. Since the model only predict thermal sensations for populations and not individuals, by error, we mean that the predicted value might overestimate or underestimate the mean response of a large group of people exposed to the conditions modeled.
- The simulation prototype only includes primary activities of walking, sitting and standing. In fact, there are more different types of primary activities, like cycling, running and lying. These were not included for the relatively small proportion in the sample data. That is, not all aspects of the usage pattern are reflected in the simulation. The simulation presents only the majority usage pattern of the environment.

## Chapter 6

# Conclusion

### 6.1 Conclusion

In this dissertation we have presented a behavior simulation model that targets on the problem of predicting and evaluating the impacts of microclimatic conditions on the spatial usage of its human inhabitants. We have proposed, implemented, and demonstrated a simulation framework that models the spatial usage pattern in association with the tangible physical built environment and the intangible microclimatic conditions. The simulation reveals the spatial usage pattern which could be considered as a virtual post occupancy evaluation. Evaluators can then see how spaces are used or how the physical environment performs under certain conditions, so as to assess if the design intention is achieved. Since the simulation generate spatial usage based on the physical built environment, the microclimatic environment and common human behavioral characteristics, it provides deeper understanding of the design environment than existing environmental assessments which do not include human interactions or human behavior simulations which do not take into account microclimatic conditions.

The simulation model was developed based on Yan's model developed in 2005. In addition to the original usability-based building model and the agent-based virtual user model, an environmental model which manages environmental data from user input, database and other simulation programs is included. It masters the collective behavioral pattern in terms of level of usage, activity type distribution and spatial distribution based on real world behavioral data. At the same time, it is closely tied to the original usability-based building model and the agent-based virtual user model. It parses intangible environmental information into the building model and records the environmental characteristics in the model area as other architectural elements. The information is perceivable and understandable by the virtual users and would serve as a base for virtual users' decision making. Meanwhile, the environmental model also generate series of maps for major activities, including thermal comfort maps, air speed comfort maps, wind chill comfort maps, outdoor thermal comfort maps, shading provision maps and shading option maps. An activity option map is eventually generated for each virtual user which shows optimum locations fulfilling his goal (what to do). On the other hand, the

behavioral rules that govern the behavior of the virtual users were also modified to cope with the inclusion of environmental preference and comfort requirement.

The simulation provides spatial usage information in three formats. Two dimensional graphical output offers a plan view to the simulation area where the paths of the virtual users could be easily identified. It also serves as a base for three dimensional output. The three dimensional output offers realistic perspective view to the model area which interactions between virtual users and the environment, and the virtual users' activities could be clearly represented. The textual output offers numerical information on the spatial usage, including the level of usage, the distribution of activity types, the average thermal and comfort states of the users.

To mimic reality, the virtual built environment is processed from traditional CAD model; the intangible environmental information is based on record from meteorological station and simulation results from certified programs; and the behavior of virtual users is based on statistics from a year round field study and well studied and defined behavioral rules which are derived from theoretical and practical environment-behavior studies. This does not only ensure quality results, but also the configuration helps to promote the usage in the design practice as the tools used are familiar in the field; and the behavioral rules, concept and the methodology employed are simple to be understood. It is expected the result of this research could change how architects and environmental behavior experts approach the design and evaluation of built environments.

## **6.2 Potential applications**

### **6.2.1 Design evaluation**

The proposed simulation could be used in the design practice as if design evaluation tool. In particular, it reflects the spatial usage which it could be used to evaluate architectural arrangement, activity planning schedule and modification of surrounding environment.

In terms of architectural arrangement, designers could place different architectural elements, like fountain and shade devices, in the environment and assess the usage of place and suitability of the placement of the architectural elements. Though vandalism is unlikely to be visualized, the general usage of space can always be visualized.

In planning activity schedule, designers can plan different activities in different areas of the urban plazas, like badminton court, mini-golf and tot-lot etc., to see if the planning is suitable. By visualizing the usage pattern, designers could see if the environment and the

microclimate are carefully considered in the designing stage. This can also be extended to the evaluation of year round activities if the urban space is considered to be multifunctional.

In case of modification of the surrounding environment, the urban space is always affected in terms of population, microclimatic environment and views etc. The simulation helps to assess the direct impact on the usage of the urban space. Results also help to identify potential improvement strategies, whether it is on the surrounding environment or on the urban space itself.

### **6.2.2 Application domain**

The prototype presented focused on the Sproul Plaza which has mild climate. By modifying the parameters in the regression equations and the behavioral rules applied, the simulation could be extended to simulation of other types of urban plaza, though it requires more inputs from behaviorists and extensive research. Meanwhile, the same concept could also be extended to other climates. By including the differences in behavior and preferences in different climates, the simulation could be used to assess usage pattern in different regions and territories. In more extreme cases where the behavioral rules and regression models are not suitable, the methodologies itself could also be used to formulate analytical procedure for other cultural or climatic settings.

On the other hand, the simulation does not only serve as a whole, the components can also be separated to serve particular functions. For example, the comfort maps and the activity option maps could be used independently for zoning arrangement or activity planning. The usability model could be developed to visualize different layers of properties (like usage, architectural elements, shading properties and air flow conditions) which contrast the current visualization trend of photorealistic rendering and visual stimuli. The agent model and behavioral rules could be developed to research environment of different properties. They could be used in the past or future environment where there is limited documentation and behavioral pattern is based on best known knowledge. This is particularly useful in the study and education of architectural/cultural heritage.

