DEVELOPMENT OF AN INDEX FOR ASSESSING THE PEDESTRIAN COMFORT OF STREET ENVIRONMENTS IN HONG KONG

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Development of an index for assessing the pedestrian comfort of street environments in Hong Kong

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Certificate of originality

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Abstract

Abstract of thesis entitled: Development of an index for assessing the pedestrian comfort of
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Walking has been actively advocated as a simple and effective means to boost individuals' physical activity levels. Comfort, which is one of pedestrian walking needs, is one of the major objectives employed by many street design guidelines and walkability audit tools. However, few methods or indices have been developed to evaluate pedestrian comfort by considering all the major built and micro- environmental factors. As such, the main aim of this study is to develop an index to assess pedestrian comfort of street environments in a holistic manner.

The index formulation was initiated by identifying a list of major built and micro-environmental factors affecting pedestrian comfort for recreational walking. 420 questionnaire responses were analyzed together with the concurrently monitored micro-environmental conditions to formulate a path model that could portray the interrelationships among pedestrian comfort, and perceptual and objectively measured street built and micro-environment characteristics. The results suggested that pedestrian comfort was influenced by both objective and subjective perceptual built and micro- environmental factors. The influence

of satisfaction of built environment involving sidewalks, amenities and landscape was found comparable to the aggregate influences of thermal sensation, perceived air quality and loudness. Thermal sensation, perceived air quality and perceived loudness have been found to mediate the associations between objectively measured parameters and pedestrian comfort for recreational walking respectively.

Next, multiple criteria decision analysis method (MCDA) was employed to develop a multivariate index for assessing pedestrian comfort by embracing thermal sensation, perceived air quality and noise annoyance (i.e. perceived loudness) as micro-environmental criteria, and sidewalks, amenities and landscape as built environmental criteria. This index targeted at assessing street segment as a basic analytical unit and was formulated by eliciting a set of importance weighting as well as indicators for individual comfort-related criteria.

Subsequently, the formulated composite index was applied to investigate the effects of morphological attributes in both street and neighborhood levels. The investigated street and neighborhood attributes were anticipated to exert influences on multiple comfort-related environmental factors on pedestrian comfort. The ultimate aim of the application of index is to provide insights for urban planners on improving pedestrian comfort of street segments. For street morphological attributes, tree-planting pattern, street orientation and aspect ratio, were studied. Tree-planting pattern and street orientation but not aspect ratio were found to significantly alter the pedestrian comfort levels of the baseline street configuration in Mongkok in Hong Kong. Tree-planting configuration with 4m or 8m-spacing yielded higher pedestrian comfort levels than the treeless throughout daytime, while the orientation that produced the most comfortable walking environment varied with time. More importantly, among micro-environmental criteria, thermal sensation was found to be the major criterion contributing to the differences in pedestrian comfort level among different orientations, tree-planting patterns or aspect ratios.

Finally, the neighborhood morphological attributes that were anticipated to significantly affect pedestrian comfort in a street segment was also investigated. This is of particular value as this study systematically explored the effects of neighborhood morphological attributes on pedestrian comfort of a street segment, which have not been fully explored in majority of neighborhood or area-scale studies. Given the unrevealed effects of neighborhood morphological attributes on the thermal comfort of a street segment and the considerable impacts of thermal comfort (i.e. thermal sensation) on pedestrian comfort stated in the previous section, this thesis revealed the effects of neighborhood morphological attributes on thermal comfort in a street segment before revealing their effects on pedestrian comfort. It was found that the hourly PET values and pedestrian comfort scores varied considerably with neighborhood morphological attributes, i.e. neighborhood compactness (BCR), surrounding building height configuration (SH/h ratio) and layout form.

For thermal comfort, taller surrounding buildings and/or more compact neighborhoods could help improve the thermal comfort conditions of both-side sidewalks. The close layout form could help improve the thermal comfort for E-W Street only. Their effects were found to vary considerably between E-W and non-E-W streets. Multivariate models have been formulated separately for E-W and non-E-W Streets to predict the hourly PET values based on neighborhood morphological attributes and microclimatic conditions. Based upon the PET values computed from the models, a series of charts have been generated to visually help determine the total number of comfort and very hot hours that will be yielded during daytime for a street being surrounded by different combinations of neighborhood morphological attributes. It was observed that a minimum of 3 comfort hours could be achieved when SH/h ratio ≥ 1.8 and BCR ⩾ 47% regardless of street orientation or layout form.

For pedestrian comfort, a higher SH/h ratio would provide a more comfortable walking environment for all different orientations. The open and close layout forms would yield the best pedestrian comfort in Non-E-W and E-W Streets, respectively, while the BCR with the highest pedestrian comfort level varied with time for all orientations. Besides, it was found that thermal sensation was the most important criterion affecting pedestrian comfort for individual neighborhood morphological attributes.

Of particular value of the findings arising from this study is that the formulated pedestrian comfort index reports the pedestrian comfort levels in an hourly basis by taking into consideration of all major built and micro-environmental criteria. The index can assist urban planners in creating comfortable street environments, and pedestrians in making decisions to walk and choose comfortable routes.

Publications arising from the thesis

Journal paper：

1. **Ma, X.**, Chau, C.K., & Lai, J.H.K. (2021). Critical factors influencing the comfort evaluation for recreational walking in urban street environments. *Cities*, 116 (May 2020), 103286. https://doi.org/10.1016/j.cities.2021.103286
2. **Ma, X.**, Leung, T.M., Chau, C.K., Yung, E.H.K., 2022. Analyzing the influence of urban morphological features on pedestrian thermal comfort. *Urban Climate*. 44, 101192. https://doi.org/10.1016/j.uclim.2022.101192
3. Development of an assessment index for evaluating the overall pedestrian comfort level of street segments in Hong Kong (will be submitted shortly).

Conference paper:

1. **Ma X.**, Chau, C.K. (2021). On the study of the relevance of health and comfort-related street environment attributes on affecting people’s recreational walking behavior. *11th Annual International Conference on Urban Studies & Planning*, Athens, Greece.

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Chapter 1 Introduction

1.1 Background

In recent decades, sedentary and physical inactive lifestyles have been pursued by many people in developed countries around the world (Van Dyck et al., 2013). People lacking adequate physical activities suffer from higher risks of being overweight and obese. This will cause Type 2 diabetes (Katzmarzyk et al., 2009), osteoporosis (Schmitt et al., 2009), metabolic syndrome (Healy et al., 2008; Swinburn and Shelly, 2008), high blood cholesterol level (Healy et al., 2008; Katzmarzyk et al., 2009; Swinburn and Shelly, 2008) and chronic diseases (Dunn et al., 2001; Healy et al., 2008; Swinburn and Shelly, 2008). World Health Organization (WHO) has identified physical inactivity as the fourth highest risk factor for global mortality, which has caused approximately 3.2 million deaths (WHO, 2020a). Globally, 1 in 4 adults did not meet the recommended levels of physical activity (WHO, 2020b). Physical activity has been identified as one of the five priority interventions against premature death and preventable morbidity and disability from diseases (Beaglehole et al., 2011).

Physical inactivity has also been reported for Hong Kong in a survey conducted by the Hong Kong Department of Health between 2015 and 2016 (Hong Kong Department of Health, 2018). The survey reported that 91% of primary and 96% of secondary students did not have sufficient physical activities. Besides, many adults undertook only necessary physical activities, e.g. walking to work or stores, and only less than 40% of the elderly in Hong Kong could achieve the level of physical activity recommended by the World Health Organization. To improve the health conditions of the population, the Department of Health in Hong Kong proposed: "A 10% relative reduction in the prevalence of insufficient physical activity among adolescents and adults by 2025" (Hong Kong Department of Health, 2018). Since 2016, the Hong Kong Government has been committed to promoting school sports culture and increasing funding for school sports activities (The Chinese University of Hong Kong, 2018). In consequence, the physical activity levels of children and youth in Hong Kong have increased since 2018. Despite so, the adults in Hong Kong are still at lower physical activity levels.

1.2 Walking in Streets

A number of physical activities have been recommended by WHO such as walking, cycling and active forms of recreation (WHO, 2020b), and walking has been actively advocated as a simple and effective means to boost individuals' physical activity levels. Walking is suitable for all age groups, which does not require special skills, equipment or support facilities, and allows people to choose their favorite movement intensity (Wang, et al., 2016). As such, urban planners, transportation and health professionals have been interested in identifying key street environmental factors and exploring effective ways to enhance individual’s walking activity level (Cain et al., 2014; Lin & Moudon, 2010; Lu et al., 2018).

Ample evidence suggested that physical built environment also played a major role on an individual’s walking level (Saelens and Handy, 2008; Leung et al., 2018). Many physical built environment features and characteristics have been shown to affect people’s propensity to walk (Lindelöw et al., 2014; Mateo-babiano, 2016) and route choices (Guo and Loo, 2013; Shatu and Yigitcanlar, 2018). Recently, the concept of walkability has been used to evaluate the extent to which an environment is pedestrian-friendly (Kelly et al., 2011; Moura et al., 2017). Many walkability indices, e.g. Walk Score (Hall and Ram, 2018), have been formulated to evaluate the pedestrian friendliness of an environment (Habibian and Hosseinzadeh, 2018). Meanwhile, a number of assessment audit tools such as Systematic Pedestrian and Cycling Environment Scan (SPACES) (Pikora et al., 2003), Microscale Audit of Pedestrian Streetscapes (MAPS) (Millstein et al., 2013), Pedestrian Environment Data Scan (PEDS) (Clifton et al., 2007), Irvine Minnesota Inventory (IMI) (Day et al., 2006), and the Analytic Audit Tool and Checklist Audit Tool (SLU) (Brownson et al., 2004) have been continuously evolved for evaluating the walking environment using street segments as a basic evaluation unit (Guo and Loo, 2013). All these tools share a common characteristic of including major physical environment features, e.g., sidewalk pavement, pedestrian amenities and greenery, as their walkability assessment criteria despite some divergences being found in their evaluation benchmarks.

Broadly speaking, walking can be categorized into two types: walking for transportation and recreation (Saelens and Handy, 2008). Walking for transportation is defined as walking to a given location, meaning a purposeful walk, while recreational walking is defined as walking for fun, relaxation or exercise. Walking for recreation has a restorative effect on the mind by reducing mental fatigue (De Young, 2010; Plambech & Konijnendijk, 2015). In particular, recreational walking behavior was affected considerably by the street environment (Ball et al., 2001), as people’s preference for the environment will influence the recreational walking decision, e.g. walking time, walking route, directly without the limitations of fixed destinations (Bunds et al., 2019). Also some situations in modern society like high availability of cars, use of technological aids and even people’s migration to suburbs that require commuting made it hard to encourage individuals to conduct more transportation walks by improving street environment (Brownson et al., 2005).

Upon closer examination, all the street environment features identified to influence walkability can be related to pedestrian walking needs (Barros et al., 2015; Morrall, 1985), e.g. accessibility, safety/security, comfort and pleasurability as proposed by Alfonzo (2005). Generally, pedestrians would assess the positive and negative aspects of a route by considering the extent to which the environmental attributes satisfy their needs (Mateo-babiano, 2016). However, theories of pedestrian needs have been developed based on Maslow's hierarchy of human needs (1954), which postulates that people will consider the basic needs before the high-order needs. The fulfilment of basic needs such as accessibility and safety/security can only achieve the fundamental of encouraging walking. If the street environment is designed to encourage long-distance/time walking, it is necessary to adequately address factors related to higher-order needs such as comfort that are often beyond the attention of pedestrian planning (Buckley et al., 2017).

Given the experience of walking along a street, pedestrian comfort feeling depended more on street-level rather than macro-level physical characteristics such as road connectivity (Asadi-Shekari et al., 2019; Ewing et al., 2016). For example, sidewalk-related features like pavement quality, width, obstruction and cleanliness of the sidewalk (Azemati et al., 2011; Bornioli et al., 2019; Cambra, 2012; Irafany et al., 2020; Kim et al., 2011; Samarasekara et al., 2012; Shaaban, 2019), the availability of amenities like benches and rubbish bins (Asadi-Shekari et al., 2019; Moura et al., 2017; Shaaban, 2019), and urban greenery including trees

(Ball et al., 2001; Santosa et al., 2018) were all correlated with pedestrian comfort. In addition to these built environment features, micro-environment attributes, e.g. thermal comfort, air quality, and noise, were also reported to affect pedestrian comfort (Ariffin and Zahari, 2013; Bélanger et al., 2009; Maghelal and Capp, 2011; Sarkar, 2003; Spinney and Millward, 2011). Moreover, street morphological attributes such as tree-planting, street orientation and aspect ratio, and urban morphological features such as neighborhood compactness, and building cluster height and layout have been reported to exert influences on multiple comfort-related environmental factors, e.g. thermal comfort and air quality (Chen et al., 2021; Thomas et al., 2013; Yin et al., 2019).

1.3 Objectives of the study

All in all, physical inactivity may lead to severe diseases and has become one of the high-risk factors for global mortality. Walking, especially recreational walking, is a simple and effective means to enhance pedestrian physical activity level by improving street environment. Given that comfort is an important higher-order pedestrian need to encourage long-time/distance walking, the main aims of the thesis are to formulate a multivariate index that can help evaluate the pedestrian comfort levels of street segments for recreational walkers and identify appropriate street configurations that can help improve the pedestrian comfort level of street environment. Specifically, the major objectives of this thesis are:

(i) To identify environmental determinants affecting pedestrian comfort for recreational walking in a street canyon.

(ii) To reveal the interrelationships between objective and perceptual major environmental factors, and pedestrian comfort.

(iii) To develop an objective and systematic approach to formulate a multivariate index to assess the pedestrian comfort of a street segment.

(iv) To apply the formulated index to investigate the effects of street morphological attributes on pedestrian comfort of a street segment.

(v) To apply the formulated index to investigate the effects of major neighborhood morphological attributes affect the pedestrian comfort of a street segment.

1.4 Significance of the studies

This study has three important aspects of contributions. First, it provides a theoretical framework about pedestrian comfort for recreational walking by revealing their relationships with subjective and objective built and micro- environmental features. This provides theoretical evidence for formulating effective strategies to improve street environments and encourage more recreational walking activities. Secondly, this study proposes a pedestrian comfort index by integrating micro-environment criteria including perceived air quality, noise annoyance and thermal sensation, and built environment criteria including sidewalks, amenities and landscape. The index is comprehensive in scope and its hourly reporting intervals can facilitate pedestrians in making decisions to walk and choose comfortable routes. Thirdly, with the aid of the formulated pedestrian comfort index, this study helps reveal the composite effects of street and neighborhood morphological attributes on pedestrian comfort of a street segment. The studied street morphological attributes include tree-planting pattern, street orientation and aspect ratio, while the studied neighborhood morphological attributes include neighborhood compactness, surrounding building height configuration and layout form. The successful application of the formulated index to explore the effects of street and neighborhood morphological attributes provides valuable suggestions for urban planners to enhance the pedestrian comfort level of street environment.

1.5 Thesis outline

This thesis includes six chapters with outline descriptions for different chapters being given as follows:

Chapter 1 provides an introduction of the background, motivation, and significance, as well as an outline of this thesis.

Chapter 2 includes a comprehensive literature review related to the topic of walking behavior, pedestrian comfort and physical street environment.

Chapter 3 aims to identify the environmental determinants for pedestrian comfort during recreational walking, as well as to explore their interrelationships.

Chapter 4 proposes a multivariate index to assess pedestrian comfort by integrating major environmental factors. Subsequently, the proposed index was applied to analyze the effects of street morphological attributes on pedestrian comfort.

Chapter 5 analyzes the effects of neighborhood morphological attributes on the pedestrian comfort of a street segment. Initial emphasis has been placed on analyzing their effects on thermal comfort due to that thermal comfort is a dominant aspect of pedestrian comfort.

Chapter 6 concludes this thesis and provides recommendations for future studies.

Chapter 2 Literature review

This chapter provides a comprehensive literature review on walking behavior, pedestrian comfort and street physical environment that are anticipated to encourage pedestrian recreational walking. The first section reviews the key physical environment features affecting walking behavior. The second section reviews pedestrian walking needs, and the third section reviews the physical environment features affecting pedestrian comfort, i.e. a higher-order walking need. The fourth section reviews the comfort evaluation methods, while the last section reviews the effects of street and neighborhood morphological attributes on comfort-related physical environmental features.

2.1 Walking behavior and physical environment

Physical environment has been found to play an important role in individuals' walking activity level (Saelens and Handy, 2008; Leung et al., 2018). The physical environment refers to the built environment (e.g., green space, housing stock, transportation networks, etc.), pollution, noise, traffic congestion, and geological and climate conditions (Quah, 2016). Cervero & Kockelman (1997) proposed 3Ds - Density (population density), Diversity (land use mix), and Design (transportation network design) - as three built environment dimensions that influence walking behavior. Later, it has been extended to 5Ds to include Distance and Destination accessibility (Ewing and Cervero, 2010). Alternative structures have also been proposed for categorizing physical environmental factors or criteria of walkable environment. Examples are: Accessibility, Pleasantness and Safety from traffic and crime in

Irvine-Minnesota Inventory; Functional, Safety, Aesthetics, Destination and Subjective in Systematic Pedestrian and Cycling Environment Scale – SPACES; Environment, Pedestrian Facility, Road Attributes and Walking Environment in Pedestrian Environmental Data Scan – PEDS and Safety, Track, Environment, Population and Purpose in STEPP (Gehrke, 2012); and Connected, Convenient, Comfortable, Convivial and Conspicuous by London Planning Advisory Committee (Gardner, et al., 1996).

Meanwhile, substantial efforts have been made to identify the physical environmental factors that are correlated with walking. Macroscale factors such as population density, connectivity, accessibility, and land use mix have been identified as environmental correlates of walking behavior (Habibian and Hosseinzadeh, 2018; Taleai and Taheri Amiri, 2017). Connectivity is related to the directness of the links and the density of crossroads in street networks. Accessibility is related to the level of convenience in reaching a building destination, such as proximity to another destination and/or accessibility to nearby transportation facilities. Land use mix is related to the surrounding facilities such as restaurants. Some micro-scale or street-level factors have also been determined as environmental correlates of walking behavior. Pavement quality, street width and slope, greenery, and the availability of pedestrian amenities like trash cans, streetlights and benches all have been shown to bear a relationship with walking behavior (Borst et al., 2009; Hahm et al., 2017; Lu et al., 2018; Rodríguez et al., 2009).

In addition, physical environmental factors alone may not help explain the experience of walking down a particular street or capture people's perceptions of physical environmental factors that may have complex or subtle relationships with walking behavior. Accordingly, initiatives have also been made to link pedestrian environmental perceptions to walking behavior. Perception of neighborhood residential density and perception of street connectivity were found to have correlations with walking behavior (Saelens et al., 2003).

Noticeably, many of these physical environmental factors and subjective perceptual factors were often determined with the aid of regression models (Borst et al., 2009; Lu et al., 2018; Rodríguez et al., 2009) or factor analysis (Frank et al., 2010; Habibian and Hosseinzadeh, 2018; Hahm et al., 2017). However, these models are often empirical in nature without strong theoretical backgrounds. Due to the lack of a theoretical framework to be tested and measures that offer sufficient comparability and control for cofounders, causal links between walking environment and walking behavior are still not clear (Bozovic et al., 2020). Hence, even after environmental correlates have been identified, there is still an immediate need to understand why these environmental factors affect people's decision to walk or not to walk. Such understandings are vital for formulating effective strategies to alter walking behavior.

2.2 Pedestrian walking needs

Arguably, pedestrian walking needs can help explain the correlation between physical environmental factors and people's propensity to walk (Alfonzo, 2005; Lindelöw et al., 2014; Mateo-babiano, 2016; Mateo-Babiano, 2012). A pedestrian's decision to walk or not to walk is more related to the extent to which the environmental attributes satisfy their needs rather than the extent of walkable environment (Mateo-babiano, 2016).

Theories of pedestrian needs have been developed based on Maslow's hierarchy of human needs (1954). Maslow's hierarchy of human needs (1954) postulates that individuals have fundamental needs. These needs are premised to be hierarchical in nature. Basic physiological needs (e.g. breathing, food, water, etc.) are found at the bottom of the hierarchy. Maslow postulates that people will consider the basic needs before the high-order needs. In a similar manner, the concept of pedestrian needs also embraced the hierarchical structure, and basic needs were considered first. However, unlike the hierarchy of human needs, the concept of pedestrian needs acknowledges that preference is derived from one’s travel needs and requirements, and may change depending on the context, thus, are less vertically restrictive (Mateo-babiano, 2016). Alfonzo (2005) put forward five pedestrian needs criteria, namely feasibility, accessibility, safety, comfort and pleasurability, which are shown in Figure 2.1. Each specific criterion can be fulfilled by a number of environmental elements (Fruin, 1971). Furthermore, this model was extended by Vikas Mehta (2008) and further elaborated by Buckley (2017). Alternatively, Mateo-Babiano and Ieda (2005; 2012) also proposed mobility, protection, ease, equitable access, enjoyment and identity as pedestrian needs. The above models share similarities in considering pedestrian needs as stimuli that would encourage walking activities, since the basis of street design is its end users although slight differences existed in needs classification.