## **6.3 Contribution to architectural design practice and education**

Architectural design is greatly influenced by technological development. More different aspects, like photorealistic rendering, solar access and life cycle cost etc., have been included in the design process to promote better quality and more habitable environment.

It is expected that with the virtual user simulation, human behavior analysis, as one of the most important aspects in building design, could be integrated into designers' daily design practices. This will encourage designers to pay more attention to users and therefore innovative buildings concerning more about the needs of people can be designed and built.

In presence, the modeling approach could contribute the architectural design practice and education in the following aspects:

The CAD models for the built environment and other environmental simulations tools are commonly known to the architectural design practice. The concept and methodology employed are also easy to be understood. This offers minimal effort in incorporating to the design practice.

The model provides immediate visualization of environmental behavior. It can assist comparison and evaluation of design alternatives, help designers to gain better understanding of human environmental behavior and incorporate behavior knowledge into design process. It can also help students in architectural education to gain intuition of how different environmental settings impact users' behavior.

The model aims at simulation of users' daily behavior and their environmental preferences under normal conditions, which are the main concerns of architects' daily design tasks.

## **6.4 Future research directions**

Simulating human behavior in built environments is a challenging task. The simulation prototype presented targets on a specific environment, the Sproul Plaza, a campus environment which the complexity of human behavior was not fully addressed. Additional work could then be done to improve the simulation for a wider application domain. Specifically, the future research directions include the followings:

- Extending the scope of simulation to include different environments, such as urban plazas, streets, and buildings. This could be done by implementing a modular design approach to allow additions and modifications without affecting the overall framework of the simulation. Increasing the modules would incrementally enlarge the scope of the simulation.
- Extending the scope of simulation to include wider range of climates. People in different climates have different climatic preferences. People in subtropical climates, like Hong Kong, prefer more activities under shades and mild wind speed. People further north, like Germany, prefer to have more sun. Even they can

adjust their thermal sensation by means of clothing or other methods, their thermal preferences and behaviors are always different. Therefore, the modular design should also be able to take into account the different climatic preferences and behavior characteristics in different climates.

- Creating libraries of behavior rules and libraries of users with different profiles. Extending the scope of simulation would increase the complexity of the behavioral rules and users profile employed which need to be taken care of. The composition of the prototype, a campus plaza, is relatively simple compared to other types of urban plazas. E.g. children generally would engage in activities with higher metabolic rates. Their paths could be associated with the configuration of tot lots or even animals. Elderly would have more social activities with others and the presence schedules could be closely related to their retired lives.
- Applying standardized typical meteorological year (TMY) data set which the simulation could be applied to more territories. TMY3 (the third generation of TMY data) data sets have hourly values of meteorological elements for a typical 1-year period. Their intended use is for computer simulations of building systems to facilitate performance comparisons of different system types, configurations, and locations in different territories. The current application of metrological record has already embedded the functional characteristics of TMY3 meteorological data sets which implementation should be potentially feasible.
- Establishing stronger linkage with external simulation programs and the models used. Currently, the process is not fully automated. Also, it focuses mainly on the textual information to be used in the building model. Graphical representation relies on the SVG and the VRML viewers which both have their weakness is supporting visualization of extra information. Indeed, it would be desirable to visualize the interaction of the users with the intangible environmental condition in this type of simulation. On the other hand, it is also a research direction that leads the prototype to become a stand-alone application that works with normal CAD models or an embedded component within existing CAD or Building Information Modeling (BIM) applications.
- Building an open-ended, layered user and building modeling system that allows designers, behaviorists, and users to collaboratively input their specific knowledge and create an evaluation and presentation system that can be used in design studios.

# References

- Ahmed, Khandaker Shabbir. 2003/1. Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environments. *Energy and Buildings* 35, (1): 103-10.
- Alofsin, Anthony, and University of Texas at Austin. Center for the Study of American Architecture, eds. 1993. *Dwelling : Social life, buildings, and the spaces between them*. Center, a journal for architecture in America ; v. 8. Austin: Center for American Architecture and Design, School of Architecture, University of Texas at Austin.
- Altman, Irwin. 1975. *The environment and social behavior : Privacy, personal space, territory, crowding*. Monterey, Calif.: Brooks/Cole Pub. Co.
- American Society of Civil Engineers. Task Committee on Outdoor Human Comfort. 2004. *Outdoor human comfort and its assessment : State of the art*. Reston, VA: American Society of Civil Engineers.
- American Society of Heating, Refrigerating and Air-Conditioning Engineers, ed. 2004. *ASHRAE Standard 55-2004 Inch-Pound ed*. Atlanta, GA.: ASHRAE.
- American Society of Heating, Refrigerating and Air-Conditioning Engineers, ed. 2004. *2004 ASHRAE handbook : Heating, ventilating, and air-conditioning systems and equipment heating, refrigerating and air-conditioning engineers, Inc*. Inch-Pound ed. Atlanta, GA.: ASHRAE.
- Aynsley, R. M. 1974/6. Effects of airflow on human comfort. *Building Science* 9, (2): 91-4.
- Archea, J. (1977). The Place of Architectural Factors in Behavioral Theories of Privacy. *Journal of Social Issues* 33:3. Blackwell Publishers.
- Arens, Ed. 1986. *Wind, sun and temperature : Predicting the thermal comfort of people in outdoor spaces*, eds. Peter Bosselmann, University of California, Berkeley. Center for Environmental Design Research. Berkeley, CA: Center for Environmental Design Research, University of California.
- Arens, Ed, and Peter Bosselmann. 1989. Wind, sun and temperature--predicting the thermal comfort of people in outdoor spaces. *Building and Environment* 24, (4): 315-20.
- Arens, Ed, R. Gonzalez, and L. Berglund. 1986. Thermal comfort under extended range of environmental conditions. *ASHRAE Transactions* 92, Part 1B, : 18-26.
- Arens, Ed, Hui Zhang, and Charlie Huizenga. 2006/1a. Partial- and whole-body thermal sensation and comfort-- part I: Uniform environmental conditions. *Journal of Thermal Biology* 31, (1-2): 53-9.



- . 2006/1b. Partial- and whole-body thermal sensation and comfort--part II: Non-uniform environmental conditions. *Journal of Thermal Biology* 31, (1-2): 60-6.
- Arthur, Paul. 1992. *Wayfinding : People, signs, and architecture*, ed. Romedi Passini. New York: McGraw-Hill Book Co.
- Aynsley, R. M. 1974/6. Effects of airflow on human comfort. *Building Science* 9, (2): 91-4.
- Bandura, A. 1969. *Principles of behavior modification*. New York, Holt, Rinehart and Winston.
- Barnett, J. 2001. Urban places, planning for the use of: Design guide. In *International Encyclopedia of the Social & Behavioral Sciences.*, ed. Neil J. Smelser and Paul B. Baltes, 16031-16035. Oxford: Pergamon.
- Batty, M. (2001). Editorial: Agent-based pedestrian modeling. *Environment and Planning B: Planning and Design* 28(3). pp. 321-326. Pion. Ltd.
- Bennett, Corwin. 1977. *Spaces for people : Human factors in design*. Englewood Cliffs, N.J.: Prentice-Hall.
- Bosselmann, Peter. 1991. *Application of computer visualization and mathematical modeling techniques in the development of planning controls designed to protect thermal comfort for pedestrians*. Working paper ;no. 549., ed. University of California, Berkeley. Institute of Urban & Regional Development. Berkeley, Calif. : University of California, Berkeley.: Institute of Urban and Regional Development.
- . 1990b. *Dynamic simulation of urban environments : Twenty years of environmental simulation at Berkeley*. Working paper ; no. 509., ed. University of California, Berkeley. Institute of Urban & Regional Development. Berkeley, Calif.: Institute of Urban and Regional Development, University of California at Berkeley.
- . 1987. *Perceptual simulations of environments*. Reprint ; no. 219., ed. Kenneth H. Craik. Berkeley, Calif.: Institute of Urban and Regional Development, University of California, Berkeley.
- . 1983. *Sun and light for downtown San Francisco* Peter Bosselmann, Juan Flores, Terence O'hare. IURD monograph ;no. 34., eds. Terence O'Hare, Juan Flores, University of California, Berkeley. Institute of Urban & Regional Development and University of California, Berkeley. Environmental Simulation Laboratory. Berkeley: Environmental Simulation Laboratory, Institute of Urban and Regional Development, College of Environmental Design.
- Bosselmann, Peter, and Toronto . Planning and Development Dept, eds. 1990a. *Sun, wind, and pedestrian comfort : A study of Toronto's central area development department by P. Bosselmann ... [et al.]*. Cityplan '91 ;25. Toronto: City of Toronto, Planning & Development Dept.
- Bosselmann, Peter, University of California, Berkeley. Institute of Urban & Regional Development, University of California, Berkeley. Building Technology Laboratory, and University of California, Berkeley. Environmental Simulation Laboratory, eds. 1984. *Sun, wind, and comfort : A study of open spaces and sidewalks in four*

- downtown areas*. [California. University, Berkeley. Institute = of Urban and Regional Development. Monograph ;no. 35]. Berkeley, Calif.: Institute of Urban and Regional Development, College of Environmental Design, University of California, Berkeley.
- Brooks, Frederick Augustus. 1959. *An introduction to physical microclimatology*. Davis: University of California.
- Brown, Robert D. 1995. *Microclimatic landscape design : Creating thermal comfort and energy efficiency*. New York: J. Wiley & Sons.
- Bruce, William. 1960. *Man and his thermal environment; physiological adjustments to conditions and assessment of comfort in buildings*. National research council, Canada. Division of Building Research. Technical paper, no. 84., eds. National Research Council of Canada. Division of Building Research, National Research Council, Canada. Division of Building Research. Technical paper,no.84. Ottawa: National Research Council, Division of Building Research.
- Bruse, M. 2005a. Assessing urban microclimate from the user's perspective – multi-agent systems as a new tool in urban biometeorology. *Ann. Meteorol.* 41, : 137-40.
- . 2005b. ITCM – a simple dynamic 2-node model of the human thermoregulatory system and its application in a multi-agent system. *Ann* 41, : 398-401.
- . 2003. Assessing urban microclimate using multi-agent simulations: A new approach to answer an old problem? Paper presented at ICUC5, Lodz, 1-5-September 2003.
- . 2002. Multi-agent simulations as a tool for the assessment of urban microclimate and its effects on pedestrian behavior. Paper presented at iEMSs Conference 2002, Lugano.
- Canter, David V. 1977. *The psychology of place*. London: Architectural Press.
- Cheng, V., and Edward Ng. 2006. Thermal comfort in urban open spaces for Hong Kong. *Architectural Science Review* 49, (3) (31 Mar. 2007): 236.
- Chow, Benny, and Jin-yeu Tsou. 2001. The impact of computer-based design tools for daylighting simulation and prediction for a built environment. Paper presented at CAADRIA 2001, Sydney.
- Chun, Chungyoon, and Akihiro Tamura. 2005/5. Thermal comfort in urban transitional spaces. *Building and Environment* 40, (5): 633-9.
- Clipson, C. 1993. Simulation for planning and design: A review of strategy and technique. In *Environmental simulation: Research and policy issues.*, eds. D. Stokols, R. W. Marans. New York: Plenum Press.
- de Freitas, C. R. 1985. Assessment of human bioclimate based on thermal response. *International Journal of Biometeorology* 29, (2) (September 30, 2005): 97-119.
- Deasy, C. M. and Lasswell, T. E. 1985. *Designing places for people : A handbook on human behavior for architects, designers, and facility managers*, ed. Thomas E. Lasswell. New York: Whitney Library of Design.