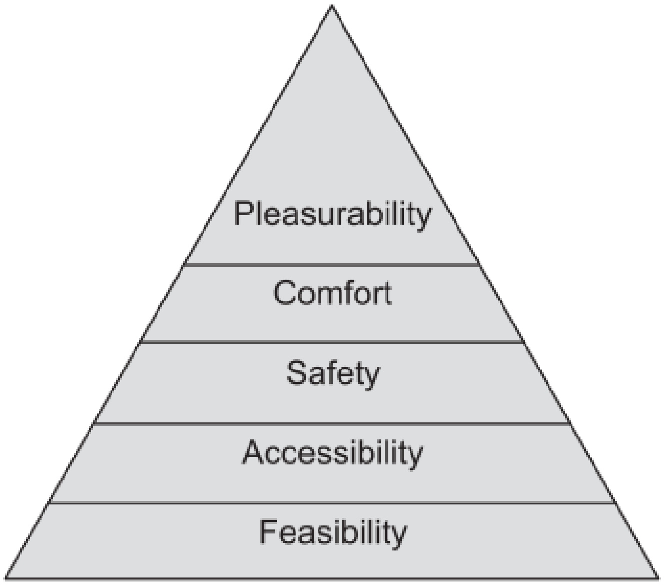


Figure 2.1 Alfonzo‘s (2005) walking needs

Factors affecting basic pedestrian needs such as accessibility and pedestrian safety have been under scrutiny (Asadi-Shekari et al., 2015; Bivina et al., 2019; Corazza and Favaretto, 2019; Hodgson et al., 2009; Tanaka, 2012; Zegeer, 1998). Adequate pedestrian crossing facilities, pedestrian refuges, curb build-outs, standard footways, tactile paving surfaces and traffic calming were determined to be able to enhance pedestrian safety (Asadi-Shekari et al., 2015; Davies, 1999; Zegeer, 1998). Built environment features such as width, availability, continuity and quality of sidewalks, road connectivity, physical barriers along sidewalks, and crossing facilities were also found to correlate with pedestrian accessibility (Bivina et al., 2019; López-Lambas et al., 2021). In comparison, comfort, being one of the higher-order walking needs, has received less attention (Shammas and Escobar, 2019). Accordingly, there is a burning need to acquire a better understanding of street physical environment attributes that can help to improve its comfort level.

2.3 Pedestrian comfort and physical environment

Pedestrian comfort is defined as the extent to which walking is accommodated to capabilities and skills of all types of pedestrians with attributes and amenities that ease the walking experiences (Saelens and Handy, 2008; Rahaman et al., 2012). It should be a matter of perception and more associated with people's sensations of multiple external environmental stimuli on street levels (Asadi-Shekari et al., 2019; Ewing et al., 2016; Mehta, 2008; Yin, 2017). Conceivably, personal characteristics exert influences on pedestrian comfort. For example, Ovstedal and Ryeng (2002) found that women evaluated comfort to lower levels than men, and older people always felt less comfortable than youth. Meanwhile, Peng et al. (2019) reported that people who had a higher walking frequency were inclined to feel more comfortable.

Many physical environment factors are needed to model the perception of comfort (Bouscasse and Lapparent, 2019). Both objective and subjective perceptual factors have been suggested to be included in the pedestrian comfort model so as to cater for different comfort reactions produced by different people through their environmental perceptions when assessing the same objectively measured environmental attribute (Ewing & Handy, 2009; Vikas Mehta, 2008). In particular, subjective environmental attributes were considered to be more influential to people's perceptions and walking behaviors when compared to objectively measured attributes (Wang et al., 2019; Zhang et al., 2018).

Broadly speaking, there are two separate streams of studies on pedestrian comfort. One stream of studies focused on identifying the effect of built environmental features on pedestrian comfort. Sidewalk conditions, e.g. the quality, width, cleanliness of sidewalks as well as the presence of obstructions all have been determined to affect pedestrian comfort. Well-maintained sidewalks without broken pavements would make pedestrian feet feel comfortable during walking (Borst et al., 2009). Narrow streets would deteriorate the comfort and enjoyment of walking and prevent pedestrians from walking more (Azemati et al., 2011; Kim et al., 2011; Lin & Chang, 2010; Samarasekara et al., 2012). Sidewalks filled with obstructions or encroachments, e.g. cars or advertisement boards from shops would lead to uncomfortable walking trips (Sarkar, 2003). Dirty sidewalks filled with litter would obstruct pedestrians to walk freely and also instill a poor aesthetic feeling (Bornioli et al., 2019; Cambra, 2012; Galanis and Eliou, 2011). Amenities also provide convenience for pedestrians to walk in streets (Asadi-Shekari et al., 2019; Moura et al., 2017). For example, benches provide pedestrians a rest during a walking trip which can encourage them to walk more (Asadi-Shekari et al., 2019). Rubbish bins are convenient for pedestrians to deal with rubbish to keep the sidewalks clean (Aghaabbasi et al., 2018). In addition, the landscape, e.g. the aesthetic appearance of building façade and greenery, influenced both affective comfort feeling and walking intentions (Ball et al., 2001; Santosa et al., 2018). Generally, dirty or ill-maintained building façades would make pedestrians feel discontent and stressed (Bornioli et al., 2019). In contrast, greenspace provides multiple benefits, such as inspiring an individual's visual aesthetic appreciation of streetscapes, increasing the duration of staying outdoors and preventing stress and negative psychological symptoms (Lu, 2019).

Another stream of studies focused on a few external micro-environmental factors that induce discomfort during walking. A majority of them targeted at mitigating wind or thermal discomfort under strong wind or hot weather conditions (Morakinyo et al., 2017; Rodríguez

Algeciras et al., 2016; Wu and Kriksic, 2012; Zhang et al., 2017; Zheng et al., 2016) as they could hinder pedestrians from walking to a great extent (Ariffin and Zahari, 2013; Bélanger et al., 2009; Spinney and Millward, 2011). Such studies were based on an underlying premise that an environment that contained a single extremely uncomfortable factor was essentially uncomfortable, and could pay little respect to the comfortable sensations produced by other factors (Silva and Mendes, 2012; Soligo et al., 1998). Apart from focusing only on factors causing extreme discomfort, it has been suggested that more factors such as noise and air quality should be included together with wind or thermal discomfort in the evaluation of pedestrian comfort (Soligo et al., 1998), e.g. Walkability guidelines issued by Civic Exchange in Hong Kong (2016) and Transport Agency in New Zealand (2009).

2.4 Comfort assessment methods

Generally, comfort has been always included either explicitly or implicitly as one of the objectives of walkability audit tools or guidelines (See Table 2.1). Tools or guidelines such as the walkability index proposed by Arellana et al. (2020), Talavera-Garcia and Soria-Lara, (2015), Shittu and Bununu (2019) and Moura et al. (2017) only employed built environment attributes to be their comfort assessment criteria. The walkability index developed by Al Shammas and Escobar (2019) only adopted micro-environment attributes as proxies for comfort assessment criteria. In contrast, other tools or guidelines, such as 5 Cs of London Planning Advisory Committee (Gardner et al., 1996), the Pedestrian Planning and Design Guide of the NZ transport agency (2009), Hong Kong walkability checklist (Civic Exchange, 2016), the walkability index developed by Ortega et al. (2020), and Radha et al. (2020), related comfort criteria to both built environment and micro-environment attributes.

Hitherto, only a few methods or indices have been developed to evaluate pedestrian comfort. Sarkar (2003) developed a method to assess pedestrian comfort by employing shady arcades or canopies as the proxy of thermal comfort in view of their abilities to protect pedestrians from extreme solar radiation, but they could not accommodate the temporal variations of microclimatic conditions. To overcome this, Labdaoui et al. (2021b) addressed this by integrating a thermal comfort index together with other 20 comfort-related attributes to form a new comfort walkability index (CWI). However, it is still not able to provide a holistic assessment as it did not embrace all the major comfort-related factors such as air quality and noise (Bunds et al., 2019). They are of utmost importance for ultra-dense Asian metropolises like Hong Kong (Cerin et al., 2011).

Table 2.1 A list of comfort-related built and micro-environmental criteria embedded within walkability tools/guidelines or comfort assessment methods

Sources	***Built-environmental features***	***Micro-environment attributes***
London Planning Advisory Committee (Gardner et al., 1996)	High-quality pavement, attractive landscape design and architecture, and seating	Noise and fumes, shelter
NZ transport agency (2009)	Seating, sidewalk width, slope and obstruction	Noise and fumes, shelter

Hong Kong walkability checklist (Civic Exchange, 2016)	Rubbish bins, landscaping and greenery, seating, sidewalk cleanliness, obstruction and width	Shelter, air pollution, noise pollution and ventilation
Arellana et al (2020)	Aesthetics of buildings, enclosure ratio, presence of trees and cleanliness	/
Tarek Al Shammas and Francisco Escobar (2019)	/	Shade, noise
Talavera-Garcia and Soria-LaraTarek (2015)	Tree density	/
Shittu and Bununu (2019)	Sidewalks and shelters, tree lines and landscaping, sidewalk obstruction	/
Radha et al. (2020)	Sidewalk width and consitency, tree, lighting and seating area	Shadow
Ortega et al. (2020)	Building height, trees, and street width	Shade, noise
Labdaoui et al. (2021)	Slower traffic speed, buffer and barriers, fewer traffic lanes, mid-block crossings, landscaping and trees, rubbish bins, crosswalk, footpath width, slope, lighting, ramp, parks and social spaces, seating, toilets, pedestrian signals, shorter crossing distance	PET
Sarkar (2003)	Adequate and continuous sidewalk, sidewalk obstruction, convenient amenities, pavement quality, seating, crowdedness	Arcades/canopies/trees, noise, air pollution

Moura et al. (2017)	Facade transparency, pavement quality (based on regularity, smoothness, slippery characteristics)	/

2.5 Effects of street and neighborhood morphological attributes on pedestrian comfort of a street segment

Understanding the effects of morphological attributes on comfort-related factors can provide urban planners with valuable insights in creating comfortable environments. Several street and neighborhood morphological attributes were reported to affect multiple comfort-related environmental factors. For example, street morphological attributes embrace tree-planting, street orientation and aspect ratio, while neighborhood morphological attributes embrace neighborhood compactness, heights of building cluster and neighborhood layout.

2.5.1 Street morphological attributes

Trees, which are common landscape features, can not only improve the landscape aesthetics but also are expected to bring changes in both air quality and thermal comfort in a street segment. Tree-planting provides a thermally comfortable walking environment for pedestrians by shade provision and evaporative cooling (Morakinyo et al., 2016; Shashua-Bar et al., 2012). In contrast, placing more trees inside canyons has been shown to deteriorate the air quality as they would obstruct the airflow and weaken the street ventilation and air pollution dispersion (Gromke and Ruck, 2012).

Street orientation and aspect ratio are the main street canyon geometry features. Both thermal comfort and air quality will vary with street orientation. E-W Streets have been repeatedly reported to be the worst orientation with the most thermal stress due to the long-time solar exposure in many different climatic zones such as Mediterranean (Achour-Younsi and Kharrat, 2016; Andreou, 2013), temperate (Taleghani et al., 2015), hot-humid (Rodríguez Algeciras et al., 2016), hot-dry (Aghamolaei et al., 2020; Ali-Toudert & Mayer, 2006) climate zones. In contrast, there was little agreement on the orientation that would produce the best thermal conditions. For example, the best thermal conditions were determined to be N-S Streets in Cuba with hot-humid climate (Rodríguez Algeciras et al., 2016), and NW-SE orientation in Thessaloniki with temperate climate (Chatzidimitriou and Yannas, 2017). On the other hand, the streets parallel to the wind direction always had better air quality due to the lower ventilation and air pollutant removal rate, and in turn streets perpendicular to wind direction always had the worst air quality (Huang et al., 2019; Sözen and Koçlar Oral, 2019).

In the meantime, aspect ratio, which is the ratio of the average height of street buildings to street width, would also affect thermal comfort, air quality and noise. Deep canyons would provide a thermally comfortable street environment by reducing street solar access (Huang et al., 2021; Johansson, 2006; Shashua-Bar et al., 2012). Also, a higher aspect ratio would improve street air quality. Street ventilation and air pollutant dispersion rate would increase due to the strong"venturi effects"(Li et al., 2020; Miao et al., 2020). In addition, narrower streets would increase the noise level due to more sound reflections (Echevarria Sanchez et al., 2016; Thomas et al., 2013).

2.5.2 Neighborhood morphological attributes

The height of building cluster would affect thermal comfort and air quality. Increasing the height of building cluster could improve the thermal comfort of an area (Perini & Magliocco, 2014; Yang et al., 2017). Significant variation in height of buildings and placing the tallest buildings in the middle of the block were also reported to be able to provide more thermally comfortable conditions (Shareef and Abu-Hijleh, 2020). Meanwhile, the air quality of streets aligned with the prevailing wind would become better when the building cluster height increased (Chen et al., 2021). Higher surrounding buildings at the border of the domain would obstruct the airflow and worsen the street air quality(Acero et al., 2021).

Similarly, building layout form could affect thermal comfort and air quality. Hitherto, it is still not clear which layout form can provide better thermal comfort. The courtyard form was found to be able to provide better thermal comfort than an E-W linear form in Delft of Netherlands (Taleghani et al., 2015) or than the point building layout in Nanjing of China (Yang et al., 2017). In contrast, the linear form was found to be able to provide better thermal comfort than half-enclosing layout form in the residential area of Xi'an in China (Yang et al., 2020). On the other hand, the area in the courtyard form has been identified to have the worst air quality, while the singular or linear layout had better air quality with smooth airflow (Sözen and Koçlar Oral, 2019; Taleghani et al., 2015).

In addition, thermal comfort, noise level and air quality are expected to vary with neighborhood compactness. The thermal comfort of an area was found to improve by increasing Building Coverage Ratio (BCR) (Perini & Magliocco, 2014), which has been defined as the ratio between the footprint of the buildings and the total area of the plot of land, but further increase in BCR beyond a specific value would worsen the thermal comfort condition (Yang et al., 2017). Similarly, although the increase of BCR was reported to reduce the wind speed of an area and deteriorate its air quality (Xuan et al., 2016), it was also found that the wind speed of the area surrounding the center building would increase with BCR (Chen et al., 2021). In the meantime, the narrow streets in a dense neighborhood or area are would increase the noise level of the street (Echevarria Sanchez et al., 2016; Thomas et al., 2013).

Due to the lack of a holistic comfort assessment method, the effects of street and neighborhood morphological attributes on the overall comfort, i.e. pedestrian comfort, have not been revealed. Besides, it was found that previous studies related to neighborhood morphological attributes always focused on the scale of an area or neighborhood rather than a street segment, in particular for most studies related to thermal comfort. There is a lack of studies focusing on the effects of neighborhood morphological attributes on pedestrian comfort as well as thermal comfort of a street segment.

2.6 Research gaps and Pedestrian comfort framework

Comfort, as a higher-order walking need, can encourage pedestrians to walk more. Micro-environmental factors including microclimate, air quality and noise, and built environmental features including sidewalks, amenities and landscape can affect pedestrian comfort. Moreover, street morphological attributes including tree-planting pattern, street orientation and aspect ratio, and neighborhood morphological attributes including neighborhood compactness, building height configuration and layout form would affect the above comfort-related micro- and built environmental factors.

Based on the above literature review, this part initially points out the existing research gaps and then proposes the theoretical framework of pedestrian comfort.

2.6.1 Research gaps

There are three major research gaps as shown in the followings:

First, there is a lack of studies that can holistically reveal whether and how the objective and subjective built and micro-environmental factors influence pedestrian comfort, although their effects on pedestrian comfort have been reported in a piecemeal manner.

Second, there is a lack of pedestrian comfort index that successfully integrated all major comfort-related built and micro-environment factors. Without such an index, it poses great challenges for urban planners and designers to determine how street morphological attributes, which exerted influences on multiple comfort-related environmental factors, affect pedestrian comfort.

Third, there is also a lack of studies revealing the effects of neighborhood morphological attributes on the pedestrian comfort as well as thermal comfort of a street segment, while most focused on the area or neighborhood. Limited studies have conducted in-depth investigations to systematically reveal and understand how neighborhood morphological attributes affect pedestrian comfort and thermal comfort of a street segment.

2.6.2 Theoretical framework of pedestrian comfort

From the view of Slater (1985)'s view that comfort is "a pleasant state of physiological, psychological and physical harmony between a human being and the environment", pedestrian comfort embraced the following aspects: physical comfort for minimizing the effort needed to undertake pedestrian activities; visual comfort related to the psychological aspect for offering mental satisfaction; tactile comfort, acoustic comfort, air quality comfort and thermal comfort all related to physiological aspect for human sensations of tactile, hearing smell and thermal stress (Sarkar, 2003). Figure 2.2 shows the theoretical framework of pedestrian comfort with regards to the individual aspects of pedestrian comfort and their proxies.

Built environment features, including sidewalks, amenities and landscape, were determined to be correlated with tactile comfort, physical comfort and visual comfort, respectively. Specifically, pedestrian feet were in touch with sidewalk surface, in turn, tactile comfort would be affected by sidewalk condition (Ovstedal and Ryeng, 2002). Amenities like benches could facilitate pedestrian walking and help reduce the efforts of pedestrian activities, which could be regarded as the proxy of physical comfort (Asadi-Shekari et al., 2019; Moura et al., 2017). The aesthetic landscape, e.g. greenery or building façade, can improve visual comfort and relieve human stress (Lu, 2019).

In contrast, micro-environment factors involving microclimate, air quality and noise were related to thermal comfort, air quality comfort and acoustic comfort, respectively, and their proxies could be expressed as thermal sensation, perceived air quality (PAQ) and perceived loudness (noise annoyance). Additional attention was given to the word 'air quality comfort' which was not common and only used to represent the comfortable feeling brought by good/fresh air in this study.

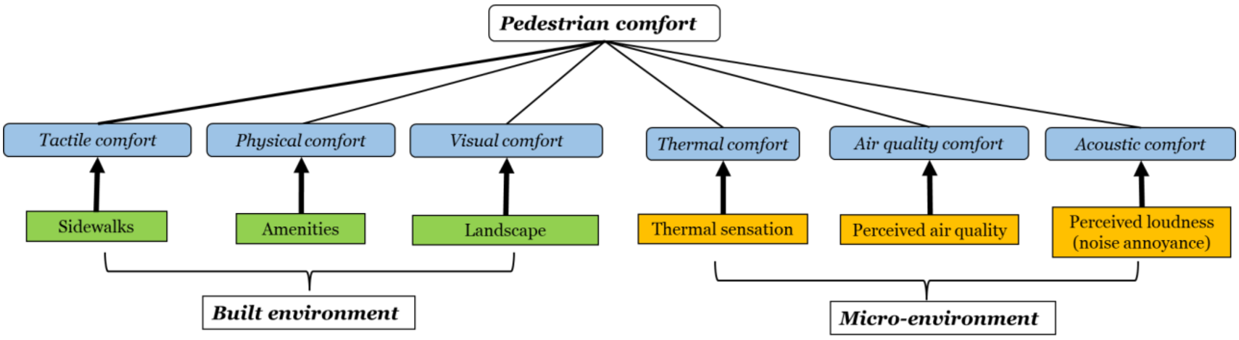


Figure 2.2 Theoretical framework of pedestrian comfort

Chapter 3 Critical factors influencing pedestrian comfort evaluation for recreational walking

This chapter aims to validate the theoretical framework proposed in Chapter 2 by revealing whether air quality, noise, microclimate, built environment and subjective perceptions of pedestrians are environmental determinants for pedestrian comfort for recreational walking and exploring their interrelationships. To start with, a number of hypotheses about the major environmental characteristics have been formulated after performing rigorous literature reviews. To verify these hypotheses, questionnaire surveys intended for eliciting pedestrian perceptions of air quality, noise, microclimate and built environment, and pedestrian comfort as well as the field measurements about objectively measured micro-environmental conditions of street environment were conducted simultaneously. Finally, a path model has been formulated to portray the interrelationships among pedestrian comfort, perceptual and objectively measured built and micro-environmental characteristics, with particular focuses on simultaneously exploring the relationships between perceptions and objective measurements of the micro-environmental attributes and their associations with recreational walking.

3.1 Hypothesis

Vikas Mehta (2008) suggested that street physical characteristics exerted influences an individual's walking behavior through two mediators: user perceptions and walking needs. Based on his proposition, we proposed a conceptual framework to portray the interrelationships among pedestrian comfort, external surroundings, perceptions of external surroundings and personal characteristics (see Figure 3.1). A number of underlying hypotheses constructed before formulating the proposed conceptual framework are listed as follows:

First, pedestrian comfort is a positive emotional reaction to external surroundings (i.e. walking environment) including physiological, physical and psychological reactions. Accordingly, the personal characteristics, such as age, gender, and frequency and purpose of visit, were assumed to affect pedestrian comfort. The external surroundings were assumed to include microclimate, air quality, and noise level as well as built environment.

Second, built environmental characteristics were proposed to be broadly categorized under sidewalks, amenities and landscape. Table 3.1 lists the key performance indicators of sidewalks, amenities and landscape. These indicators have already been included in the comfort criteria of existing walkability audit tools and comfort assessment methods. These tools/methods were identified from relevant research papers, review articles and standard guidelines via Google Scholar, Scopus and Web of Science using the keywords ‘comfort’, ‘walkability’, ‘assessment tools’, ‘street’, and ‘streetscape’ from 2000 to 2021.

Third, an individual’s perceptions of microclimate, air quality and noise were assumed to be correlated with their corresponding objectively measured parameters. Thermal sensation was assumed to be related to objectively measured microclimatic conditions, including air temperature, wind speed, solar radiation and relative humidity. Perceived air quality (PAQ) and loudness were assumed to be correlated with particulate matter concentration and sound pressure level (SPL) respectively.

Table 3.2 shows the major hypotheses embodied within the proposed conceptual framework after conducting comprehensive literature reviews on relevant earlier findings.

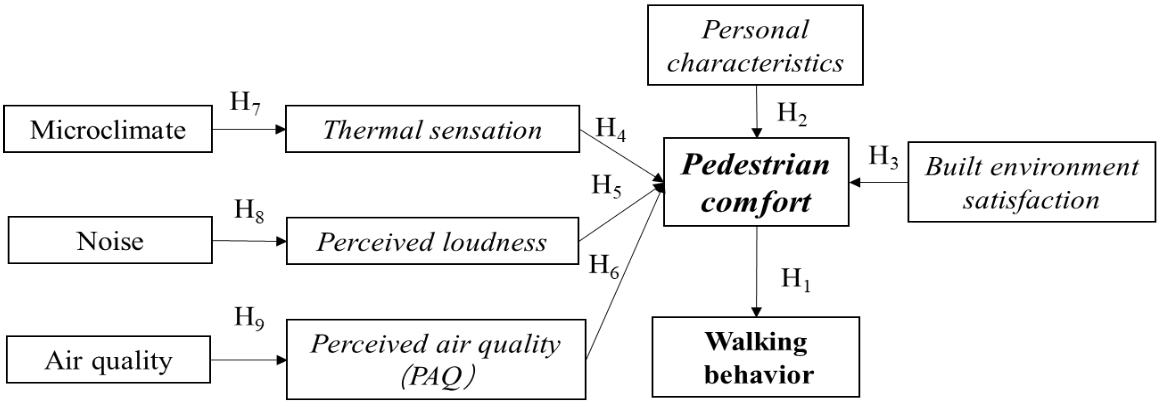


Figure 3.1 The proposed conceptual framework for the path model

Table 3.1 Key performance indicators for sidewalks, amenities and landscape

Built Environment Criterion	Indicator	References
Sidewalks	Width	(Civic Exchange, 2016; Labdaoui et al., 2021a; Ortega et al., 2020; Radha et al., 2020; Sarkar, 2003)
	Obstruction	(Civic Exchange, 2016; Moura et al., 2017; NZ Transport Agency, 2009; Sarkar, 2003; Shittu and Bununu, 2019)
	Cleanliness	(Arellana et al., 2020; Civic Exchange, 2016)
	Quality	(Moura et al., 2017; Sarkar, 2003; Shittu and Bununu, 2019)
Amenities	Seating area	(Civic Exchange, 2016; Labdaoui et al., 2021a; Radha et al., 2020; Sarkar, 2003)
	Trash receptacles	(Civic Exchange, 2016; Labdaoui et al., 2021a)

Landscape	Trees	(Arellana et al., 2020; Civic Exchange, 2016; Labdaoui et al., 2021a; Ortega et al., 2020; Radha et al., 2020; Shittu and Bununu, 2019; Talavera-Garcia and Soria-Lara, 2015)
	Building aesthetic	(Arellana et al., 2020; Civic Exchange, 2016)

Table 3.2 Major hypotheses of the proposed conceptual framework

Hypothesis	Description	References
H1:	Pedestrian comfort influences walking behavior	(Bornioli et al., 2019; Dean et al., 2020)
H2:	Personal characteristics influence Pedestrian comfort	
H2$_{A}$	Age/Gender→ Pedestrian comfort	(Ovstedal and Ryeng, 2002)
H2$_{B}$	Frequency of visit→ Pedestrian comfort	(Van Holle et al., 2012)
H2$_{C}$	Purpose of visit →Pedestrian comfort	(Ovstedal and Ryeng, 2002)
H3:	Built environment satisfaction influences Pedestrian comfort	
H3$_{A}$	Satisfaction of sidewalks → Pedestrian comfort	(Alfonzo, 2005); (Florez et al., 2014)$^{\#}$; (Sarkar, 2003); (Van Holle et al., 2012)
H3$_{B}$	Satisfaction of amenities → Pedestrian comfort	(Cain et al., 2014)*; (Erna et al., 2016)*; (Cain et al., 2017)*; (Asadi-Shekari et al., 2019)
H3$_{C}$	Satisfaction of landscape → Pedestrian comfort	(Pikora et al., 2002)*; (Santosa et al., 2018); (Ball et al., 2001)*

H4:	Thermal sensation influences Pedestrian comfort	(Ovstedal and Ryeng, 2002); (Sarkar, 2003); (Chan et al., 2017)#; (Lin, 2009)#
H5:	Perceived loudness influences Pedestrian comfort	(Ovstedal and Ryeng, 2002); (Sarkar, 2003); (Peng et al., 2019)#; (Al Shammas and Escobar, 2019)
H6:	Perceived air quality influences Pedestrian comfort	(Ovstedal and Ryeng, 2002); (Sarkar, 2003); (Peng et al., 2019)#; (Moudon et al., 2007)*; (Pantavou et al., 2017)#
H7 :	Microclimatic conditions influence Thermal sensation	
H7A	Wind sensation/Wind speed → Thermal sensation	(Peng et al., 2019); (Hou et al., 2017); (Wu and Kriksic, 2012)
H7B	Solar sensation/Solar radiation → Thermal sensation	(Chan et al., 2017)(Peng et al., 2019)
H7C	Humidity sensation/ Relative humidity → Thermal sensation	(Chan et al., 2017); (Hou et al., 2017)
H7D	Air temperature→ Thermal sensation	(Chan et al., 2017); (Hou et al., 2017); (Wu and Kriksic, 2012)
H8 :	Noise level influences Perceived loudness	
	SPL → Perceived loudness	(Kang et al., 2012)
H9:	Air quality influences PAQ	
	Particulate matter concentration → PAQ	(Nikolopoulou et al., 2011)

Note: '→' denotes that exists a statistically significant effect.

‘*’ denotes that a statistically significant relationship was found for walking behavior.
‘#’ denotes that a statistically significant relationship was found for comfort perception.

3.2 Methodology

3.2.1 Research Design

In order to verify all our hypotheses listed in Table 3.2, go-along interviews were employed to collect all the relevant data on pedestrians’ perceptions of micro-environment, satisfaction of built environment and pedestrian comfort as well as the objectively measured micro-environmental conditions of street environments. Figure 3.2 shows an outline of the methods employed for collecting data to formulate a path model to study the interrelationships among all the studied factors.

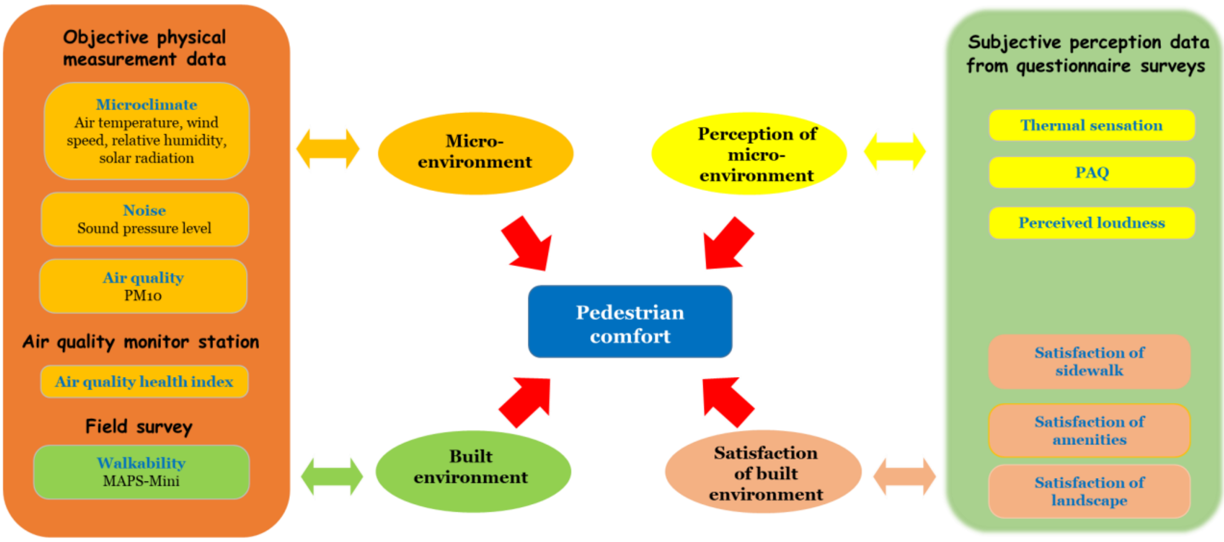


Figure 3.2 An outline of methods employed for collecting different types of data to formulate a path model

3.2.2 The climate and urban morphology in Hong Kong

This study was carried out in Hong Kong, which is located at a latitude of 22°15’N and a longitude of 114°10’E. Hong Kong has a subtropical climate with relatively long hot-humid summer periods (i.e. May to September). During the hot-humid summer days, the daily maximum temperature can be up to 33°C, and the relative humidity is often above 80% (Peng and Jim, 2013). Figure 3.3 shows the monthly mean values of daily maximum, mean and minimum air temperature and relative humidity in Hong Kong between 2010 and 2020 (HKO, 2020).

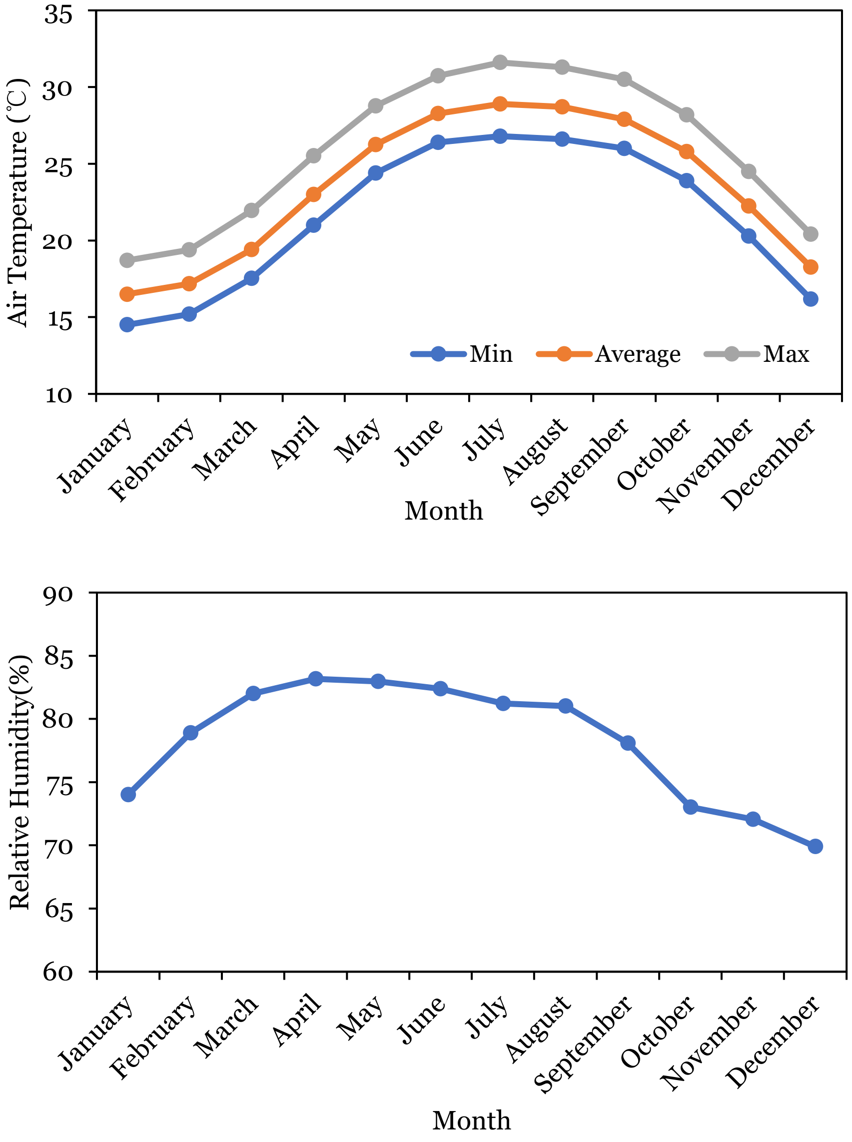


Figure 3.3 Monthly mean values of daily maximum, mean and minimum air temperature and relative humidity between 2010 and 2020

Hong Kong is one of the densest built cities in the world with 7.5 m population living in area of 1106 km^2, in which only 25% of land has been developed (Ng et al., 2011). Regular street blocks and building layouts, and rows of canyons formed by tall buildings lining along narrow streets are commonly observed in urban areas. Figure 3.4 shows the regular street blocks and building layouts in West Kowloon.

Figure 3.4 Urban morphology in Hong Kong

3.2.3 Site selection

In this study, street segments of 100-200m long were selected as an analytical unit. Street segments were selected from four streets in Hong Kong with mixed road and foot traffic as our target survey sites. They were selected to represent streets with considerable variations in levels of air pollution, noise and walkability. Daily road traffic count was assumed proxies for air pollution and noise level of a local street environment. MAPS-Mini tool, which has been considered reliable for evaluating walkability in many countries, was used as a reference in extracting a list of objectively measured environmental attributes for sidewalk, landscape and amenities.

Figure 3.5 shows the map locations of the four survey streets with their major characteristics being summarized in Table 3.3. The selected segment in Nathan Road is a popular shopping street located in the city center area with heavy road traffic flows. It had a high walkability level as it embraced wide and fully tree-lined sidewalks and provided many seats for people to rest. In contrast, Sha Tin Wai Road is a local street within a residential neighborhood. The sidewalk was partially tree-covered with only two seats being available at the transit stop. Its road traffic counts were similar to those of Nathan Road. Both Nathan Road and Sha Tin Wai Road were selected to represent streets with high walkability levels. In contrast, Portland Street and Shanghai Street, which are located in the same commercial and residential neighborhood, were selected to represent streets with low walkability levels. They both had narrow sidewalks and did not provide any sitting benches or tree shade. They varied in road traffic counts, with medium and light traffic counts in Shanghai Street and Portland Street respectively.

Table 3.3 Physical characteristics of the street environment

Segment location	Nathan Road	Sha Tin Wai Road	Portland Street	Shanghai Street
Marked Map Location	A	B	C	D
Walkability level* (MAPS-Mini score)	High (81%)	Moderate (62%)	Low (48%)	Low (52%)

Average daily road traffic count**	25980 (heavy)	27140 (heavy)	5700 (light)	17370 (medium)

Note: * The MAPS-Mini score was computed using the MAPS-Mini Protocol and Picture Guide (Cain et al., 2012).

** The average daily road traffic counts of the streets in 2017 were extracted from the Hong Kong Transport Department (HKSAR Transport Department, 2017).

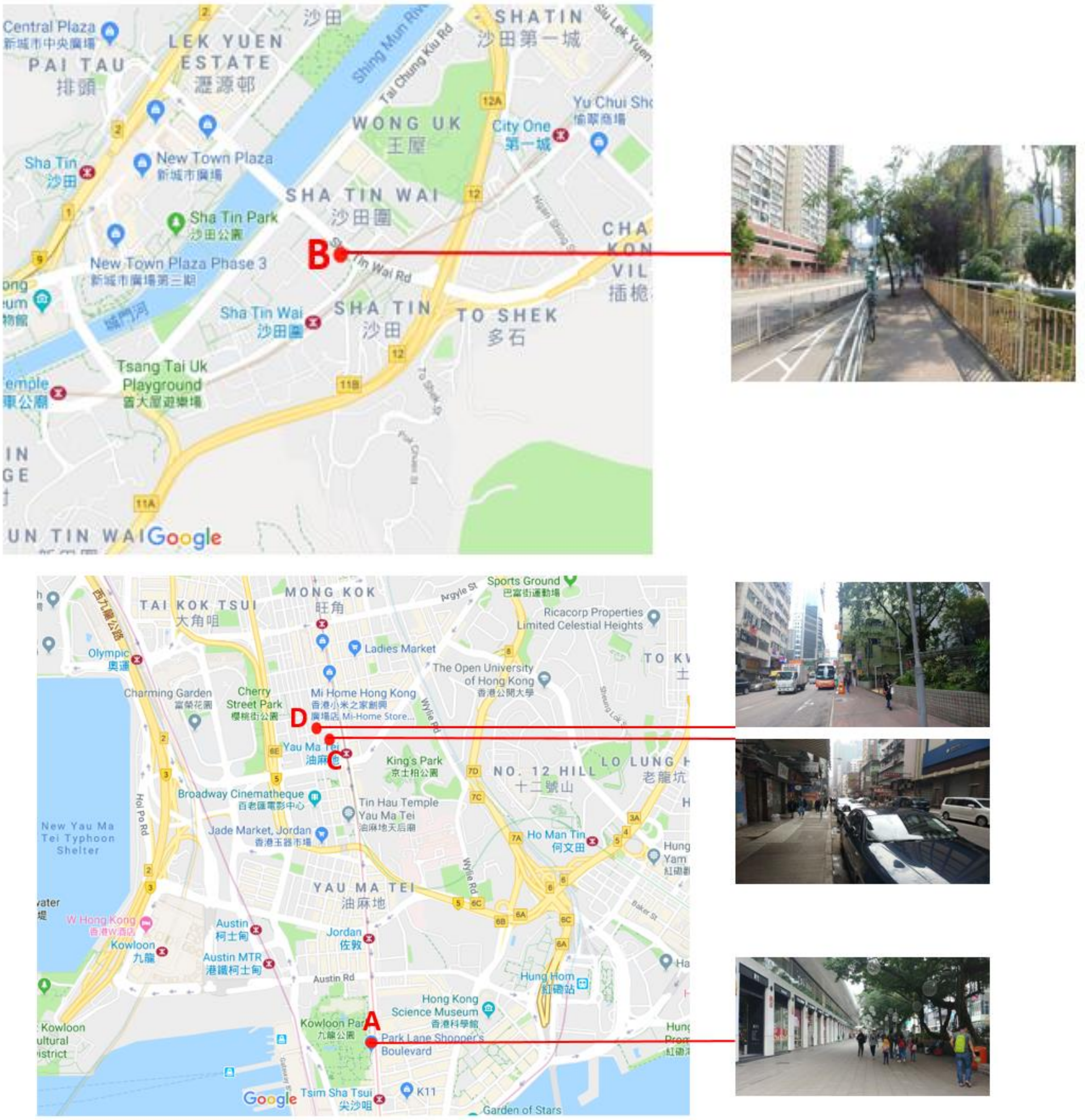


Figure 3.5 Four survey streets with mixed road and foot traffic

3.2.4 Questionnaire Surveys

Respondents were approached in a random manner and initially briefed about the purposes of the surveys. The surveys were conducted via street-level face-to-face and consents would be obtained from respondents before starting the surveys. The surveyed days were chosen to avoid extreme hot weather and severely high air pollution days as our objective was to elicit pedestrians' perceptions under normal conditions. Questionnaire surveys and physical measurements were conducted from 11 am to 4 pm (i) between December 2018 and March 2019, and (ii) in September 2019 so as to avoid extremely hot summer days and severely high air pollution days (with AQHI⩾8) in Hong Kong.

The questionnaire contained four major sections with an ultimate aim to reveal the potential linkages among pedestrian comfort, behavior toward recreational walking and the surroundings of the street environment as well as their perceptions (See Appendix 1 and 2). Section 1 aimed to elicit pedestrian's satisfaction of the built environment of the survey street. Three questions were designed to elicit pedestrians' satisfaction of the major built environmental attributes, namely sidewalk, amenities and landscape. They were all rated on a 7-point verbal scale (-3-3), ranging from '*Very Dissatisfied*', '*Dissatisfied*', '*Slightly Dissatisfied*', '*Neutral*', '*Slightly Satisfied*', '*Satisfied*' to '*Very Satisfied*'. The attributes of sidewalk, amenities and landscape were explained to the respondents before eliciting their responses. Sidewalk attribute was described in terms of width, obstruction, cleanliness of sidewalk and pavement quality (i.e. the presence of major trip hazards, e.g. heaves, misalignment, cracks, overgrowth). Amenities attribute was described in terms of presence of benches and rubbish bins. Landscape attribute was described in terms of street façades (i.e.

aesthetic architectural design) and street greenery (i.e. trees or grass paved in the pedestrian area).

Section 2 aims to elicit pedestrians' perceptions of the micro-environment of the survey street, including wind sensation, solar sensation, humidity sensation, thermal sensation, perceived loudness and PAQ. They were rated using 7-point verbal scales (-3-3), ranging from Extreme conditions (e.g. '*Extremely Weak Wind*', '*Extremely Weak Solar Radiation*', '*Extremely Dry*', '*Extremely Cold*', '*Extremely Quiet*', '*Extremely Bad Air Quality*'); '*Neutral*'; and Opposite extreme conditions (e.g. '*Extremely Strong Wind*', '*Extremely Strong Solar Radiation*', '*Extremely Humid*', '*Extremely Hot*', '*Extremely Noisy*', '*Extremely Good Air Quality*').

Section 3 aims to elicit pedestrians' comfort in the survey street environment and their behavior towards recreational walking. In the context of our study, pedestrian comfort is limited to physical and micro-environmental effects of street environment to provide an ability for an individual to walk in an urban street (Mehta, 2008). In responding to the survey questions, respondents were requested to imagine that they were walking for recreation along the present street environment without the needs to consider the constraints of time, safety, crowdedness and road traffic conditions. First, they were asked to rate their comfort levels of the street environment as a whole using a 6-point verbal scale (-3--1,1-3) - "*Very Uncomfortable*", "*Uncomfortable*", "*Slightly Uncomfortable*", "*Slightly Comfortable*", "*Comfortable*", "*Very Comfortable*". Second, they were enquired whether they were willing to walk for recreation in the current survey street environment. If the answer was "Yes", they would be asked to state how long they were willing to walk for recreation in the survey street environment. They were given 4 choices which differ in time interval, i.e. 1-4 minutes, 5-10 minutes, 10-20 minutes, and over 20 minutes.

Section 4 aims to record respondents' purpose and frequency of walking in the survey street environment, as well as their personal characteristics, including gender, age, clothing value, resident location, education level, occupation, sensitivity to thermal environment, air quality and sound, and self-reported health assessment.

3.2.5 Field Measurements

A mobile measurement station was used to measure and record the present environmental conditions near respondents during face-to-face interviews. Figure 3.6 shows the photos of the mobile measurement station, which was assembled to measure outdoor temperature, relative humidity, wind speed, globe temperature, solar radiation intensity and PM10 concentration. All the data were continuously recorded at pedestrian levels throughout the periods of conducting questionnaire surveys. The mobile station was kept stationary for 5 minutes at the location where respondents were interviewing so as to minimize the measurement errors. However, the SPL values of the streets were only recorded for 5 minutes before conducting face-to-face questionnaire surveys in order to avoid the disturbances caused by Aerosol Monitor. Table 3.4 lists the specification details of the measurement instrument.