- Durgin, F. H. 2002. Evaluating pedestrian level winds. *Journal of Wind Engineering and Industrial Aerodynamics*.
- Dimoudi, Argiro, and Marialena Nikolopoulou. 2003/1. Vegetation in the urban environment: Microclimatic analysis and benefits. *Energy and Buildings* 35, (1): 69-76.
- Doherty, T. J. 1988. *Evaluation of the physiological bases of thermal comfort models*, ed. Ed Arens. Berkeley, Calif.: T.J. Doherty : E. Arens.
- Durgin, F. H. 2002. Evaluating pedestrian level winds. *Journal of Wind Engineering and Industrial Aerodynamics*.
- Egan, M. David. 1975. *Concepts in thermal comfort*. Englewood Cliffs, N.J.: Prentice-Hall.
- Eliasson, Ingegärd, Igor Knez, Ulla Westerberg, Sofia Thorsson, and Fredrik Lindberg. Climate and behavior in a Nordic city. *Landscape and Urban Planning* In Press, Corrected Proof, .
- Energy Systems Research Unit (ESRU). Thermal comfort models. in Strathclyde University [database online]. Glasgow, UK, [cited 10/17 2006].
- Environmental Analytics (Berkeley, CA). 1997. *UC Berkeley thermal comfort program*. Berkeley, CA: .
- Fanger, P. O. 1970. Thermal comfort. analysis and applications in environmental engineering.
- Fuller, R. A. and Gaston, K.J. 2009. The scaling of green space coverage in European cities, in *Biology Letters*. doi:10.1098/rsbl.2009.0010.
- Gagge, A. P., A. P. Fobelets, and L. Berglund. 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions* 92, (2): 709-31.
- Gehl, Jan. 1996. *Public spaces, public life*, ed. Lars Gemzoe. Copenhagen: Danish Architectural Press and the Royal Danish Academy of Fine Arts, School of Architecture.
- . 1987. *Life between buildings : Using public space*. New York: Van Nostrand Reinhold.
- Gehl, Jan, and European Transport Conference. 1998. *The form and use of public space*.
- Givoni, Baruch. 1998. *Climate considerations in building and urban design*. New York: Van Nostrand Reinhold.
- . 1969. *Man, climate, and architecture*. Elsevier architectural science series. Amsterdam, New York: Elsevier.
- . 1963. Estimation of the effect of climate on man; development of a new thermal index.
- . 1960. *The relative effect of air temperature and humidity at still air and rest conditions*, ed. Haifa. Israel Institute of Technology. Building Research Station. Haifa: .

- . 1960. *Statistical evaluation of comfort indices*, eds. S. Zacks, Haifa. Israel Institute of Technology. Building Research Station. Haifa: .
- Givoni, Baruch, Mikiko Noguchi, Hadas Saaroni, Oded Pochter, Yaron Yaacov, Noa Feller, and Stefan Becker. 2003/1. Outdoor comfort research issues. *Energy and Buildings* 35, (1): 77-86.
- Glaser, D.C. and Cavallin-Calanche, H. E. (1999). Representations and Meanings: cognitive models for simulations of architectural space. *4th International Design Thinking Research Symposium on Design Representation* (W. Porter and G. Goldschmidt, eds.), Cambridge, MA: MIT, pp. 129-144.
- Gómez, Francisco, Luisa Gil, and José Jabaloyes. September 2004. Experimental investigation on the thermal comfort in the city: Relationship with the green areas, interaction with the urban microclimate. *Building and Environment* 39, (9): 1077-1086.
- Grayson, G. B. 1975. *Observations of pedestrian behavior at four sites*. TRRL report - transport and road research laboratory ; no. LR 670., ed. Transport and Road Research Laboratory. TRRL report no. LR 670. Crowthorne, Eng.: Transport and Road Research Laboratory.
- Grothmann, Torsten, and Anthony Patt. 2005/10. Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Global Environmental Change Part A* 15, (3): 199-213.
- Gulyás, Ágnes, János Unger, and Andreas Matzarakis. 2006/12. Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modeling and measurements. *Building and Environment* 41, (12): 1713-22.
- Haklay, M., O'Sullivan, D., et al. 2001. So go downtown: Simulating Pedestrian Movement in Town Centres. *Environment and Planning B: Planning and Design* 28(3): pp.343-359. Pion. Ltd.
- Hall, Edward Twitchell. 1966. *The hidden dimension*. 1st ed. Garden City, N.Y.: Doubleday.
- Hedge, Alan. Thermal comfort. human factor: Ambient environment. in Cornell University [database online]. 2003 [cited 10/21 2005].
- Helbing, D., Schweitzer, F., et al. 1997. Active Walker Model for the Formation of Human and Animal Trail System. *Physical Review E* 56, 2527-2539.
- Helbing, D., Molnar, P., et al. (2001). Self-organizing Pedestrian Movement. *Environment and Planning B: Planning and Design* 28(3): pp. 361-383. Pion. Ltd.
- Honjo, Tsuyoshi, and Tadashi Takakura. 1990-1991. Simulation of thermal effects of urban green areas on their surrounding areas. *Energy and Buildings* 15, (3-4): 443-6.
- Höppe, Peter. 2002/7. Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings* 34, (6): 661-5.
- Hoyt, Douglas V. 1997. *The role of the sun in climate change*. New York ; Oxford, England: Oxford University Press.

- Huang, Jianhua. 2007. Prediction of air temperature for thermal comfort of people in outdoor environments. *International Journal of Biometeorology* (January 12, 2007).
- Huizenga, Charlie, and Hui Zhang. Feb 2006. Two-node model in Berkeley.
- Huizenga, Charlie, Hui Zhang, and Ed Arens. 2001/7. A model of human physiology and comfort for assessing complex thermal environments. *Building and Environment* 36, (6): 691-9.
- Huizenga, Charlie, Hui Zhang, Ed Arens, and Danni Wang. 2004/0. Skin and core temperature response to partial- and whole-body heating and cooling. *Journal of Thermal Biology* 29, (7-8): 549-58.
- Humphrey, M. A. 1976. Field studies of thermal comfort compared and applied. *Building Services Engineer* 44, (1): 5-27.
- Hunt, J. C. R., E. C. Poulton, and J. C. Mumford. 1976. The effects of wind on people; new criteria based on wind tunnel experiments. *Building and Environment* 11, (1): 15-28.
- Innova AirTech Instruments A/S. Thermal comfort. in Innova AirTech Instruments A/S [database online]. Denmark, 1997-2001].
- Institute of Public Administration, New York. 1975. *Pedestrian needs and accommodations : A study of behavior and perception*, eds. Alex Eckmann, Robert Schwartz, Richard Ridley and United States. Federal Highway Administration. Washington, : Springfield, Va.: Dept. of Transportation; Available through National Technical Information Service.
- Irazábal, C. E. (1994). *Towards a computer-aided design assistant: A virtual user*. Unpublished Master's Thesis, University of California, Berkeley.
- Isyumov, N., and A. G. Davenport. 1975. Comparison of full-scale and wind tunnel wind speed measurements in the commerce court plaza. *Journal of Wind Engineering and Industrial Aerodynamics* 1, : 201-12.
- Ittelson, William H., and City University of New York. 1973. Environment and cognition.
- Jones, Margaret Hubbard. 1980. *Measuring pedestrian behavior*.
- Kalay, Yehuda E. 2004. *Architecture's new media : Principles, theories, and methods of computer-aided design*. Cambridge, Mass.: MIT Press.
- Kamei, I., and E. Maruta. 1979/8. Study on wind environmental problems caused around buildings in Japan. *Journal of Wind Engineering and Industrial Aerodynamics* 4, (3-4): 307-331.
- Kaplan, Rachel, and Stephen Kaplan, eds. 1978. *Humanscape : Environments for people*. N. Scituate, Mass.: Duxbury Press.
- Katzschner, Lutz. Mapping of thermal comfort. Germany, 2003 [cited Sept 22, 2003 Available from [http://www.uni-kassel.de/fb13/agluft/field\\_surveys\\_Kassel/mapping\\_thermal\\_Comfort/](http://www.uni-kassel.de/fb13/agluft/field_surveys_Kassel/mapping_thermal_Comfort/)].

- Katzschner, Lutz, Ulrike Bosch, and Mathias Rottgen. 2002. Behavior of people in open spaces in dependency of thermal comfort conditions. Paper presented at PLEA, .
- Kerridge, J., Hine, J., et al. 2001. Agent-based modeling of pedestrian Movements: The Questions That Need to Be Asked. *Environment and Planning B: Planning and Design* 28(3): pp. 327-341. Pion. Ltd.
- Knez, Igor, and Sofia Thorsson. 2006. Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. *International Journal of Biometeorology* 50, (5) (Thursday, March 16, 2006): 258-68.
- Lam, Selina, and Jin-yeu Tsou. 2002. Open space and its social implication in Hong Kong public housing estates. Paper presented at 2nd Great Asian Streets Symposium: Public Space 2002 (GASS), National University of Singapore, Singapore.
- Lewin, K., Adams, D. K., et al. 1935. *A dynamic theory of personality: selected papers*. New York, McGraw-Hill.
- Lewin, K. 1936. *Principles of topological psychology*. New York, London, McGraw-Hill book company inc.
- Li, Shaogang. 1994. Users' behavior of small urban spaces in winter and marginal seasons. *Architecture and Behavior* 10, (2): 95-110.
- Marcus, Clare Cooper, and Wischemann, T. 1990. Campus outdoor spaces. *People places: design guidelines for urban open space*. C. C. Marcus and C. Francis, ed., Van Nostrand Reinhold, New York: pp. 143-169.
- Marsh, Andrew. Thermal comfort. in Square One [database online]. Sydney, Australia, [cited 10/9 2001]. Available from <http://www.squ1.com/>.
- Matzarakis, Andreas, Helmut Mayer, and M. G. Iziomon. 1999. Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology* 43, (2) (February 19, 2004): 76-84.
- Matzarakis, Andreas, and M. Mayer. Impact of street trees on the thermal comfort of people in summer. A case study in Freiburg (Germany). *MERCHAVIM* 6, : 285-300.
- Matzarakis, Andreas, and K. Zaninovic. 2006. Thermal sensation in different meteorological situations in town centre and suburbs of zagreb. Paper presented at 6th International Conference ob Urban Climate, Urban Climate Group, Department of Geosciences, Göteborg University, Sweden.
- Mayer, E. 1993. Objective criteria for thermal comfort. *Building and Environment* 28, (4): 399-403.
- Mayer, Helmut, and Peter Höppe. 1987. Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology* 38, (1) (December 28, 2004): 43-9.
- Melbourne, W. H. 1978. Criteria for environmental wind conditions. *Journal of Industrial Aerodynamics* 3, : 241-9.