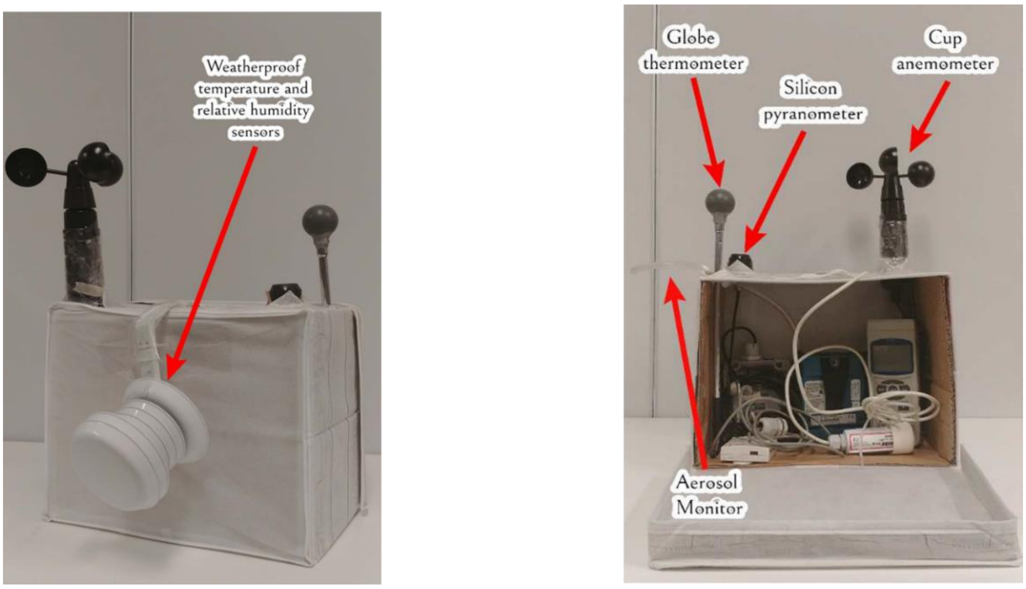


Figure 3.6 Mobile measurement station

Table 3.4 Specification details of measurement instrument contained inside the mobile measurement station

Instrument	Measurement parameter	Operating range	Measurement range	Accuracy
HOBO U23 Prov2 Temperature/Relative Humidity Data Logger with weatherproof temperature and relative humidity sensors	Air temperature	-40°C to 70°C with a resolution of 0.02°C at 25°C	-40 to 70°C	±0.21°C
	Relative Humidity	-40°C to 70 C with a resolution of 0.03°C	0 to 100%	±2.5°C
Cup Anemometer Model:AM-4257SD with SD Card real time data recorder	Wind speed	Operating temperature: 0 to 50°C Operating	0.9 to 35.0 m/s	±(2%+0.2 m/s)

		humidity: less than 85% R.H.		
Globe thermometer (consisted of a 40 mm grey table tennis ball and temperature sensor)	Globe temperature	-20 to 70℃	-20 to 70℃	±0.35℃
Silicon Pyranometer	Solar radiation Intensity	-40 to 75℃	0 to 1280 W/m^2	±5%
SidePak™ Personal Aerosol Monitor AM510	PM10 concentration	0 to 50℃ Operational humidity: 0 to 95% RH, non-condensing	Aerosol concentration range: 0.001 to 20 mg/m^3 Particle size range: 0.1 to 10 µm	±0.001 mg/m3 over 24 hours using 10-second time-constant
Sound Level Meter Hand-held Analyzer Type 2270	Sound pressure level$_{(A)}$	–10 to +50℃	–100.0 dB(A) to 200.0 dB(A)	±1%

3.2.6 Data analysis

SPSS v.25 was employed for performing statistical analyses such as Pearson correlation analysis and *t*-test using the collected measurement data and questionnaire survey responses. Path analysis was also applied to reveal the bilateral relationships between street built and micro- environmental characteristics and pedestrians' perceptions. Path analysis is an extension of multiple regression model, which can be viewed as a special case of Structural Equation Modelling (SEM) (Peng et al., 2019). Path analysis has been widely applied in many fields, including biology, psychology, sociology and econometrics (Davis et al., 2007; Ramkissoon et al., 2013). It has also been applied successfully to the analyses of outdoor thermal comfort (Chan et al., 2017; Peng et al., 2019) and noise annoyance (Izumi and Yano, 1991), which are influenced by both subjective human perceptions and objectively measured factors. Path analysis can overcome the potential shortcomings of conventional linear models (Peng et al., 2019) as it can help to estimate the direct and indirect effects between variables and thus can reveal the complex multi-lateral relationships among variables. In this study, the path model was formulated with the aid of Amos v.25.

3.3 Results

3.3.1 Descriptive statistics

In total, 420 questionnaire responses were administered in the four survey streets. 116 responses were obtained from Shanghai Street, 111 from Nathan Road, 108 from Portland Street, and 85 from Sha Tin Wai. The number of responses obtained from Sha Tin Wai was the lowest, which corresponded to its lowest pedestrian flow in the residential neighborhood. Table 3.5 summarizes the personal characteristics of the respondents. Half of the respondents were male, 80% were aged 20-59, and over half had an educational background of bachelor or above. Around 37% were residents living in the survey streets, and over 60% had not been walking in the survey streets frequently. 56% reported that they were walking for recreation during the survey. No significant statistical differences were observed in pedestrian comfort between respondents who were walking for recreation in the survey street and those who were not ($\lambda^2=12.345$, $p>0.05$). Accordingly, their responses have been combined in subsequent data analysis.

Table 3.6 shows a summary of air temperature, relative humidity, solar radiation intensity, wind speed, PM10 concentration and SPL data recorded from individual streets. Air quality health index (AQHI), which is calculated using the concentration of O_3, NO_2, SO_2 and Particular Matter (PM), was obtained from the nearest air quality monitor station of the Hong Kong Observatory. A higher AQHI value implies a higher air pollution level. Table 3.7 summarizes the respondents' perceptions of the external surroundings of the street environment. Generally, the majority of the respondents were satisfied with sidewalks, amenities and landscape of the survey street environment. However, they tended to be less satisfied with the micro-environment. Most of them perceived the street environment noisy, air quality bad and wind too weak. Also, they felt the street warm and humid.

Table 3.5 A summary of personal characteristics of the respondents

Variable	Category	Number (Percentage)
Gender	Male	217 (51.70%)
	Female	203(48.30%)
Age	≤19	28 (6.70%)
	20-39	173 (41.20%)
	40-59	131 (31.20%)
	60-69	48 (11.40%)
	≥70	40 (9.50%)
Place of Residence	Non-local	261 (62.10%)
	Local	159 (37.90%)
Education	Grade school or below	33 (7.90%)
	Middle school	36 (8.60%)
	High school	114 (27.10%)
	Bachelor or above	237 (56.40%)
Occupation	Self-employed	44 (11.70%)
	Employed	167 (39.80%)
	Students	83 (19.80%)
	Unemployed	14 (3.30%)
	Homemakers	29 (6.90%)
	Retired	77 (18.30%)
	Others	6 (1.40%)
Purpose of walk	Non-recreational	187 (45.50%)
	Recreational	233 (55.50%)
Frequency of Walk	First time	45 (10.00%)
	Occasionally	223 (53.10%)
	Frequently	152 (36.20%)

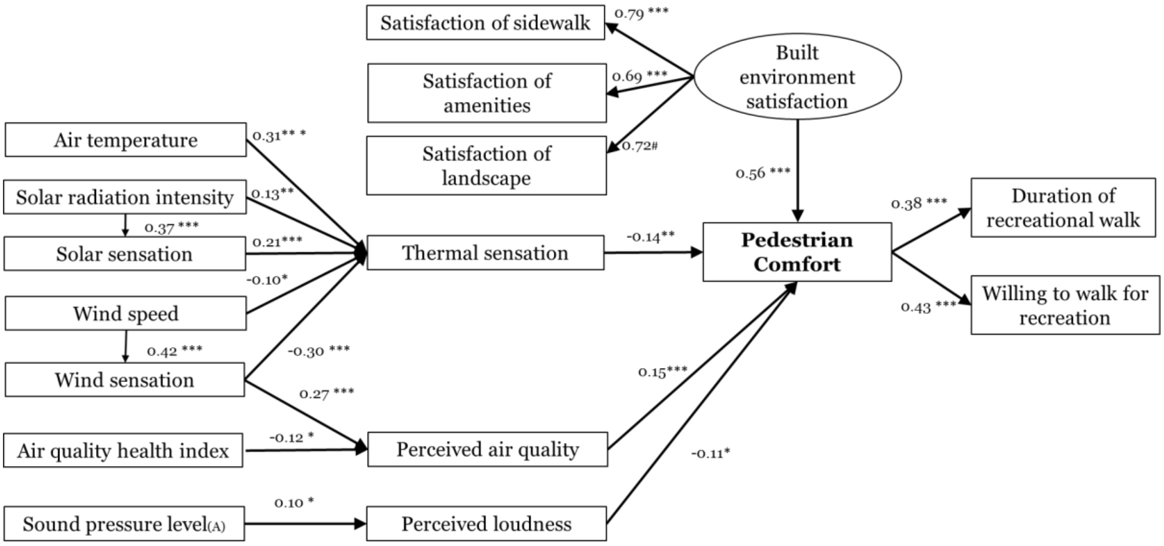
Table 3.6 Objectively measured micro-environmental conditions in the survey streets

Objectively measured micro-environmental conditions	Mean	Standard deviation	Range
Air temperature (°C)	26.92	5.23	18.65-37.50
Relative humidity (%)	62.87	9.10	39.99-81.27
Solar radiation intensity (W/m^2)	123.08	137.44	3.59-847.66
Wind speed (m/s)	0.76	0.72	0.00-4.60
PM10 concentration (mg/m^3)	0.09	0.08	0.00-0.06
SPL (dB(A))	67.11	3.13	58.84-72.37
Air quality health index (AQHI)	4.23	1.193	2-7

Table 3.7 Perceived micro-environmental conditions in the survey streets

Perceived micro-environmental conditions	Mean	Standard deviation	Range
Satisfaction of sidewalks	0.33	1.331	-3-3
Satisfaction of amenities	0.46	1.192	-2-3
Satisfaction of landscape	0.10	1.245	-3-3
Perceived loudness	0.66	0.982	-3-2
PAQ	-0.57	1.097	-3-3
Thermal sensation	0.51	1.263	-2-3
Wind sensation	-0.55	1.102	-3-2
Solar sensation	-0.44	1.198	-3-3
Humidity sensation	0.04	0.806	-3-3

3.3.2 Path model



‘***’ = $p<0.001$; ‘**’ = $p<0.005$; ‘*’ = $p<0.05$; ‘#’ represents baseline.

Figure 3.7 Estimated coefficient values for individual factors of the formulated path model

Due to the mild winter climatic conditions of Hong Kong in 2018 (i.e., with the lowest temperature of 18.7 °C), only one path model was constructed to cover the recorded narrow temperature range using 420 questionnaire responses. Figure 3.7 shows the final path model with the estimated correlation values being shown for individual factors. All the observed variables are in rectangular shape while the latent variable is in elliptical shape. The coefficient values shown in the model have been normalized to facilitate easy comparison with each other. A high coefficient value suggests a strong causal relationship between dependent and independent variables, while a low coefficient value suggests a weak relationship. A positive coefficient sign implies that the value of the independent variable varies directly with the value of the dependent variable. Conversely, a negative coefficient sign implies that the value of the independent variable varies inversely with the value of the dependent variable. The formulated path model depicts the inter-relationships among pedestrian comfort, recreational walk behavior, physical street environmental characteristics as well as perceptions of street environment. Table 3.8 shows a comparison of the goodness-of-fit index values for the model against the generally accepted model fit criteria (Hooper et al., 2008). The formulated model is considered to be a reasonably good representation of the inter-relationships since its values met with the requirements laid down for χ^2/df, Goodness-of-fit index (*GFI*), and the Root Mean Square Error of Approximation (*RMSEA*) commonly employed for evaluating the goodness-of-fit of path models.

Table 3.8 Acceptance criteria and calculated values of various goodness-of-fit indices for the model

Goodness-of-fit index	Acceptance value	Model value
Chi-square degrees of freedom (χ^2/df)	2.0-5.0	3.490
Goodness-of-fit index (*GFI*)	> 0.9	0.917
Root mean square error approx. (*RMSEA*)	≤0.08	0.077

A latent variable "*Built environment satisfaction*" was constructed with the three observed indicator variables being shown on the side (*Average Variance Extracted*=0.54>0.5 acceptable value). This suggests that built environment satisfaction could be measured by satisfactions of sidewalks, amenities and landscape. All three satisfactions were positively correlated with the MAPS Mini score (i.e. the satisfactions of sidewalks (r=0.333), amenities (r=0.232) and landscape (r=0.499)), implying that they were all positively correlated with walkability level. In addition, satisfaction of sidewalks (*r*=0.79) was more strongly related to pedestrian comfort than satisfaction of landscape (*r*=0.72) or satisfaction of amenities (*r*=0.69).

Pedestrian comfort was found to relate to not only satisfaction of built environment but thermal sensation, PAQ and perceived loudness as well. PAQ (*r*=0.15), perceived loudness (*r*=-0.11) and thermal sensation (*r*=-0.14) individually were found to exert only moderate influences on pedestrian comfort. However, their aggregate effect size should not be overlooked as they were comparable to that of built environment (*r*=0.56 vs 0.40=0.15+0.14+0.11). It is observed that thermal sensation was influenced by microclimatic conditions (i.e. air temperature (*r*=0.31), solar radiation intensity (*r*=0.13), and wind speed (*r*=-0.10)) as well as microclimatic sensations (e.g. wind sensation (*r*=-0.30) and solar sensation (*r*=0.21)). In addition, PAQ was more correlated with wind sensation (*r*=0.27) than air quality health index (r=-0.12), while perceived loudness was moderately related to SPL (*r*=0.10). It can also be seen that pedestrian comfort was influenced more by PAQ or thermal sensation than perceived loudness.

In line with our original expectation, respondents would be more willing to walk for recreation (*r*=0.43) and spend more time on recreational walking (*r*=0.38) if they perceived the street environment comfortable.

3.4 Summary of this chapter

A path model has been formulated to provide an integrated view on how various factors affect pedestrian comfort for recreational walking in a street segment within a high-dense city.

The path analysis has also successfully revealed the interrelationships among the relevant perceptual and objectively measured built and micro-environmental factors in urban street canyon environments. Moreover, the proposed theoretical framework of pedestrian comfort in Chapter 2 has been validated by their interrelationships. The main findings concluded from their interrelationships are discussed as follows:

First, pedestrian comfort was influenced by both objective and subjective perceptual built environmental factors as well as micro-environmental factors such as noise, air quality and microclimate. The lack of inclusion of major micro-environmental factors or built environmental factors, such as sidewalk characteristics, amenities and landscape, in many earlier studies made the pedestrian comfort evaluation biased and less comprehensive (Al Shammas and Escobar, 2019; Arellana et al., 2020; Labdaoui et al., 2021a; Soligo et al., 1998; Wu and Kriksic, 2012). The outcomes would produce sub-optimal strategies to improve street comfort level (Nag et al., 2020; Wai et al., 2020). In contrast, the scope of our study should be more thorough as we have included air quality, noise and microclimate as well as the built environment, which all have been shown in this study to be major determinants for pedestrian comfort during recreational walking.

Second, the relative influence of built environment satisfaction involving sidewalks, amenities and landscape was found comparable to the aggregate relative influences of PAQ, perceived loudness and thermal sensation on pedestrian comfort. This finding diverged from those reported in two earlier studies related to the decision to walk and walkability partly due to differences in the number and characteristics of major attributes investigated. Bunds et al. (2019) revealed that air pollution and noise were the first and third dominant factors respectively for pedestrian's decisions to walk for recreation. Respondents were presented with noise and air pollution levels in hypothetical scenarios of discrete choice experiments but were not asked to include microclimate in their decisions. In Labdaoui et al.'s study (2021), microclimate was found to be the third most important attribute when compared to other 20 sidewalk related attributes but the attributes for comparison did not embrace air quality or noise.

Also, the differences in relative influences determined were due to differences in the range of conditions of attributes investigated between our studies and earlier studies. In addition to characteristics of attributes, the relative influence of attributes perceived by people was also dependent on the ranges of conditions of attributes. Specifically, the relative influence of individual attributes will vary with the range of conditions of the attributes even for the same set of attributes. So far, earlier walking comfort studies tended to focus only on revealing a set of important weightings at very high temperatures, high or very high pollution levels. The important weightings revealed by Bunds et al. (2019) on hypothetical scenarios were based on the tradeoffs decisions made between high and low air pollutant levels, and/or high and low noise levels. The relative importance of comfort-related attributes in Algeria was obtained by comparing the importance of attributes associated with sidewalks with that of very high daytime air temperature in summer in the Mediteranrean climate zone (Labdaoui et al., 2021). Conceivably, under extreme conditions, the relative influence of a specific attribute would sharply increase if it was the one causing extreme discomfort or even health threats to pedestrians (Chan and Ryan, 2009; Ferrer et al., 2015; Moudon et al., 2007; Spinney and Millward, 2011). On the contrary, the findings of this study serve to bridge the existing research gap by revealing the relative importance of various built and micro-environmental attributes under the normal ranges of conditions, which are more frequently encountered in our daily life situations and more favorable for recreational walking. This provides more valuable information to guide urban planners in directing their efforts towards improving the comfort level of street environments in cities where high temperatures and/or high pollution levels do not frequently occur.

Third, our study added to the existing knowledge by simultaneously exploring the relationship between perceptions and objective measurements of the same micro-environmental attributes and their associations with recreational walking comfort. Our results confirmed that pedestrian comfort cannot be necessarily explained and interpreted in a univocal manner on the basis of the objective external environmental factors but should also be investigated from the subjective point of view through questionnaire surveys. In this study, the perceptions of microenvironment including thermal sensation, PAQ and perceived loudness were found to mediate the associations between objectively measured microclimate, air quality and noise, and individual recreational walking comfort respectively. Although linking objective, tangible and measurable environmental characteristics directly to pedestrian comfort (Labdaoui et al., 2021a; Sarkar, 2003; Zakaria and Ujang, 2015) could facilitate the translation of study results into intervention strategies (Lin and Moudon, 2010), it underrated the existence of the direct relationship between subjective environmental factors, and human perceptions and health-related behavior (Wang et al., 2019). Subjective assessment is likely to be also influenced by other factors, such as an individual's socio-demographic characteristics, preferences and experiences (Desgeorges et al., 2021).

Accordingly, the inclusion of the micro-environmental perception as a mediator between objectively measured micro-environmental characteristics and pedestrian comfort into the final model can not only help corroborate pedestrian comfort and walking behavior better but also provide more valuable suggestions on intervention strategies (Bivina and Parida, 2019; Ewing and Handy, 2009; Mehta, 2008; Saelens et al., 2003b; Vallejo-Borda et al., 2020).

Finally, similar to earlier studies, our study revealed that thermal sensation was correlated with air temperature, wind speed and solar radiation (Chan et al., 2017; Krüger et al., 2011; Peng et al., 2019), and perceived loudness was positively correlated with SPL (Engel et al., 2018; Mohammadi et al., 2020). However, there were some interesting findings of this study which may provide some insights. In this study, PAQ in street canyons was found to be positively correlated with wind speed. Although up to now there are still no fully established relationships between PAQ and specific indicators, air movement was shown in some earlier studies to be correlated with PAQ in indoor environments with low air movement (Melikov and Kaczmarczyk, 2012; Zhai et al., 2015). In such environments, improvement in air movement would reduce air stuffness and increase air quality satisfaction, and the degree of improvement due to air movement was more pronounced at warm and humid conditions, and high background pollution levels (Melikov and Kaczmarczyk, 2012). This was postulated to be also applicable to street canyons in urban cities where the air quality is poor (Huang et al., 2021) , and the wind speed is very low and, in the worst case, the air is stagnant (Du et al., 2017). This seems to be reasonable as wind is an important natural mechanism for removing air pollutants in canyons. Also, wind has strong influences on visibility and odor (Zhao et al., 2013), which have been believed to be the major human sensories for perceiving air quality

(Bickerstaff and Walker, 2001; Cerin et al., 2013). On the other hand, some studies have also linked subjective air quality perception to objectively measured concentrations of relevant air pollutants, e.g. NO_x, VOC gases and PM (Engel et al., 2018; Pantavou et al., 2017). However, no such correlation was observed between PM_{10} and PAQ in this study. On the contrary, PAQ was also found to moderately correlate with air quality index in this study. This is possibly because the air quality perceptions of some respondents might have been influenced by daily air quality reports before they went out to streets (Koenigstorfer, 2018), or because the air quality index was positively correlated with the actual air pollutant concentrations that influence air quality perception (Tan et al., 2021).

Chapter 4 Development of a multivariate index for assessing the pedestrian comfort of street segments for recreational walkers

The findings in Chapter 3 suggested built environment features including sidewalk, amenities and landscape and thermal sensation, PAQ and perceived loudness were major factors affecting pedestrian comfort. Hence, this chapter aims to propose a multivariate index that can help assess the pedestrian comfort of a street segment by integrating these major built and micro- environmental factors. The index was formulated by identifying a set of key indicators for comfort-related criteria as well as eliciting their importance weightings.

In the end of this chapter, the formulated composite index has been applied to investigate the effects of street morphological attributes. The investigated street morphological attributes were anticipated to exert influences on multiple comfort-related environmental factors of pedestrian comfort. The ultimate aim is to provide valuable insights for urban planners. The studied street morphological attributes include tree-planting pattern, street orientation and aspect ratio.

4.1 Methodology

Basic Premises

Pedestrian comfort evaluation is an inherent multi-attribute problem. Multi-Attribute criteria decision making (MCDM) can be used to address problems involving a finite and discrete set of alternative options that have to be evaluated on the basis of conflicting objectives (Mulliner et al., 2016), such as those influencing pedestrian comfort. MCDM methods can handle the varying significance of decision criteria through weightings. By being able to handle quantitative and qualitative data, MCDM plays a vital role in the field of walkability decision-making where many aspects are often intangible. MCDM includes different aggregation models, but the simplest one is the Weighted Sum model (Kumar et al., 2017). Also, this model has been commonly used in the walkability and comfort fields (Arellana et al., 2020; Labdaoui et al., 2021b; Talavera-Garcia and Soria-Lara, 2015). It can be employed when specific preference independence conditions hold, which is represented by

$$J(a) = \sum w_i J_i(a) \tag{4.1}$$

Where w_i (i=1, 2...m) is a weighing factor for i_{th} objective function and J(a) is a function of designed vector.

In formulating the framework, a set of major criteria and key performance indicators have been identified and they are suitable for universal applications. Given that pedestrian preferences and perceptions of street environment are also influenced by local culture, geographical context and climate conditions (Guo and Loo, 2013; Labdaoui et al., 2021b), a set of weights and scoring scales have also been determined to suit the peculiar characteristics of compact city in Hong Kong.