- Mertens, Elke. 1999/10. Bioclimate and city planning – open space planning. *Atmospheric Environment* 33, (24-25): 4115-23.
- Miles, Don C. 1978. *Plazas for people*, eds. Robert S. Cook, Cameron B. Roberts and Project for Public Spaces. New York: Project for Public Spaces.
- Moore, G. T. 1987. Environment and behavior research in North America: history, developments, and unresolved issues. in *Handbook of environmental psychology*. D. Stokols and I. Altman. New York, John Wiley & Sons, Inc. pp. 1371-1410.
- Nagara, Koichi, Yoshiyuki Shimoda, and Minoru Mizuno. 1996/2. Evaluation of the thermal environment in an outdoor pedestrian space. *Atmospheric Environment* 30, (3): 497-505.
- Nahemow, L. and Lawton, M. 1973. *Toward an ecological theory of adaptation and aging*. *Environmental Design Research*. W. F. E. Preiser. Stroudsborg, Penna., Dowden, Hutchinson & Ross. 1.
- New York . City Planning Commission. 1976. *Plazas for people : Streetscape & residential plazas*. New York: The Commission.
- Nikolopoulou, Marialena, ed. 2002. *Designing open spaces in the urban environment: A bioclimatic approach*. Greece: Center for Renewable Energy Sources (CRES).
- Nikolopoulou, Marialena, Nick Baker, and Koen Steemers. 2001. Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Solar Energy* 70, (3): 227-35.
- Nikolopoulou, Marialena, and Spyros Lykoudis. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment* In Press, Corrected Proof, .
- Nikolopoulou, Marialena, and Koen Steemers. 2003/1. Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings* 35, (1): 95-101.
- O'Neill, M. J. (1992). A Neural Network Simulation as a Computer-Aided Design Tool for Evaluating Building Legibility. *Evaluating and Predicting Design Performance*. Y.E. Kalay, ed., John Wiley & Sons, New York. pp. 347-366.
- Olgay, Victor. 1963. *Design with climate: Bioclimatic approach to architectural regionalism. some chapters based on cooperative research with Aladar Olgay*, ed. Aladar Olgay. Princeton, N.J.: Princeton University Press.
- Ozel, F. 1993. *Computer simulation of behavior in spaces. environmental simulation - research and policy issues*. New York: Plenum Press.
- Parsons, K. C. 2003. *Human thermal environments : The effects of hot, moderate, and cold environments on human health, comfort, and performance*. 2nd ed. London ; New York: Taylor & Francis.
- Passini, Romedi. 1984. *Wayfinding in architecture*. Environmental design series ; v. 4. New York: Van Nostrand Reinhold.

- Paszynski, Janusz. 1991. Mapping urban topoclimates. *Energy and Buildings* 16, (3-4): 1059-62.
- Preiser, Wolfgang F. E., Harvey Rabinowitz, and Edward T. White. 1988. *Post-occupancy evaluation*. New York: Van Nostrand.
- Pressman, Norman. 1994. Climatic factors in play areas and public space. *Architecture and Behavior* 10, (4): 417-27.
- Proshansky, Harold M. 1976. *Environmental psychology : People and their physical settings*, eds. William H. Ittelson, Leanne G. Rivlin. 2d ed. New York: Holt, Rinehart and Winston.
- Ratcliff, M. A., and J. A. Peterka. 1990. Comparison of pedestrian wind acceptability criteria. *Journal of Wind Engineering and Industrial Aerodynamics* 36, : 791-800.
- Reynard, Gerard Kimbal. 1971. Problems of research in architectural psychology.
- Reynolds, C. W. 1987. Flocks, Herds, and Schools: A Distributed Behavioral Model, in *Computer Graphics*, 21(4), *SIGGRAPH '87 Conference Proceedings*, pages 25-34.
- Robitu, Mirela, Marjorie Musy, Christian Inard, and Dominique Groleau. Modeling the influence of vegetation and water pond on urban microclimate. *Solar Energy* In Press, Corrected Proof, .
- Rotter, J. 1954. *Social learning and clinical psychology*. New York, Prentice-Hall.
- San Francisco (Calif.), and San Francisco (Calif.). Board of Supervisors. 1985. *Downtown plan : An ordinance of the city and county of San Francisco*. [San Francisco]: Office of the Clerk, Board of Supervisors.
- Scudo, Gianni. Thermal comfort. in *Built Environment Sciences & Technology (BEST)*, Politecnico di Milano, Via Durando 10, 20158 Milano [database online]. Oct 25, 2002 [cited Feb 6 2006]. Available from <http://www.map21ltd.com/COSTC11/comfort2.htm> (accessed Feb 6, 2006).
- Shannon, R. E. (1975). *System simulation: The art and the science*. Englewood Cliffs, NJ, Prentice Hall.
- Shriver, Katherine. 1997. *Influence of environmental design on pedestrian travel behavior in four Austin neighborhoods*.
- Sillitoe, K. K. 1969. *Planning for leisure: An enquiry into the present pattern of participation in outdoor and physical recreation and the frequency and manner of use of public open-spaces among people living in the urban areas of England and Wales*. Government social survey. SS 388., eds. Great Britain. Dept. of Education and Science, Great Britain. Government Social Survey Dept. Social Survey 388. London: H.M.S.O.
- Skinner, B. F. 1953. *Science and human behavior*. New York, The MacMillan Company.
- Soligo, M. J., P. A. Irwin, and C. J. Williams. 1993. Pedestrian comfort including wind and thermal effects. Paper presented at The Third Asia Pacific Symposium on Wind Engineering, Hong Kong.



- Soligo, M. J., P. A. Irwin, C. J. Williams, and G. D. Schuyler. 1997. A comprehensive assessment of pedestrian comfort including thermal comfort. *Journal of Wind Engineering and Industrial Aerodynamics* 77 & 78, : 753-66.
- Sommer, Robert. 1969. *Personal space; the behavioral basis of design*. A spectrum book. Englewood Cliffs, N.J.: Prentice-Hall.
- Spagnolo, Jennifer, and Richard de Dear. 2003/5. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment* 38, (5): 721-38.
- Stahl, F. 1982. Computer Simulation Modeling for Informed Design Decision Making. *13th Annual Conference of the Environmental Design Research Association* (P. Bart, A. Chen & G. Francescato, eds.), Washington, DC. EDRA, pp. 105-111.
- Stathopoulos, Ted. 1985/8. Wind environmental conditions around tall buildings with chamfered corners. *Journal of Wind Engineering and Industrial Aerodynamics* 21, (1): 71-87.
- Stathopoulos, Ted, and A. Baskaran. 1996/11. Computer simulation of wind environmental conditions around buildings. *Engineering Structures* 18, (11): 876-85.
- . 1990/9. Boundary treatment for the computation of three-dimensional wind flow conditions around a building. *Journal of Wind Engineering and Industrial Aerodynamics* 35, (1-3): 177-200.
- Stathopoulos, Ted, and D. Surry. 1983/12. Scale effects in wind tunnel testing of low buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 13, (1-3): 313-26.
- Stathopoulos, Ted, Hanqing Wu, and C. Bedard. 1992/10. Wind environment around buildings: A knowledge-based approach. *Journal of Wind Engineering and Industrial Aerodynamics* 44, (1-3): 2377-88.
- Stathopoulos, Ted, Hanqing Wu, and John Zacharias. 2004/3. Outdoor human comfort in an urban climate. *Building and Environment* 39, (3): 297-305.
- Steinfeld, E. 1992. Toward artificial users. In *Evaluating and predicting design performance.*, ed. Yehuda E. Kalay, 329-346. New York: Wiley.
- Stolwijk, J. A. J., and J. D. Hardy. 1966. Temperature regulation in man-A theoretical study. *Pflügers Arch.* 291, : 129-62.
- Swaid, H., M. Bar-El2, and M. E. Hoffman. 2004. A bioclimatic design methodology for urban outdoor spaces. *Theoretical and Applied Climatology* 48, (1) (December 28, 2004): 49-61.
- Tacken, M. 1989. A comfortable wind climate for outdoor relaxation in urban areas. *Building and Environment* 24, (4): 321-4.
- Thorsson, Sofia, Tsuyoshi Honjo, Fredrik Lindberg, Ingegärd Eliasson, and Eun-Mi Lim. 2004. Thermal comfort conditions and patterns of behavior in outdoor urban spaces in Tokyo, Japan. Paper presented at Plea2004 – The 21st Conference on Passive and Low Energy Architecture. Eindhoven, The Netherlands, 19-22.