Formulating pedestrian comfort index

The ultimate aim of this study is to develop a multivariate index to help assess and compare the pedestrian comfort levels of street segments in a more objective manner. The index, which was targeted at assessing one street segment as a basic analytical unit, was formulated by integrating both comfort-related built and micro- environmental attributes as assessment criteria. The procedures for formulating the proposed pedestrian comfort index included the following three stages (See Figure 4.1):

1) *Identification of major criteria and associated indicators*: a number of major micro- and built environmental criteria would be identified together with the associated indicators through literature review.
2) *Scorings of associated indicators for individual criteria:* scorings would be formulated for associated indicators of individual criteria with their upper and lower bounds being established by reference to relevant literature and most up-to-date standards.
3) *Aggregation of criteria for index formulation:* the criteria were aggregated to formulate the pedestrian comfort index utilizing MCDM method based on the relative importance weightings of criteria elicited from pedestrians using go-along interviews.

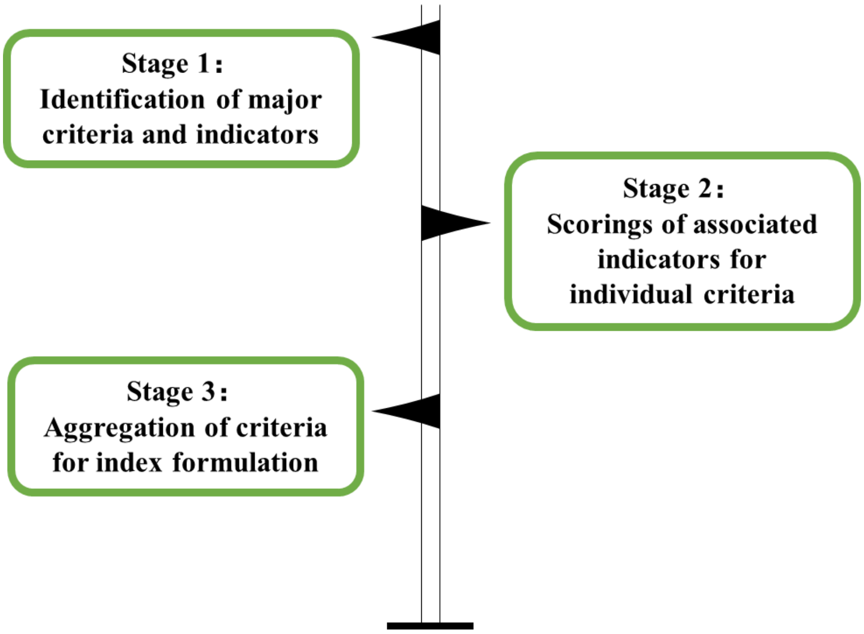


Figure 4.1 The proposed pedestrian comfort assessment framework for street environments

4.1.1 Identification of criteria and key performance indicators

From the perspective of pedestrians, comfort is a pleasant state of physiological, psychological and physical harmony between a human being and the environment (Slater,1985). Given that walking is an experience, pedestrian comfort should embrace subjective evaluations of both micro- and built environment criteria.

4.1.1.1 Major criteria

Based upon extensive literature review, comfort-related criteria can be broadly classified into two major categories, i.e. built environment and micro-environment. Sidewalks, amenities, landscape, thermal sensation, PAQ and perceived loudness have been identified as major built and micro-environmental criteria for pedestrian comfort. Based on our previous survey findings in Chapter 3, their size of influences on pedestrian comfort were found to be comparable such that they could be placed on the same hierarchical level during decision making. In this part, noise annoyance, which was closely correlated to perceived loudness, replaced perceived loudness as one criterion, as the empirical relationship between noise annoyance and SPL values has been determined to evaluate pedestrian comfort in a more objective manner (See Equation (4.2)). The criteria are shown in Figure 4.2 together with their associated indicators.

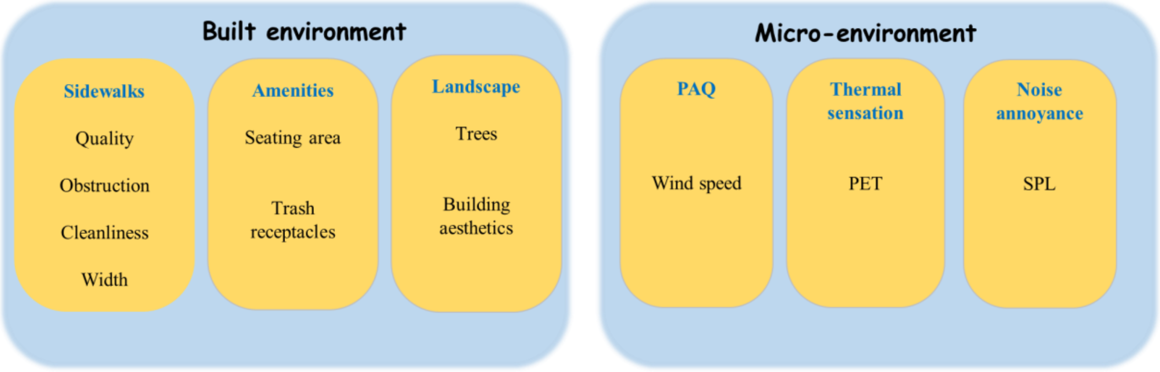


Figure 4.2 List of built and micro- environmental criteria and key performance indicators

4.1.1.2 Key performance indicators for built environment

In line with the findings reported in Mehta, (2008), it was hypothesized that the subjective perceptions of built environment criteria were correlated with the corresponding objectively measured built environment criteria. The objective built environment indicators were identified from the comfort related criteria of a number of existing walkability audit tools and comfort assessment methods and listed in Table 3.1.

4.1.1.3 Key performance indicators for thermal sensation, PAQ and noise annoyance

In order to reveal the impacts of daily variations of microclimatic conditions on human comfort, thermal sensation/comfort index Physiological Equivalent Temperature (PET) (Höppe, 1999) was used to evaluate human perceptions about microclimate of street segments with consideration of microclimate due to solar radiation, wind speed, air temperature and relative humidity. PET adopts an evaluation in ◦C of thermal sensation, which are easily understood by urban planners and policy makers, and can be employed in both hot and cold climates (Johansson et al., 2014). It has been validated in different climatic zones and widely applied in outdoor thermal environment (Acero et al., 2021; Ali-Toudert and Mayer, 2007; Gulyás et al., 2006; Morakinyo et al., 2018).

In this study, wind speed was used as a proxy for PAQ as it has been shown to be linearly and positively correlated with PAQ, which was determined and discussed by the findings of Chapter 3. On the other hand, SPL value was linked to noise annoyance perception using the previously determined positive and linear relationships reported by Chau et al. (2018) and Li et al. (2009).

4.1.2 Scorings of key performance indicators

4.1.2.1 Built environment

Points system was employed as the scoring method of the built environment attributes in this study. This was similar to the scoring method employed by Asadi-Shekari et al. (2017, 2014, 2013) and Labdaoui et al. (2021) for evaluating pedestrian level of service (PLOS). The lowest score earned was 0 which corresponded to the existing conditions that completely failed to fulfill the standards. The highest score earned was 1 which corresponded to the conditions that completely fulfilled the standards. Scores lying between 0 and 1 were assigned to the conditions that partially fulfilled the standards. References were made to the Hong Kong Planning Standards and Guidelines (Planning Department in Hong Kong, 2011), the PLOS standard (Asadi-Shekari et al., 2019), and Microscale Audit of Pedestrian Streetscapes (MAPS) (Cain and Kelli, 2016). As we only focused on evaluating short segments, binary scores of 0 or

1 were assigned for the presence or absence of some key features of amenities in place of continuous scale as employed by PLOS or MAPS (Aghaabbasi et al., 2018; Asadi-Shekari et al., 2014, 2013). Likewise, binary scores of 0 and 1 were assigned for assessing street cleanliness and building aesthetic based on the existence or absence of key features affecting the visual effect on pedestrian perception (Sallis, 2010). Finally, the scores of sidewalks, amenities and landscape of the surveyed road segments were determined as the “percentage of possible maximum score (Total score of relevant items / possible maximum score of relevant items)”. The total score was the sum of all computed items and was intended to represent the cumulative effect of attributes, while the possible maximum score represents the highest/best cumulative effect of attributes. Table 4.1 shows the scoring methods of sidewalks, amenities and landscape at segment level.

Table 4.1 The scoring methods of sidewalks, amenities and landscape at segment level

Attribute	Key performance indicators	Scoring method
Sidewalks	Pavement Quality *	$S = (S_1 + S_2)/2$ $S_1 = l_1/N_1$ l_1= The sidewalk length in one side – the length of sidewalk without contributing to major trip hazards (e.g. heaves, misalignment, cracks, overgrowth, incomplete sidewalk) N_1= Length of sidewalk in one side $S_2 = l_2/N_2$

	l_2= The sidewalk length in opposite side – the length of sidewalk without major trip hazards (e.g. heaves, misalignment, cracks, overgrowth, incomplete sidewalk) N_2= Length of sidewalk in opposite side
Obstruction*#	W= The sidewalk width without obstruction (e.g. barrier, signs, and street furniture) (m) C = The area of sidewalk without obstruction (m²) $N = \begin{Bmatrix} (length\ of\ street\ (both\ sides)) \times\ 1.5\ if\ W < 1.5\ m \\ (length\ of\ street\ (both\ sides)) \times\ W\ if\ W \geq 1.5\ m \end{Bmatrix}$ S = C/N If W varies in different sections of street, S = $(\sum_{i=1}^{k}(PC_i \times L_i)/(length\ of street\ (both\ sides))$ i= 1, 2, 3…. k (different sections of street with various width of the sidewalk without obstruction) $PC_i = C_i/N_i$ C_i = The area of sidewalk in Section i (m²) $N = \begin{Bmatrix} (length\ of\ street\ (in\ section\ i)) \times\ 1.5\ if\ W < 1.5\ m \\ (length\ of\ street\ (in\ section\ i)) \times\ W\ if\ W \geq 1.5\ m \end{Bmatrix}$ L_i = Length of street in Section i
Cleanliness#	$S = (S_1 + S_2)/2$ $S_1 = \begin{Bmatrix} 1\ if\ no\ noticeable/excessive\ litter\ in\ one\ sidewalk \\ 0\ if\ any\ noticeable/excessive\ litter \end{Bmatrix}$ S_2 $= \begin{Bmatrix} 1\ if\ no\ noticeable/excessive\ litter\ in\ opposite\ sidewalk \\ 0\ if\ any\ noticeable/excessive\ litter \end{Bmatrix}$
Width *%	W= The width of sidewalk (m) C = The area of sidewalk (m²)

		$N = \begin{cases} (length\ of\ street\ (both\ sides)) \times 4.5 & if\ W < 4.5\ m \\ (length\ of\ street\ (both\ sides)) \times W & if\ W \geq 4.5\ m \end{cases}$ S = C/N If W varies in different sections of street S= $(\sum_{i=1}^{k}(PC_i \times L_i)/(length\ of street\ (both\ sides))$ i=1, 2, 3…. k (different sections of street with various width of the sidewalk) $PC_i = C_i/N_i$ C_i = The area of sidewalks in section i (m^2) $N = \begin{cases} (length\ of\ street\ (in\ section\ i)) \times 4.5 & if\ W < 4.5\ m \\ (length\ of\ street\ (in\ section\ i)) \times W & if\ W \geq 4.5\ m \end{cases}$ L_i = Length of street in section i
	Sidewalk Score*	=Total score/ possible maximum score (4)
Amenities	Seating area*	C = Length of street with standards seating area + their support length (m) N = Length of street (in both sides) (m) $S = C/N$ As the length of street was around 100-200m with in the required support length of standard (200 – 400m), the score method was as follows: S=1 if there are benches in the street S=0 if there are no benches in the street
	Trash receptacles *	C = Length of street with standards trash receptacle area+ their support length (m) N = Length of street (both sides) (m) $S = C/N$

		As the length of street was around 100-200m with in the required support length of standard (200 – 400m), the score method was defined as follows: S=1 if there are trash receptacles in the street S=0 if there are no trash receptacles in the street
	Amenities Score*	= Total score/ possible maximum score (2)
Landscape	Trees*	D = Distance between trees (m) $C = \left\{ \begin{array}{c} \frac{(Length\ of\ street\ with\ tree * 9)}{D} if\ D\ >\ 9 \\ Length\ of\ street\ with\ tree\ if\ D\ \leq\ 9 \end{array} \right\}$ N = Length of street (both sides) $S = C/N$
	Building aesthetic#	$S = (S_1 + S_2)/2S_1$ $= \left\{ \begin{array}{c} 1\ if\ \ well\ maintained\ in\ one\ side\ building \\ 0\ if\ any\ dirty\ or\ broken\ part\ \ in\ one\ side\ building \end{array} \right\}$ S_2 $= \left\{ \begin{array}{c} 1\ if\ \ well\ maintained\ \ in\ opposite\ side\ building \\ 0\ if\ any\ dirty\ or\ broken\ part\ \ in\ opposite\ side\ building \end{array} \right\}$
	Landscape Score	= Total score/ possible maximum score (2)

Note: '*' denotes those adapted from PLOS (Asadi-Shekari et al., 2019).

'#' denotes those adapted from MAPS (Cain and Kelli, 2016).

'%' denotes those adapted from Hong Kong Planning Standards and Guidelines (Planning Department in Hong Kong, 2011).

4.1.2.2 Thermal sensation, PAQ and noise annoyance

The software ENVI-met was used to predict the PET values and wind speeds in order to compute the corresponding thermal sensation and PAQ scores. ENVI-met has been previously validated and used to predict street microclimate in Hong Kong (Chan and Chau, 2021; Morakinyo et al., 2019). PET values were computed directly using the BIO-met module within the software. In this study, the PET values were calculated based on a 35-year-old man of 1.70m in height and 68.6 kg in weight. This represented the body built of an average male adult in Hong Kong (Census and Statistics Department, 2019; Department of Health, 2014). The adult had a walking speed of 1.21 m/s, clothing insulation value of 0.45, and a sum of metabolic work of 159 W/m^2 (Chan and Chau, 2021). As for noise, SPL values were predicted by the CRTN model that has long been applied by the Environmental Protection Department in Hong Kong (Mak et al., 2010; Noise Advisory, 1978). The CRTN model includes correction terms to adjust the reference noise level for traffic flow, i.e. road surface, distance, ground effects (soft or hard), barrier and reflection effects of site layout and etc.

Linear scoring scales spanning from 0 to 1, which were similar to those reported by Al Shammas and Escobar (2019) and Taleai and Taheri Amiri (2017), were employed to map with the corresponding PET values, wind speeds and SPL values. The upper and lower limits were established by reference to relevant current literature and standards. For thermal sensation, the scoring method of PET values in this study was determined by reference to that formulated by Labdaoui et al. (2021), and was linked to the PET classification suggested by Cheng and Ng (2006, 2012) and Morakinyo et al. (2020) for Hong Kong with a subtropical climate. In formulating the air quality scoring scale, PAQ was assumed to link to wind speeds categorized according to wind sensation criteria. Wind speeds were proposed to be linked to wind sensation criteria in Hong Kong (Du et al., 2017). For noise, the scoring method of SPL values was formulated by referring to the linear and positive relationship between noise annoyance and SPL as reported by Li et al. (2009) based on an earlier field study in Hong Kong, and is depicted as follows:

$$\text{Noise annoyance level} = -4.27 + 0.15 \times \text{SPL} \quad (55\text{dB(A)} < \text{SPL} < 75\text{dB(A)}) \tag{4.2}$$

Table 4.2 shows scoring methods adopted for thermal sensation, PAQ and noise annoyance at segment level.

Table 4.2 The scoring methods adopted for thermal sensation, PAQ and noise annoyance at segment level

Criterion	**Key performance indicator**	**Scoring method (*S*= *Score*)**	
Thermal sensation	PET value	S=0	if cold/ hot/ very cold/ very hot sensation (PET <17°C or PET >37°C)
		S =0.25	if cool/ warm sensation (17°C ≤PET < 21°C and 33°C < PET≤37°C)
		S =0.5	if slightly warm/ Slightly cool sensation (21°C ≤PET < 25°C and 29°C < PET≤33°C)
		S =1	if neutral sensation (25°C ≤PET≤29°C)
PAQ	Wind speed (v)	S=0	if no noticeable breeze (0 ≤v < 1.5 m/s)
		S =0.33	if light breeze (1.5 ≤v < 1.8 m/s),
		S =0.67	if gentle breeze (1.8≤v < 3.6m/s)
		S =1	if moderate breeze (3.6≤v < 5.3m/s)
Noise annoyance	SPL values	S =0	if noise annoyance level=10
		S =0.1	if noise annoyance level =9

....	....
S =0.9	if noise annoyance level =1
S =1	if noise annoyance level =0

4.1.3 Aggregation of criteria for index formulation

Face-to-face questionnaire surveys were conducted in the surveyed streets to elicit the importance weightings of six criteria. With aid of go-along interviews, the weightings derived are more realistic in portraying the daily decisions made by pedestrians. Subsequently, the collected responses about the perceptions of sidewalks, amenities and landscape, thermal sensation, PAQ, noise annoyance and overall comfort were employed to construct a multivariate ordered logit model. The details of the questionnaire surveys have been reported in Section 3.2.4 of Chapter 3.

To facilitate calculations and interpretations of scores, the coefficient estimates of the constructed model were transformed into the weights of individual criteria such that the aggregate of their weightings was equal to 1 (Arellana et al., 2020). Table 4.3 shows the estimated coefficient values (β_i) and weightings of individual criteria (w_i). As a broader comparison, built environment was found to be more important than micro-environment (w= 0.6 vs 0.4). Sidewalks was the most important criterion for pedestrian comfort, followed by amenities, landscape, PAQ and thermal sensation, and in turn noise annoyance.

Table 4.3 The weightings of criteria

Criterion	Coefficient (β_i)	Weighting (w_i)
Sidewalks	0.484	0.236

Amenities	0.418	0.204
Landscape	0.324	0.158
Thermal sensation	0.280	0.136
PAQ	0.294	0.143
Noise annoyance	0.252	0.123

The determined criteria weights have been finally incorporated into the following model form:

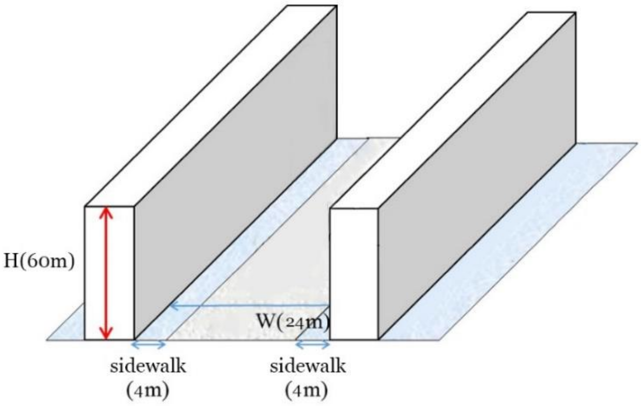
$$Pedestrian\ Comfort\ score = 0.236 \times S_{sidewalks} + 0.204 \times S_{amenities} + 0.158 \times S_{landscape} + 0.136 \times S_{thermal\ comfort} + 0.143 \times S_{PAQ} + 0.123 \times S_{noise\ annoyance} \quad (4.3)$$

Where Si were the scores of individual criteria i.

The higher the pedestrian comfort score, the more comfortable pedestrians feel during walking. It is noteworthy pointing out that the set of relative importance values determined is only applicable for normal weather days within the ranges of air temperature and air quality health index being reported in this paper. Conceivably, these conditions should be more commonly encountered in our daily life situations and considered more favorable for recreational walking.

Analyzing the effects of specific street morphological attributes

Finally, it was intended to assess and compare pedestrian comfort levels of three different types of street configurations. The configurations were hypothetically constructed by varying the levels of three attributes of the baseline street configurations, which were expected to exert influences on multiple comfort-related built and micro-environmental criteria of pedestrian comfort. Figure 4.3 shows a sketch of the baseline street configuration based on the average conditions of street segments within Mongkok. Table 4.4 shows the characteristics of baseline street configuration together with its traffic-related pattern. The street characteristics were determined with aid of Google Earth (Chiang et al., 2017), while the traffic-related patterns were determined from the traffic census of Hong Kong Transportation Department (Mak et al., 2010). In short, the baseline street configuration bears the following major characteristics: (i) N-S street orientation, (ii) the aspect ratio of 2.5 (cf. H=60m and W=24m), (iii) treeless.



Note: Grey: Street Buildings; Blue: Surrounding buildings

Figure 4.3 A sketch showing the baseline street configuration

Table 4.4 The street characteristics and traffic flow patterns of the baseline street configuration

Factor	**Key performance indicators**	**Baseline street configuration**
Street characteristics	Aspect ratio	2.5

	Orientation	N-S
	Tree-planting	Treeless
Traffic-related patterns	Hourly traffic count	359/h-682/h
	Traffic speed	50km/h (Speed limit value)
	Percentage of heavy vehicles	2%
	Road Surface type	Impervious
	Gradient	0%

The first street morphological attribute pertains to landscape feature while the other two pertain to street canyon geometry. Tree-planting will affect landscape, thermal sensation and PAQ. Street orientation would affect thermal sensation and PAQ. Aspect ratio would affect thermal sensation, PAQ and noise annoyance. Table 4.5 shows their effects on individual comfort-related criteria. The corresponding attribute levels of the baseline street configuration are shown in the followings:

(i) Tree-planting– treeless, 4m and 8m spacing.

(ii) Major street orientation–N-S, E-W. NE-SW, NW-SE.

(iii) Aspect ratio (H/W) = 1.9 (i.e. H=60m and W=32m), 2.5 (i.e. H=60m and W=24m), 3.0 (i.e. H=60m and W=20m).

Table 4.5 The effects of street canyon geometry and landscape feature on the comfort-related criteria

Features	**Landscape (a)**	**Thermal sensation* (b)**	**PAQ (c)**	**Noise annoyance (d)**	**References**

Tree-planting#	+ve	+ve*	-ve	N/A	(Lu, 2019; Santosa et al., 2018; Smardon, 1988) [a] (Morakinyo et al., 2017; Ng et al., 2012; Ouyang et al., 2020)[b] (Abhijith et al., 2017; Gómez et al., 2013; Gromke and Ruck, 2012)[c].
Major Street orientation	N/A	Varied with orientation- E-W was the worst	Varied with wind direction: highest wind speed at parallel wind direction; lowest wind speed at perpendicular wind direction	N/A	(Achour-Younsi and Kharrat, 2016; Ali-Toudert and Mayer, 2006; Deng and Wong, 2020; Yin et al., 2019)[b] (Ali-Toudert, 2005; Sözen and Koçlar Oral, 2019)[c]
Aspect ratio	N/A	+ve*	+ve	-ve	(Abdollahzadeh and Biloria, 2020; Achour-

					Younsi and Kharrat, 2016; Lau et al., 2016; Yin et al., 2019)[b] (Miao et al., 2020; Sözen and Koçlar Oral, 2019)[c] (Echevarria Sanchez et al., 2016; Thomas et al., 2013)[d]

Note: '+ve' denotes level of landscape, thermal sensation, PAQ or noise annoyance scores varied directly with the value of the corresponding factor.