- Thorsson, Sofia, Maria Lindqvist, and Sven Lindqvist. 2004. Thermal bioclimatic conditions and patterns of behavior in an urban park in Goteborg, Sweden. *International Journal of Biometeorology* 48, (3) (February 23, 2004): 149-56.
- Tsou, Jin-yeu, Benny Chow, and Selina Lam. 2002. Performance-based simulation for the planning and design of hyper dense urban habitation, in *Proceeding of the 7th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRRIA)*, Multimedia University Malaysia.
- Tu, X. (1996). *Artificial Animals for Computer Animation: Biomechanics, Locomotion, Perception, and Behavior*. Dissertation. Graduate Department of Computer Science, University of Toronto.
- Van Andel, Joost. 1994. Behavior mapping and urban design: Graphic versus non-graphic information about environment-behavior relations. Paper presented at The Urban Experience - A People-Environment Perspective, in *Proceedings 13th International Conference of the IAPS*, Manchester (UK).
- Walsh, Aaron E., and Mikaël Bourges-Sévenier. 2001. *Core Web3D*. Upper Saddle River, NJ: Prentice Hall PTR.
- Westerberg, U. 1994. Climatic planning - physics or symbolism? *Architecture and Behavior* 10, (1): 49-71.
- White, Edward T. 1991. *Post-occupancy evaluation and the corporate architect*. Tucson, Ariz.: Architectural Media Ltd.
- Whyte, William Hollingsworth. 1980. *The social life of small urban spaces*. Washington, D.C.: Conservation Foundation.
- Yan, Han. 2003. Developing an advanced thermal comfort model for environmental design.
- Yan, Wei. 2005. Simulating users' behavior in built environments. Ph.D., Dissertation, University of California, Berkeley.
- Zacharias, John. 2001/12. Path choice and visual stimuli: Signs of human activity and architecture. *Journal of Environmental Psychology* 21, (4): 341-52.
- Zacharias, John, Ted Stathopoulos, and Hanqing Wu. 2004/9. Spatial behavior in San Francisco's plazas: The effects of microclimate, other people, and environmental design. *Environment and Behavior* 36, (5): 638-658.
- . 2001/03. Microclimate and downtown open space activity. *Environment and Behavior* 33, (02): 296-315.
- Zhang, Hui, Charlie Huizenga, Ed Arens, and Yu Tiefeng. 2005. Modeling thermal comfort in stratified environments. Paper presented at 10th International Conference on Indoor Air Quality and Climate, Beijing.
- Zhang, Hui, Charlie Huizenga, Ed Arens, and Tiefeng Yu. 2001/9. Considering individual physiological differences in a human thermal model. *Journal of Thermal Biology* 26, (4-5): 401-8.

Zimring, C. M., E. Do, E. Domeshek, and J. Kolodner. 1995. Supporting case-study use in design education: A computational case-based design aid for architecture. In *Computing in civil engineering*. Mohesen, J. P. ed., 1635-1642. New York: American Society of Civil Engineers.

# Appendix: Sample survey

## Effect of Microclimate on Human Behavior in Small Urban Spaces

### **Introduction:**

“Hello. This is Fung Ki LAM, a graduate student of the Department of Architecture. I am carrying out a study of the effect of microclimate on user behavior in the Sproul Plaza. I would like to invite you, a user of the Plaza, for a short questionnaire regarding your thermal sensation and usage of the Plaza. No personal information will be included. The results of the study will be analyzed as a whole and no individuals will be identified. To participate in this study, you must be over 18. If you are over 18 and agree, I will ask you only a few questions and it will take at most 5 minutes.”

### **PART I To be filled by the researcher**

Date/ Time:	_____	Temp:	_____
Location:	_____	Humidity:	_____
Activity:	_____	Wind Speed:	_____
	_____	Shade:	_____

### **PART II To be filled by interviewee (Please check all appropriate boxes.)**

1. What is your purpose of visiting the Sproul Plaza?

- Have dynamic activities like jogging, cycling and playing frisbee.  
 Have static activities like reading, resting and eating.  
 Gathering and socializing with friends and colleagues.  
 Enjoy art display or civil activities like drama, music and speech.  
 Just to fill gap. I have to go somewhere later.  
 Others: \_\_\_\_\_

2. How often do you visit the Plaza?

- |  |   |
|--|---|
| <input type="checkbox"/> Few times a day.  | <input type="checkbox"/> Few times a month. |
| <input type="checkbox"/> Few times a week. | <input type="checkbox"/> Few times a year.  |

3. What is the general time you carry out activities in the Plaza?

- |   |   |
|---|---|
| <input type="checkbox"/> Early morning (before 8 am). | <input type="checkbox"/> Afternoon (2 pm - 5 pm). |
| <input type="checkbox"/> Morning (8 am - 11 am).      | <input type="checkbox"/> Evening (5 pm - 7 pm).   |
| <input type="checkbox"/> Lunch period (11 am - 2 pm). | <input type="checkbox"/> Night (7 pm).            |

4. Usually, for how long do you stay in the Plaza?

- |   |  |
|---|--|
| <input type="checkbox"/> <10 minutes.   | <input type="checkbox"/> 30 minutes to 1 hour. |
| <input type="checkbox"/> 10-20 minutes. | <input type="checkbox"/> > 1 hour.             |
| <input type="checkbox"/> 20-30 minutes. |  |

5. What did you do/ where were you right before you came to the Sproul Plaza?

Survey #: \_\_\_\_\_

- I was in an air-conditioned/ ventilated environment (including classrooms and buses, etc).
- I was in a non ventilated environment (including classrooms and buses, etc).
- I walked/ had other form of exercise for more than 10 minutes.
- Others: \_\_\_\_\_.

6. Please rate your current thermal sensation in below.

-4	-3	-2	-1	0	1	2	3	4
Very cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot

7. Do you prefer warmer/ cooler?

-3	-2	-1	0	1	2	3
Much cooler	Cooler	Slightly cooler	I'm fine	Slightly warmer	Warmer	Much warmer

8. Do you prefer more/ less wind speed?

-3	-2	-1	0	1	2	3
Much less	Less	Slightly less	I'm fine	Slightly more	More	Much more

9. Do you prefer more/ less sun?

-3	-2	-1	0	1	2	3
Much less	Less	Slightly less	I'm fine	Slightly more	More	Much more

10. Do you prefer more/ less shade?

-3	-2	-1	0	1	2	3
Much less	Less	Slightly less	I'm fine	Slightly more	More	Much more

### **PART III Contact**

Thanks for your participation. If you have any questions regarding this study, please feel free to contact me at [selinalam@berkeley.edu](mailto:selinalam@berkeley.edu)