'-ve' denotes level of landscape, thermal sensation, PAQ or noise annoyance scores varied inversely with the value of the corresponding factor.

'N/A' denotes the level of landscape, thermal sensation, PAQ or noise annoyance scores did not vary with the value of the corresponding factor.

'*' denotes the thermal sensation score at most of time within the subtropical climatic zone

'#' denotes those related to tree coverage ratio.

The pedestrian comfort levels for individual configurations were all evaluated based on September 16th, 2019, which was the hottest day during the survey period in our previous field measurement campaigns with the consideration of the subtropical climate characteristics of Hong Kong with a hot and humid summer and a relatively mild winter. Its climatic conditions were used as inputs to ENVI-met model to calculate the PET values and wind speeds to portray a normal hot summer day in Hong Kong.

4.2 Results

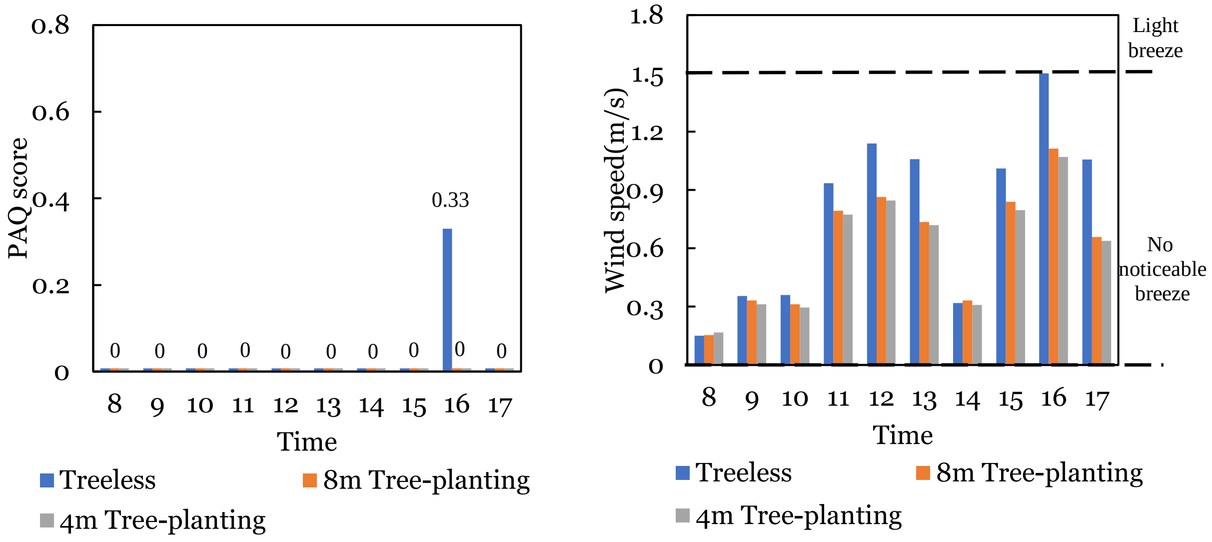
4.2.1 Effects of street morphological attributes on pedestrian comfort

4.2.1.1 Tree-planting

In addition to the impact on the landscape aesthetics, tree-planting was also expected to alter the PAQ and thermal sensation in a street segment.

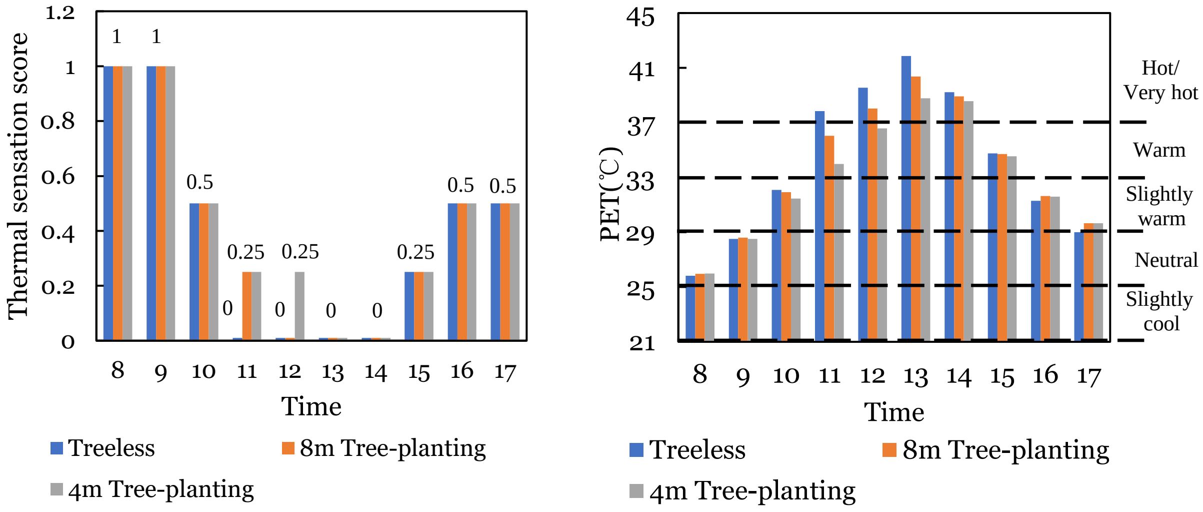
The landscape scores of 4m and 8m tree-planting were similar, which was higher than the treeless (0.5 and 0.5 > 0). Besides, throughout daytime periods, 4m and 8m tree-planting yielded similar thermal sensations except 12:00 (i.e. 0.25 vs 0), and they were better than treeless configuration (i.e. the average thermal sensation scores = 0.43, 0.40, 0.38 in Figure 4.4 (c)). Conversely, the air quality of the treeless was perceived to be better than 4m and 8m tree-planting (i.e. the average PAQ score = 0.03, 0, 0 in Figure 4.4 (a)).

Due to the combined effect of landscape, thermal sensation and PAQ, Figure 4.5 shows that 4m and 8m tree-planting configurations yielded similar pedestrian comfort levels, and they were better than the treeless configuration throughout the entire daytime period (i.e., the average pedestrian comfort scores = 0.45, 0.45, 0.37). In comparison to PAQ, thermal sensation played a more significant role on affecting pedestrian comfort among different tree-planting patterns (i.e. the average pedestrian comfort score due to thermal sensation and PAQ would increase by up to 0.007 and 0.004).



(a) PAQ scores

(b) Wind speeds



(c) Thermal sensation scores

(d) PET values

Figure 4.4 The hourly profiles of (a) PAQ scores, (b) Wind speeds, (c) Thermal sensation scores and (d) PET values for different tree-planting patterns

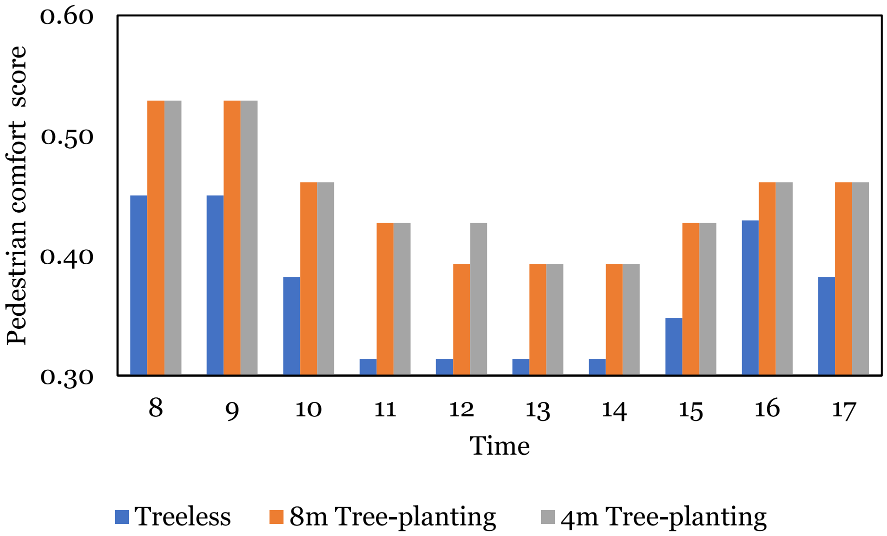


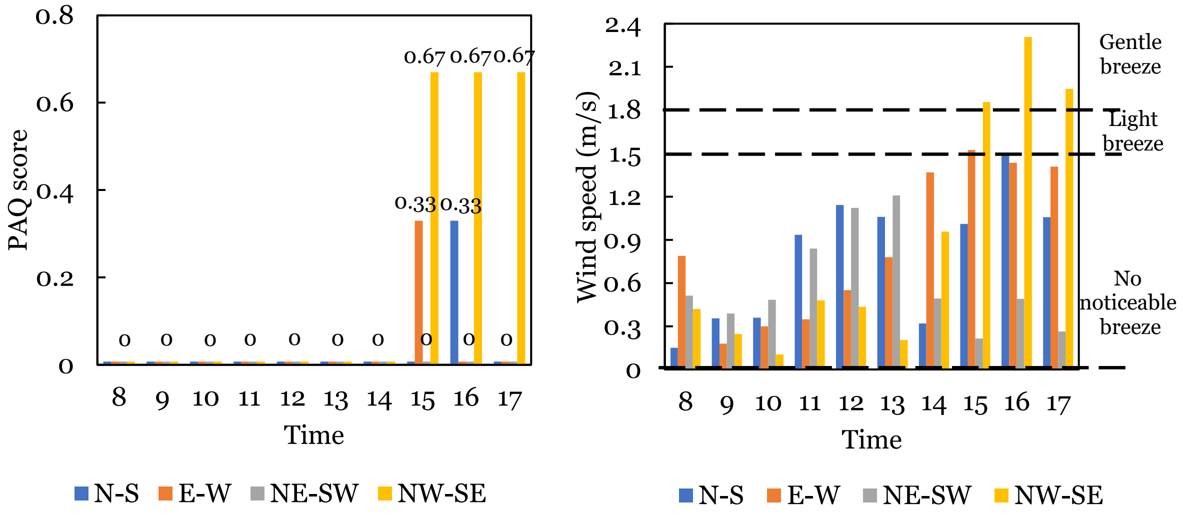
Figure 4.5 The hourly profiles of pedestrian comfort scores of streets for different tree-planting patterns

4.2.1.2 Street geometry

Unlike trees, street geometry only affected the micro-environment conditions. The effects of street orientation and aspect ratio on pedestrian comfort are going to be analyzed in the followings.

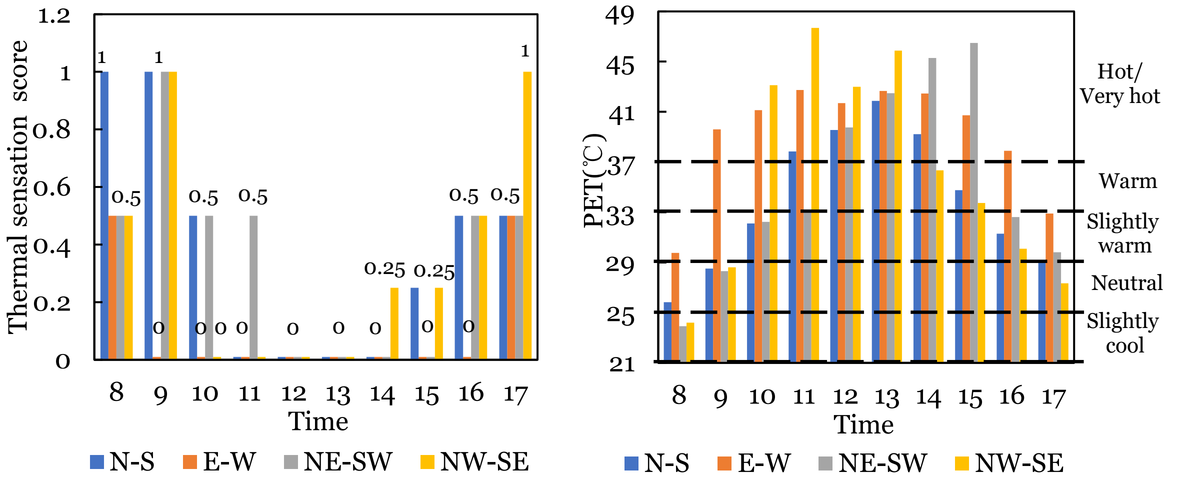
4.2.1.2.1 Street orientation

Both the PAQ and thermal sensation of a street segment were expected to vary with its orientation. Air quality was perceived to be better in NW-SE than N-S, NE-SW and E-W Streets throughout the daytime period (i.e. the average PAQ scores = 0.20, 0.03, 0.03, 0 for NW-SE, E-W, N-S and NE-SW Streets (See Figure 4.6 (a)). In contrast, the orientation with the best thermal sensation varied with time. N-S, NE-SW and NW-SE Streets yielded the best thermal sensation at 8:00, 9:00-11:00 and 14:00-17:00, respectively (i.e. at 8:00, thermal sensation score = 1 for N-S, and 0.5 for NE-SW, E-W and NW-SE Streets; at 9:00-11:00, the average thermal sensation scores = 0.67 ,0.5, 0.33, 0 for NE-SW, N-S, NW-SE and E-W Streets; at 14:00-17:00, the average thermal sensation scores = 0.50, 0.31, 0.25, 0.13 for NW-SE, N-S, NE-SW and E-W Streets (See Figure 4.6 (c)). In contrast, the thermal sensations were similar during 12:00-13:00 for four orientations (i.e. 0).



(a) PAQ scores

(b) Wind speeds



(c) Thermal sensation scores

(d) PET values

Figure 4.6 The hourly profiles of (a) PAQ scores, (b) Wind speeds, (c) Thermal sensation scores and (d) PET values for different street orientations

In Figure 4.7, it can be observed that the street orientations yielding the highest pedestrian comfort scores varied with time. N-S Street provided the most comfortable walking environment at 8:00 (i.e. 0.45 for N-S, 0.38 for NW-SE, E-W and NE-SW Streets), NE-SW Street at 9:00-11:00 (i.e. the average pedestrian comfort scores = 0.40, 0.31, 0.38, 0.36 for NE-SW, E-W, N-S and NW-SE Streets), and NW-SE Street at 14:00-17:00 (i.e. 0.45, 0.37, 0.35, 0.34 for NW-SE, N-S, NE-SW and E-W Streets). In contrast, similar pedestrian comfort levels were obtained for all street orientations at 12:00-13:00 (i.e. 0.31). Moreover, it was found that thermal sensation was the major criterion affecting pedestrian comfort among different orientations (i.e. the average pedestrian comfort score due to thermal sensation and PAQ would increase by up to 0.04 and 0.03).

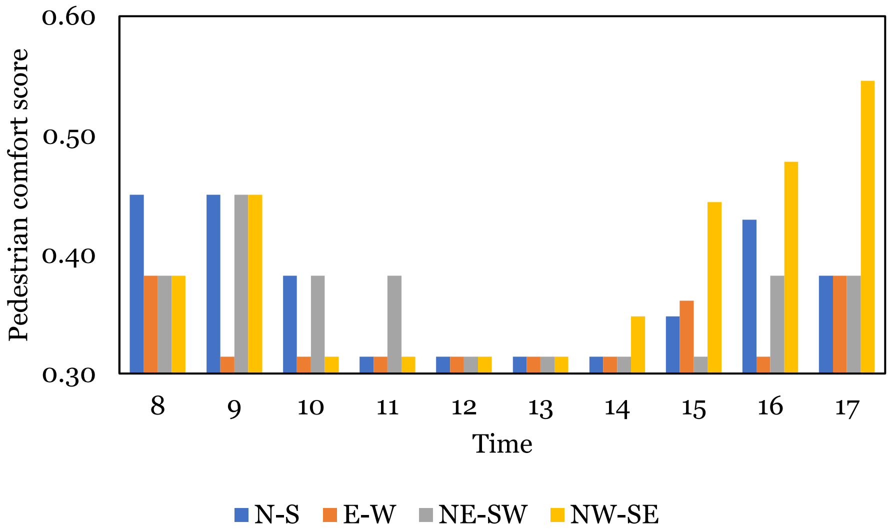
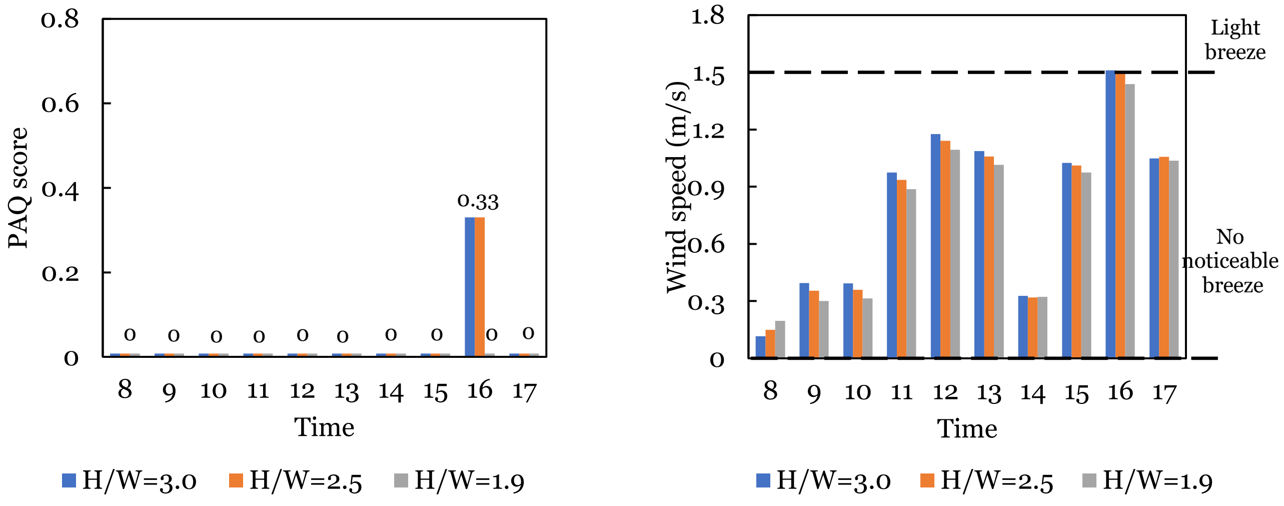


Figure 4.7 The hourly profiles of pedestrian comfort scores for different orientations

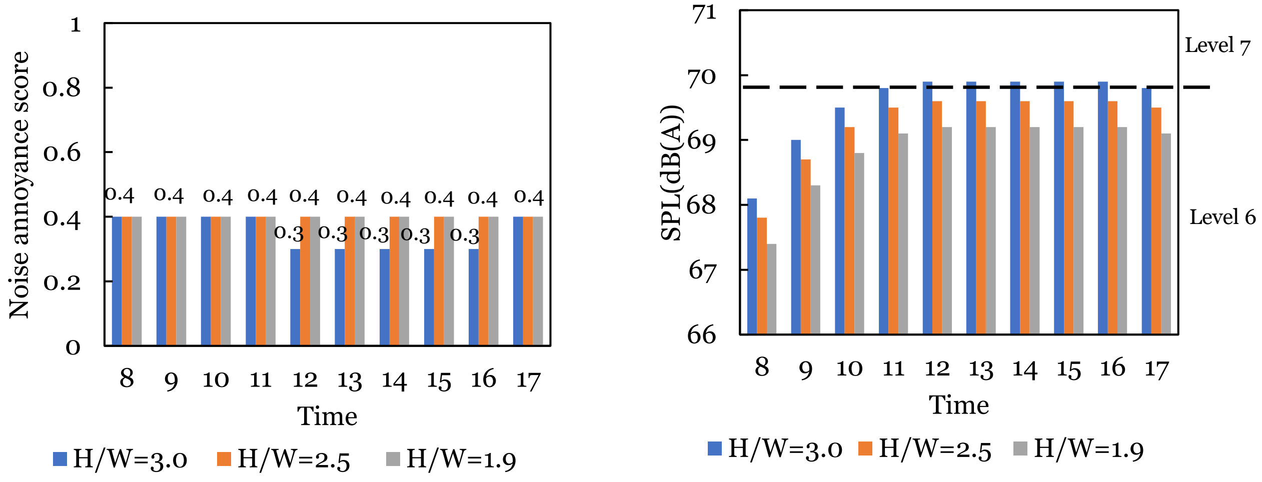
4.2.1.2.2 Aspect ratio (H/W)

Thermal sensation, PAQ and noise annoyance of a street segment were found to vary with aspect ratio. The air quality of H/W= 2.5 and 3.0 were perceived better than that of H/W=1.9 (i.e. the average PAQ scores= 0.03, 0.03, 0 in Figure 4.8 (a)). In contrast, the noise annoyance scores of H/W= 1. 9 and 2.5 were higher than that of H/W =3.0 (i.e. the average noise annoyance scores= 0.40, 0.40, 0.35 in Figure 4.8 (c)). On the contrary, H/W= 3.0 produced best thermal sensation (i.e. the average thermal sensation scores = 0.40, 0.38, 0.33 in Figure 4.8 (e)).

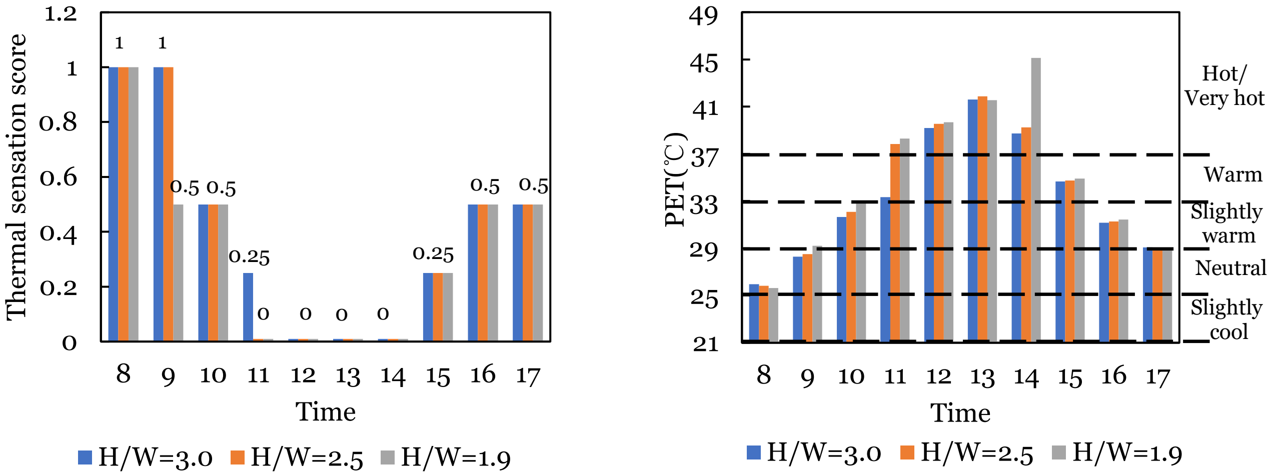


(a) PAQ scores

(b) Wind speeds



(c) Noise annoyance scores (d) SPL values



(e) Thermal sensation scores (f) PET values

Figure 4.8 The hourly profiles of (a) PAQ scores, (b) Wind speeds, (c) Noise scores, (d) SPL values (e) Thermal sensation scores, and (f) PET values for different aspect ratios

Given the complex effects of thermal sensation, noise annoyance and PAQ, it can be observed that the aspect ratio yielding the highest pedestrian comfort level varied with time (See Figure 4.9). At 8:00-11:00 and 17:00, H/W = 3.0 produced better pedestrian comfort than H/W= 1.9 or 2.5 (i.e. the average pedestrian comfort scores = 0.40, 0.39, 0.38). Conversely, at 12:00-16:00, H/W = 2.5 would provide a more comfortable walking environment (i.e. the average pedestrian comfort scores = 0.37, 0.35, 0.35). It is worthy-noted that thermal sensation played a more significant role on pedestrian comfort than noise annoyance and PAQ (i.e. the average pedestrian comfort score due to thermal sensation, noise annoyance and PAQ would increase by up to 0.01, 0.006 and 0.004)

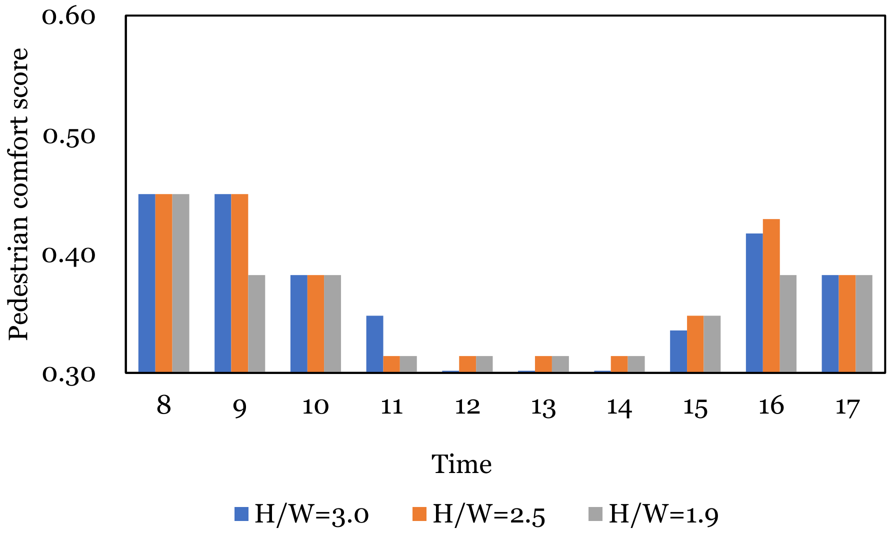
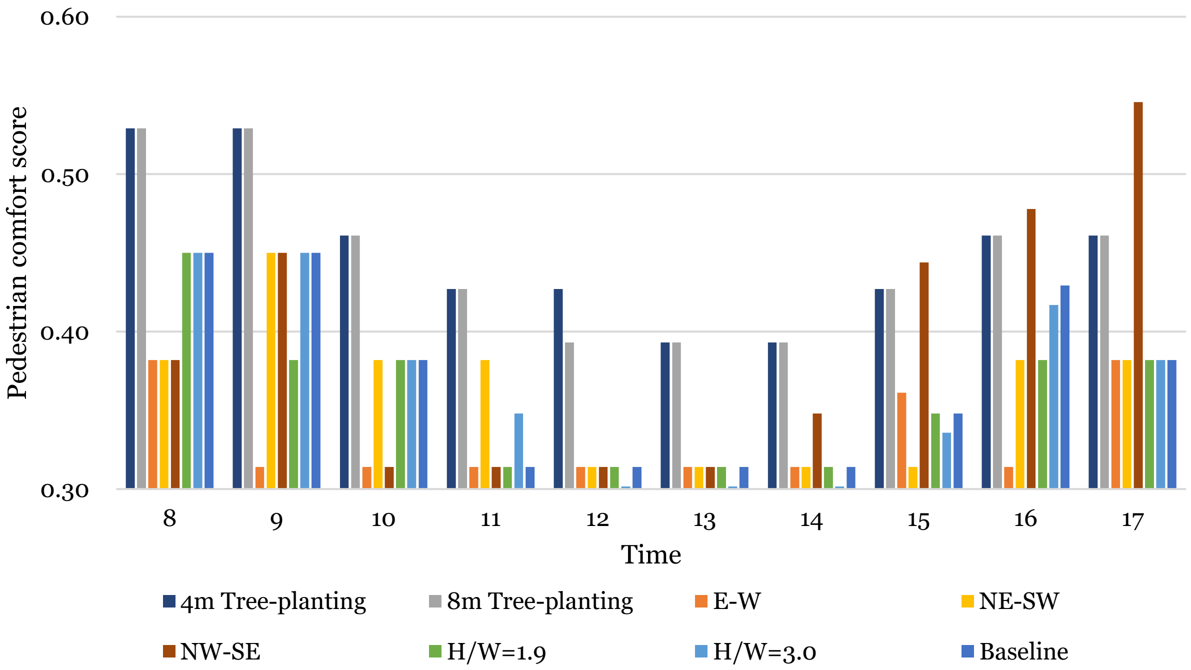


Figure 4.9 The hourly profiles of pedestrian comfort scores for different aspect ratios

4.2.2 Comparing the effects of street morphological attributes

Figure 4.10 shows pedestrian comfort scores for all different levels of street morphological attributes during different daytime periods. It can be observed that the levels of attributes yielding the highest pedestrian comfort score varied with daytime period. At 8:00-14:00, 4m and 8m tree-planting yielded the highest pedestrian comfort scores. In contrast, the NW-SE orientation surpassed 4m and 8m tree-planting to yield the highest pedestrian comfort score at 15:00-17:00 In addition, the amounts of variation in pedestrian comfort score due to changes in tree-planting pattern and orientation were significant and comparable. In contrast, aspect ratio did not exert much influence on pedestrian comfort (i.e. the average pedestrian comfort score would increase by up to 22, 18 and 3% if tree-planting pattern, orientation and H/W had been altered respectively).



Note: The baseline street configuration: treeless, N-S oriented, and aspect ratio = 2.5

Figure 4.10 The scores of pedestrian comfort for different street morphological attributes

4.3 Summary of this chapter

This part of the study successfully employed multiple criteria decision analysis method to formulate a multivariate index that can help urban planners to assess the pedestrian comfort of street segments with an aim to encourage recreational walking. The formulation of the pedestrian comfort index was initiated by establishing a comprehensive assessment framework by including both the comfort-related micro-environmental criteria (i.e. PAQ, noise annoyance and thermal sensation), and built environmental criteria (i.e. sidewalks, amenities and landscape). Subsequently, the index was applied to assess and compare the pedestrian comfort levels of different types of street configurations, which were hypothetically constructed by varying their attributes that might exert impacts on multiple criteria of pedestrian comfort. Although the index was formulated with the targeted application for Hong Kong, the framework can be generalized for use in other urban cities in the world. Above all, the findings provide a string of valuable insights for urban planners and are discussed as follows:

First, our index is more comprehensive in scope than other indices developed so far since it embraced thermal sensation, PAQ and noise annoyance as well as built environment features as major assessment criteria. The utmost importance of inclusion of thermal sensation, PAQ and noise annoyance can be demonstrated by the results determined from the pedestrians during go-along street questionnaire surveys that they three together contributed to 40% of the total pedestrian comfort weightings. Also, our street configuration analysis successfully demonstrated the great value of incorporating them into the index as they can help reveal the important role of micro-environmental factors in explaining the temporal differences in pedestrian comfort levels of streets having different orientations and aspect ratios. For example, thermal sensation was found to be the major criterion accounting for the differences in pedestrian comfort levels among street orientations and aspect ratios.

Second, the multivariate index scores computed from this study can more robustly and objectively help assess the effects of micro-environmental criteria on pedestrian comfort level of street environment for facilitating recreational walking due to the following three propositions. (i) Individual subjective comfort criteria have been linked to objective physical micro-environmental parameters by means of well-established empirical relationships, e.g.

PET for thermal sensation and SPL for noise annoyance. (ii) The scoring methods stipulated for individual micro-environmental criteria e.g. PAQ were all formulated by directly mapping to their respective absolute rather than relative comfort performance scales in such a way that any changes in scoring points were linearly correlated with changes in absolute comfort performance levels. (iii) Based on the multiple decision criteria method, the pedestrian comfort index is hypothesized to be a weighted sum of individual comfort criteria. In the absence of solid scientific evidence revealing the relative contribution of built and micro-environmental criteria on pedestrian comfort, the set of weightings for the major comfort criteria determined from pedestrians during go-along interviews in urban streets (Mateo-babiano, 2016) should be considered one of the best approaches.

Third, the dynamic nature of the formulated index presents the pedestrian comfort level of street environment on an hourly basis, which has already taken into account the impacts of fluctuating micro-environmental conditions, and provides a more appropriate level of information for facilitating recreational walkers in making their walking and route-choice decisions than static micro-climatic features or data. For example, the hourly PET value is a more accurate dynamic representation of thermal sensation than static proxies such as shady arcades or canopies over the daily period (Sarkar, 2003) since it can more accurately take into consideration the widely fluctuating thermal conditions during mornings and afternoons. Hourly SPL data employed in our index should outperform the long-term temporal average SPL from noise maps in the walkability index proposed by Shammas and Escobar (2019) and Ortega et al. (2020) in facilitating recreational walkers in making their walk and route choice decisions.

Fourth, the findings successfully revealed the individual effects of tree planting patterns, street orientation and aspect ratio on pedestrian comfort, which have not been revealed in any other studies before. Noticeably, 4m and 8m tree-planting configurations yielded higher pedestrian comfort levels than the treeless throughout the daytime period during summer. Besides, the street orientation and aspect ratio that produced the most comfortable walking environment varied with time. The most comfortable walking environment occurred in N-S, NE-SW and NW-SE Streets at 8:00, 9:00-11:00 and 14:00-17:00 respectively despite similar pedestrian comfort levels being occurred at 12:00-13:00 for all orientations. The most comfortable walking environment occurred in the streets with H/W = 3.0 at 8:00-11:00 and 17:00, and for H/W = 2.5 at 12:00-16:00. In addition, it is noteworthy pointing out that the pedestrian comfort level differences among street morphological attributes were mainly attributed to the differences of thermal sensation.

Finally, the findings from this part of the study provide more holistic views and valuable insights for urban planners than earlier studies which only focused on a single aspect of comfort, e.g. thermal sensation (Abdollahzadeh and Biloria, 2020; Deng and Wong, 2020; Morakinyo et al., 2017), PAQ (Abhijith et al., 2017; Wania et al., 2012) or noise annoyance (Thomas et al., 2013). For example, (i) tree-planting pattern and aspect ratio but not orientation would exert significant influences on pedestrian comfort, which is in big contrast with the findings determined based on a single comfort criterion, such as thermal sensation (Lai et al., 2019; Srivanit and Jareemit, 2020) that street orientation and aspect ratio exerted larger influences than tree-planting pattern. (ii) Tree-planting configurations with 4m and 8m spacing provided better pedestrian comfort than the treeless configuration despite treeless canyon configuration being reported to have better air quality as trees would obstuct the airflow (Abhijith et al., 2017; Gromke and Ruck, 2012). (iii) Highest pedestrian comfort levels occurred in H/W= 2.5 although the best thermal sensation was perceived at H/W=3 as deeper canyons could provide more shade for pedestrians in summer (Abdollahzadeh and Biloria, 2020; Achour-Younsi and Kharrat, 2016; Lau et al., 2016; Yin et al., 2019) or the best acoustic environments were obtained at H/W=1.9 due to quieter environment in wider streets (Echevarria Sanchez et al., 2016; Thomas et al., 2013). The foregoing examples demonstrate the necessity of employing a multivariate pedestrian comfort index to provide more holistic views to inform urban planners of creating a comfortable street.

Chapter 5 Effects of neighborhood morphological attributes on pedestrian comfort of a street segment

As seen in earlier chapter, the formulated index has been applied to investigate the effects of street morphological attributes on the pedestrian comfort in a street segment. However, a street never exists in isolation. It is of particular interest to reveal the full picture concerning how morphology will affect pedestrian comfort in a street segment by considering the immediate surrounding neighborhood environment. Neighborhood morphological attributes should also affect multiple comfort-related environmental factors. As most neighborhood pedestrian comfort studies mainly focused on an area or neighborhood, there is a burning need to acquire a better understanding on how neighborhood morphological attributes affect the pedestrian comfort in a street segment. This chapter aimed to explore systematically the effects of neighborhood morphological attributes on the scale of a street segment.

Given the unrevealed effect of neighborhood morphological attributes on the thermal comfort of a street segment and the considerable impacts of thermal comfort on pedestrian comfort, the effects of neighborhood morphological attributes on thermal comfort and pedestrian comfort of a street segment formed the major parts of this chapter. Firstly, this part aims to reveal the effect of major neighborhood morphological attributes including surrounding building height configuration, layout form and neighborhood compactness on the thermal comfort of a street segment under different orientations. Second, it aims to formulate multivariate models that can help to analyze the effect of the combinations of neighborhood morphological attributes on the thermal comfort of a street segment. Finally, it attempts to analyze how major neighborhood morphological attributes affect the pedestrian comfort of a street segment.

5.1 Significant impact of thermal comfort

Chapter 4 suggests that thermal sensation (i.e. thermal comfort) exerted a much larger impact than PAQ or noise annoyance on pedestrian comfort of a street segment when street morphological attributes varied. Specifically, the variations of the average pedestrian comfort score due to the change in thermal sensation were larger than changes in PAQ or noise annoyance when aspect ratio, orientation and/or tree-planting pattern varied (i.e. 0.01> 0.006 >0.004; 0.4>0.3; 0.007>0.004). Likewise, thermal sensation was also expected to play the most important role on pedestrian comfort of a street segment when neighborhood morphological attributes varied. Hitherto, thermal comfort of a street segment has not been fully investigated when it was surrounded by different neighborhood morphological attributes as earlier studies mainly focused on their effects on a neighborhood or an area. Specifically, knowledge of the effects of neighborhood morphological attributes on the thermal comfort of a street segment is vital in the understanding of their effects on pedestrian comfort of a street segment.

Accordingly, this chapter is going to present the effects of neighborhood morphological attributes on the thermal comfort of a street segment before their effects on the pedestrian comfort of a street segment.

5.2 Methodology

5.2.1 Thermal comfort simulation

The software ENVI-met was used to predict the thermal comfort of a street segment, which has been mentioned in Chapter 4. It has been widely used in predicting thermal comfort and evaluating the cooling effect of various urban planning approaches (Acero et al., 2021; Deng and Wong, 2020; Galal et al., 2020; Srivanit and Jareemit, 2020). Some of these studies were focused on subtropical areas such as Hong Kong (Chan and Chau, 2021; Morakinyo et al., 2019). ENVI-met is a 3D non-hydrostatic model, which applies the Yamada and Mellor E-ε, turbulence model to close the Reynold Average Navier-Stokes (RANS) equation. The model calculates the mass, momentum and energy budget by Eulerian approach for the air flow, distribution of temperature, specific humidity and radiative fluxes inside the atmosphere (Tsoka et al., 2018). ENVI-met model can be used to simulate the microclimate in urban environments and evaluate the effects of atmosphere, vegetation, architecture and materials down to 0.5m in spatial scale and 1-5 s in time scale. In addition, the data computed from the ENVI-met model can be used to calculate values of some common thermal comfort indices, i.e. PET, UTCI, and PMV, by using the BIO-met module within the software.

For a more systematic and comprehensive analysis of the effect of neighborhood morphological attributes on thermal comfort, this part included the on-site measurement, ENVI-met model validation and parametric design simulations involving three types of neighborhood morphological attributes and street orientation.

5.2.1.1 On-site measurement

A field campaign was performed on 21st August, which was a summer day in Hong Kong, in 2020 to collect site measurement data for validating the simulation model. Figure 5.1 shows a site area located in the east side of Tsim Sha Tsui (TST), which is a commercial area with typical urban morphology and selected for validation. This area is characterized by having streets with height-to-width (H/W) ratios ranging from 2.5 to 5.4 and NW-SE/NE-SW orientations. The campaign was carried out between 10:00 and 16:00 to avoid peak morning and evening flows of crowds and road traffic (Transportant Department HKSAR, 2018), which might impair the accuracies of simulation results. Seven locations within the site area were selected for our field measurement. They comprised one fixed measurement point and six mobile points being monitored by two mobile stations for two selected routes. The fixed microclimatic station was placed at the center of the site area for the entire measurement period. The mobile stations moved along the selected routes for each cycle of measurement. The same measurement route was repeated within three periods, i.e. morning (10:00-11:00), noon (12:00-13:00) and afternoon (14:00-15:00). Figure 5.1 shows the locations of measurement points in the site. The location of the fixed microclimatic station is marked as Center, while the mobile point locations within the two selected routes are marked as Points A1-3 and B1-3. Figure 5.1 also shows the microclimatic station containing the measurement instrument for recording the microclimatic conditions including air temperature, wind velocity, relative humidity, solar radiation and globe temperature. To monitor the thermal environment at pedestrian level, all measurements were taken at 1.5 m above the ground. The sampling intervals of data loggers were set to 10 seconds. The measurement duration at each selected point was set to 5 minutes to ensure the stability of the measurement results (Acero and Arrizabalaga, 2018; Ng and Cheng, 2012). The specification details of all instruments are listed in Table 5.1.

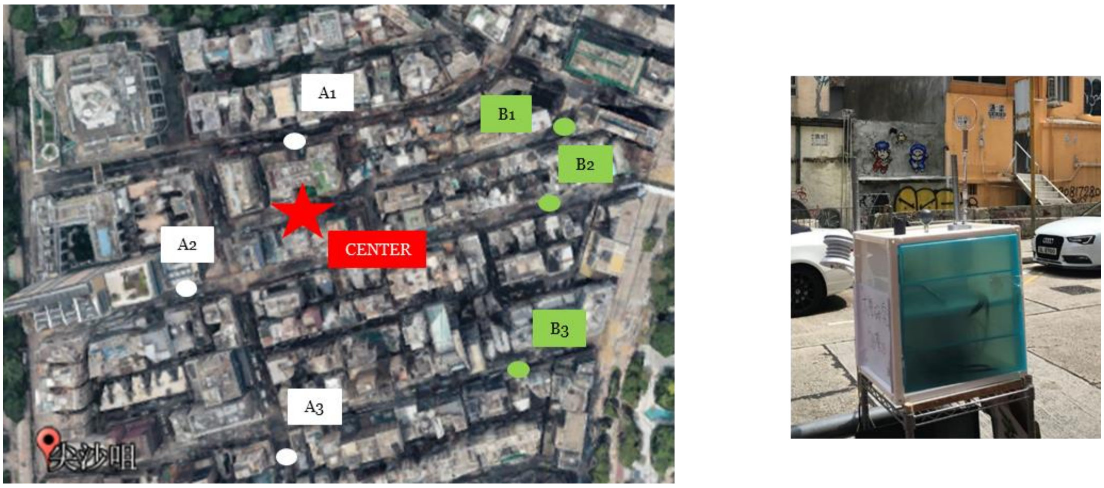


Figure 5.1 Monitoring points and microclimatic station

Table 5.1 Instrument assembled inside the mobile microclimatic station

Instrument	Measured parameter	Operating range	Measurement range	Accuracy
HOBO U23 Prov2 Temperature/Relative Humidity Data Logger with weatherproof temperature and relative humidity sensors	Air temperature	-40°C to 70°C with a resolution of 0.02°C at 25°C	-40°C to 70°C	± 0.21°C
	Humidity	-40°C to 70°C with a resolution of 0.03°C	0 to 100%	± 2.5°C
Dantec low velocity flow analyzer with	Wind speed	-20 °C to 80 °C	0.01 m/s to 30 m/s	± 2% (0.2 - 20 m/s)

Robust temperature-compensated velocity probe (54T35)				± 5% (20 - 30 m/s)
Globe thermometer with a 40 mm black ball and temperature sensor) (Niu et al., 2015)	Globe temperature	-20°C to 70°C	-20°C to 70°C	± 0.35°C
Silicon Pyranometer	Solar radiation	-40 °C to 75 °C	0 to 1280 W/m^2	± 5%

5.2.1.2 Model validation

The data obtained from the field measurement campaign were used to confirm the validity of the ENVI-met model. The ENVI-met model was constructed with reference to the characteristics of the TST area (Figure 5.1). The dimensions of simulation domain were 776m×500m×336m with a horizontal (Δx and Δy) and vertical (Δz) grid sizes of 4m and 3m respectively. The simulation started at 6:00 before sunrise and ran for 12h for daytime. The buildings were assumed to be made of concrete (Tan et al., 2016), while the streets were mainly made of concrete overlaid with asphalt. The input meteorological conditions of the measurement day (i.e. hourly air temperature and relative humidity, mean wind speed and major wind direction) were obtained from the nearest weather station, i.e. Hong Kong Observatory. Specifically, the wind speeds at 10 m height as the inputs of the ENVI-met model were obtained by converting the wind speed data extracted from the Hong Kong Observatory (42 m above ground level) using the following wind profile power law expression (Davenport, 1960; Ng et al., 2011; Zhao and Fong, 2017).

$$V_{10} = V_h(10/h)^{0.35} \tag{5.1}$$

where V_h=the wind speed (m/s) at the height of h.

The cloud cover was assumed to be 0 okta as mostly clear skies were observed on the measurement day. The default values defined within the ENVI-met were used for all other settings. Table 5.2 lists a summary of input details for the simulation models. The air temperature (Ta) and mean radiant temperature (*Tmrt*) predicted at 1.5m height by the constructed model were compared against those collected from the field measurements for validation. The *Tmrt* values were calculated using the following equation:

$$Tmrt = [(GT + 273.15)^4 + \frac{1.1\times10^8 V^{0.6}}{\varepsilon Di^{0.4}} \times (GT - Ta)]^{0.25} - 273.15 \tag{5.2}$$

where *Tmrt* is mean radiant temperature (°C); *GT* is globe temperature (°C); Ta is air temperature (°C) ; *V* is wind speed (m/s); ε is globe's emissivity and D_i is diameter of the globe (m).

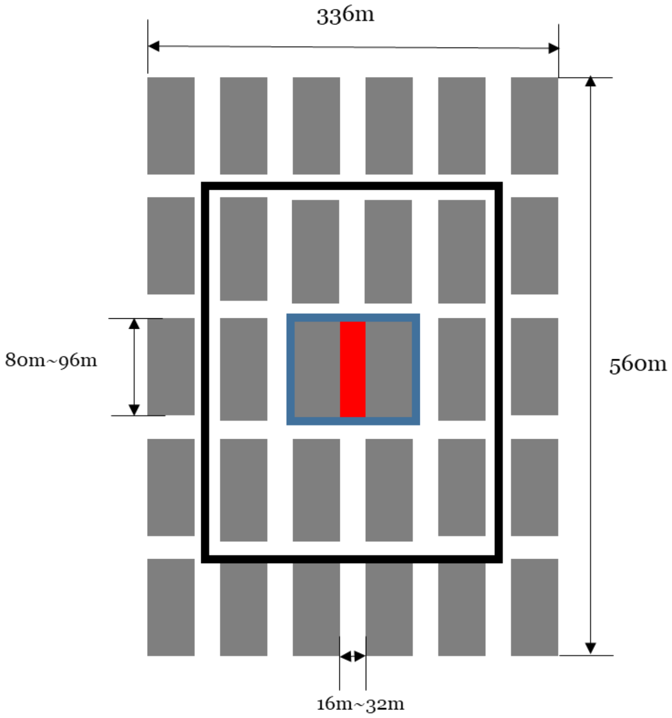
Table 5.2 Input values for the ENVI-met simulation models

Factor	Setting
Model size and resolution	776 m ×500 m ×336m; Δx =4m, Δy =4m, Δz =3m; (The lowest Δz grid is divided into 5 cells)
Date	21. 08. 2020
Air temperature (°C)	Hourly profile from the nearest weather station Min: 27.8 °C ; Max:33.0 °C
Relative Humidity (%)	Hourly profile from the nearest weather station Min: 60.9 % ; Max:89.7 %
Wind speed at 10m (m/s) and wind direction	0.92m/s; 110 deg
Solar adjustment factor	1 ; 0 okta

and cloud cover	
Building	Wall albedo=0.2; Heat transmission walls=2.0 W/m^2 K Roofs albedo =0.3; Heat transmission roofs= 2.0 W/m^2 K
Ground	Albedo of asphalt road =0.2

5.2.1.3 Parametric design simulations

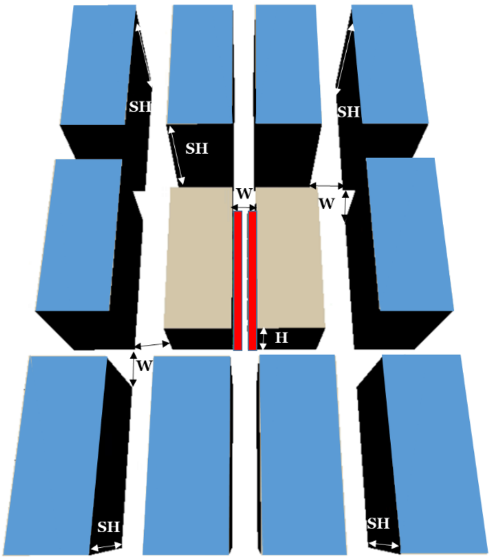
Figure 5.2 shows the simulated domain area, which was set by reference to previous studies conducted by Chen et al. (2021) and Li et al. (2020). Of our major focus was the street segment in the center of the whole area highlighted by red color (hereinafter called the Street). The area enclosed within the blue rectangle embraced the Street and its Street Buildings. The study area (enclosed within the black rectangle) embraced the Street and its Street Buildings surrounded by an additional outer layer of buildings. The incorporation of the outmost layer of buildings could reduce the effects of the domain borders on the simulation of the study area (Acero et al., 2021). All the combinations shown in Figure 5.8 formed by variations of neighborhood morphological attributes within the study area were constructed with an aim to investigate their effect on the thermal comfort of a street segment.



Note: The simulated domain, the study area enclosed within the black rectangle, the Street and its street buildings enclosed within blue rectangle, and the Street in red color

Figure 5.2 The simulated domain

Figure 5.3 shows the schematic diagram depicting the study area and the Street. Major emphasis was given to the sidewalk areas of the Street highlighted in red color, and the thermal comfort in the sidewalk areas (i.e. pedestrian thermal comfort) were analyzed for individual configurations. The sidewalk was set as 4m wide by reference to the current Planning Standards and Guidelines of Hong Kong (Planning Department in Hong Kong, 2011), while the remaining areas of the Street were traffic lanes. The linear block buildings abutting on two sides of the Street (i.e. grey color buildings) are hereinafter called Street Buildings. The Surrounding Buildings (i.e. blue color buildings) were defined as all the buildings surrounding the Street Buildings were at a distance of one street width from the Street.



Note: Red: The sidewalks of the Street; White: Surrounding streets; Grey: Street Buildings; Blue: Surrounding buildings

Figure 5.3 A schematic diagram showing the study area and the Street

In order to investigate the effect of surrounding building height configuration, the ratio of relative height of Surrounding Buildings to Street buildings was used as an indicator for studying its effect on thermal comfort. Also, the neighborhood compactness was expressed in terms of building coverage ratio (BCR), which was in line with those suggested by other studies (e.g. Stewart and Oke, 2012; Zheng et al., 2018). The building layout, BCR and height of buildings were identified from the existing morphology in Hong Kong. Figure 5.4 shows three building layout forms investigated in this study, i.e. Close, Semi and Open, which were modified from two typical urban forms, i.e. linear and courtyard (Clark et al., 1972; Taleghani et al., 2015). Figure 5.5 shows the three layout forms commonly observed in Hong Kong. In this study, the building coverage ratio was set as 30, 45 or 60% by reference to the commonly observed BCRs reported by Zheng et al. (2018). Figure 5.6 shows the examples of the existing urban morphology in Hong Kong bearing the studied building coverage ratios. Whereas the configuration of 30% BCR with regular street blocks and building layouts was constructed hypothetically for future planning purposes. Street width (W) was set as 16m, 24m or 32m (Ng et al., 2012), and assumed to be the uniform within the study area for the BCR of 60%, 45% and 30% respectively. The height of the Street Buildings (H) was fixed as 60m, which was the typical building height in Hong Kong (Ng et al., 2012), while those of the Surrounding Buildings (SH) were set as 30, 60 or 120m, which corresponded to SH/h ratios of 0.5, 1 or 2 (Hang and Li, 2010). Figure 5.7 shows the existing surrounding building height configurations in Hong Kong.

Accordingly, 144 configurations were constructed to evaluate the effects of neighborhood morphological attributes on thermal comfort of a street segment. Figure 5.8 shows the four building layout forms (Open, Semi-1, Semi-2, Close), four height ratios of Surrounding Buildings to Street Buildings (SH/h= 0.5, 1, and 2) and three building coverage ratios (BCR=30, 45 and 60%), and four axis orientations (N-S, E-W, NE-SW, NW-SE). All the scenarios were simulated based on the climatic conditions of August 21st, which were used to represent those of a hot summer day in Hong Kong. The model settings were the same as those of the validated model shown in Table 5.2.

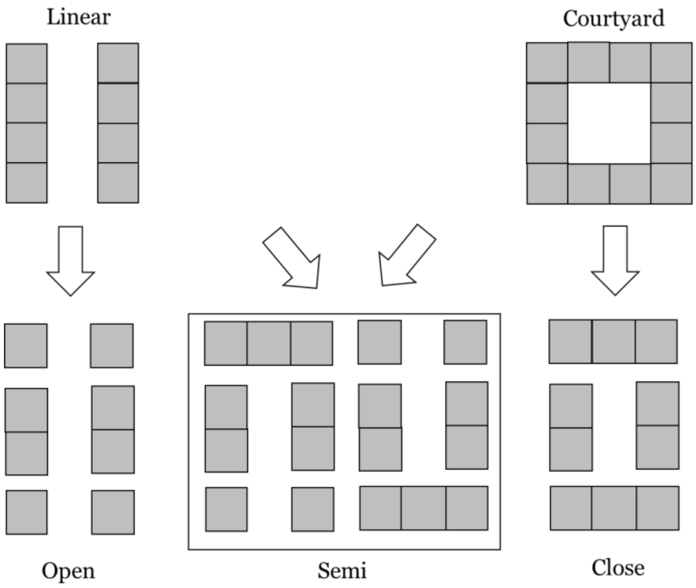


Figure 5.4 Building layout forms derived from Taleghani et al. (2015)

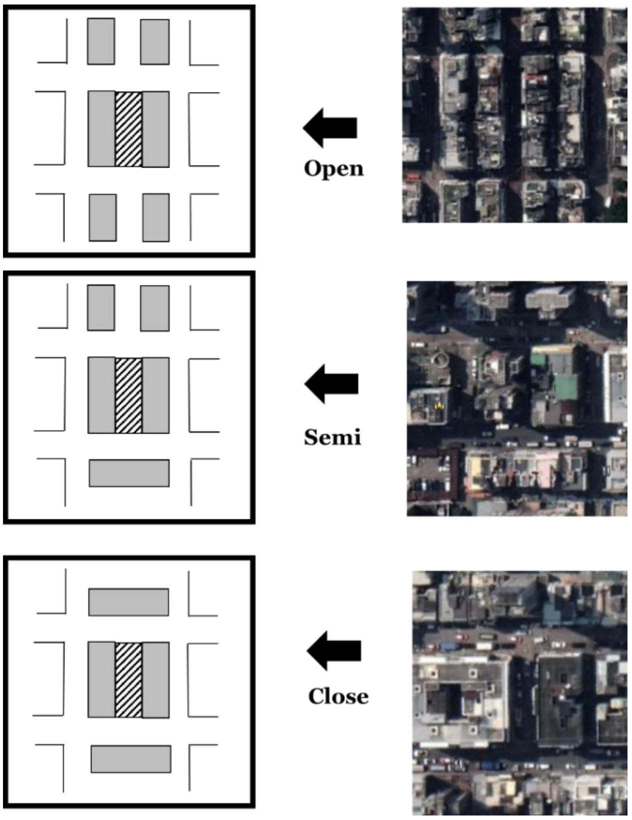


Figure 5.5 Three studied building layouts (Left) which were constructed to portray the existing building layouts in Hong Kong (Right)

(a) BCR: 40-50%

(b) BCR: 60-70%

Figure 5.6 The urban morphology having different building coverage ratios that can be found in Hong Kong

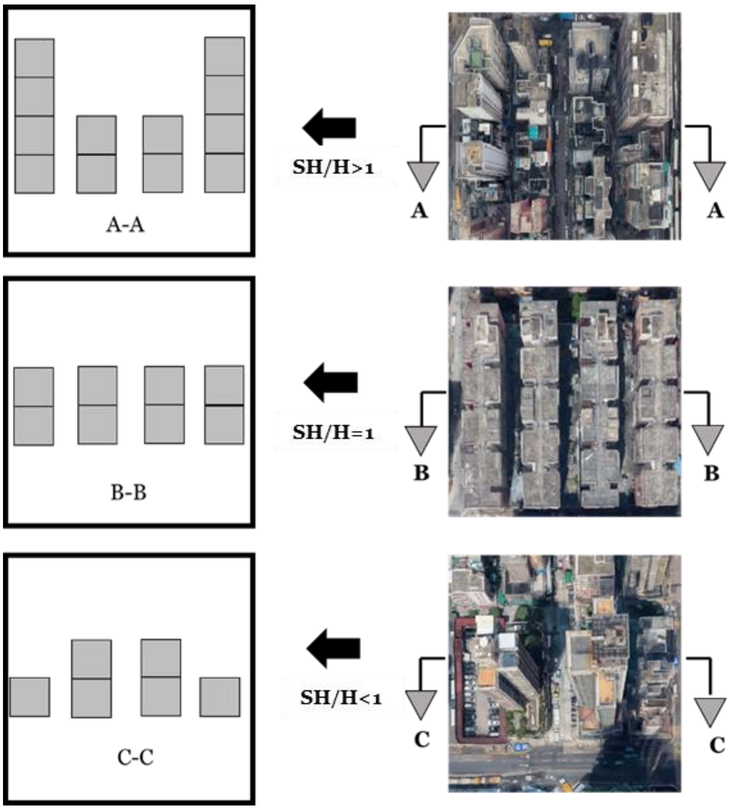


Figure 5.7 Cross sections showing three studied surrounding building height configurations (Left) which portray different types of existing configurations in Hong Kong (Right)

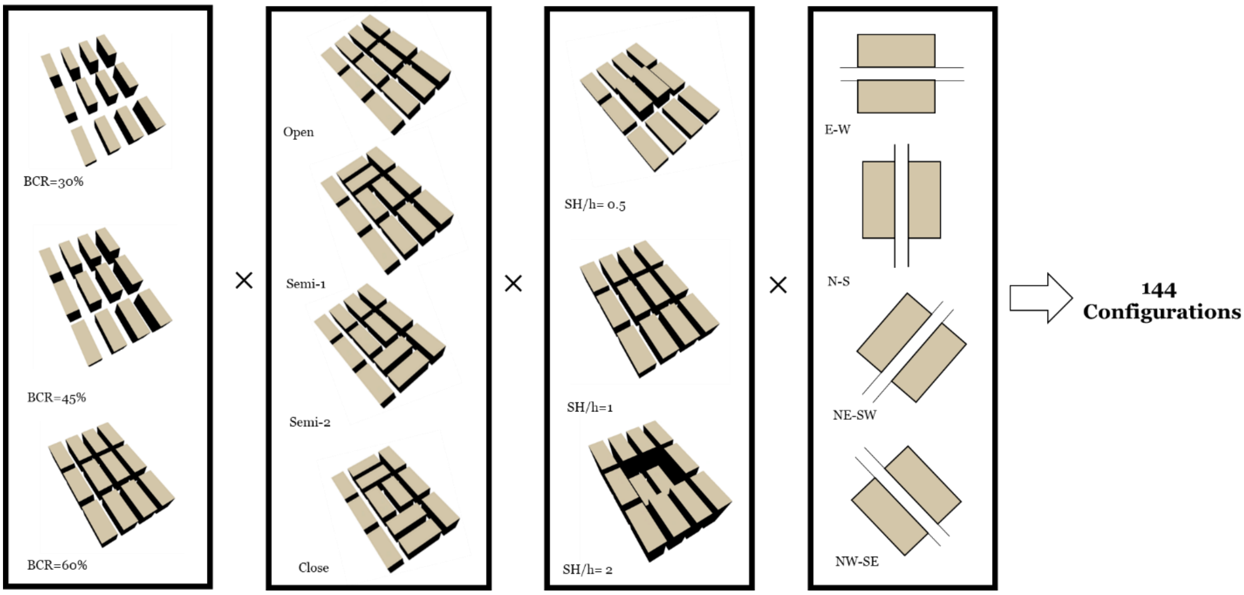


Figure 5.8 Visual representations of combinations of various neighborhood morphological attributes within the study area

5.2.1.4 Thermal comfort evaluation

The outputs of the ENVI-met model including air temperature, wind speed, relative humidity and mean radiant temperature were then input into Bio-met module to calculate PET values. PET, which is a thermal comfort index based on the Munich Energy-balance Model for Individuals (MEMI) (Lin et al., 2010; Sharmin et al., 2019), has been widely used to predict outdoor thermal comfort. PET can be easily understood by urban planners and policy makers (Deb and Alur, 2010; Deng and Wong, 2020; Lin et al., 2010; Sharmin et al., 2019) as it is expressed in terms of Degree Celsius (°C). Also, PET has been less criticized in comparison with UTCI with the examination of the positive and strong relationship between PET and outdoor thermal conditions (Potchter et al., 2018). PET evaluates thermal comfort by considering thermal conditions, radiation and wind data, metabolic rate, and other personal factors such as age, gender and clothing value (Müller et al., 2014). Table 5.3 shows the thermal sensation classification for Hong Kong based on the one suggested by Morakinyo et al. (2018). With reference to the suggestions made by Yin et al. (2019) and Taleghani et al. (2015), comfortable perception defined in this study included thermal sensation of slightly cool, neutral and slightly warm, which corresponds to a range of 21- 33°C in PET value.

Table 5.3 Thermal sensation classification for Hong Kong

PET (°C)	Thermal Perception	Physiological stress
<13	Very cold	Extreme cold stress
13–17	Cold	Strong cold stress
17–21	Cool	Moderate cold stress
21–25	Slightly cool	Slight cold stress
25–29	Neutral	No thermal stress
29–33	Slightly warm	Slight heat stress
33–37	Warm	Moderate heat stress
37–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

The PET values in this study were calculated based on a 35-year-old man of 1.70m in height and 68.6 kg in weight. This represented the body built of an average male adult in Hong Kong (Census and Statistics Department, 2019; Department of Health, 2014). The adult had a walking speed of 1.21 m/s, clothing insulation value of 0.45, and a sum of metabolic work of 159 W/m^2 (Chan and Chau, 2021).

5.2.2 Data analysis

Given that our ultimate aim was to create a comfortable pedestrian walking environment, our major focus was placed on the comfort of the sidewalks in both sides of the Street. The baseline configuration was defined with the following characteristics: 60m high Street Buildings, 60m high Surrounding Buildings (i.e. SH/h=1), open layout form and 30% BCR.

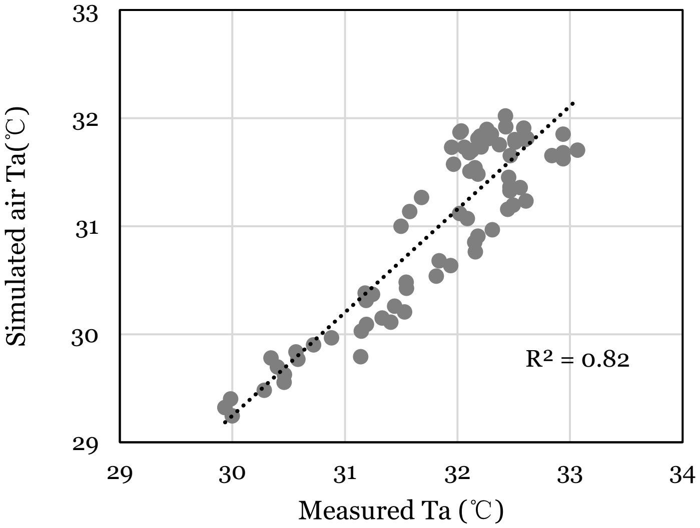
In the first stage, the effects of neighborhood morphological attributes on thermal comfort of a street segment were investigated thoroughly. To start with, our analysis embraced the variation analyses of wind speed, air temperature, mean radiant temperature and PET_{SW}, i.e. the hourly spatial averages of the PET values over the entire sidewalks in both sides, for the baseline configuration with the variations of neighborhood morphological attributes including neighborhood compactness, surrounding building layout form and height configuration to determine their effects on the thermal comfort of a street segment. In addition, multivariate regression models were also formulated to predict hourly PET_{SW} values for all different combinations of investigated street orientations, building layout forms, BCR and SH/h ratios throughout the daytime period (between 8:00- 17:00). The predicted PET_{SW} values would be subsequently used to determine the total number of comfort hours (i.e. PET_{SW} between 21°C- 33°C) and very hot hours (i.e. $PET_{SW}>41°C$) yielded during daytime period by individual configurations.

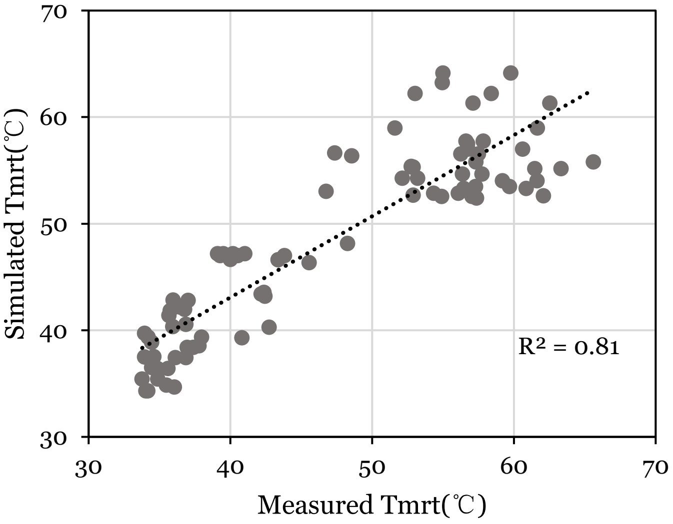
In the second stage, the score variation of thermal sensation, noise annoyance, PAQ and pedestrian comfort were performed to reveal the effects of various neighborhood morphological attributes on pedestrian comfort of a street segment. The detailed traffic conditions refer to Table 4.4.

5.3 Results

5.3.1 Comparisons between the measured and simulated data

With the reference to the previous studies of Lin et al. (2021), Ouyang et al. (2020) Chen and Ng (2013) and Liu et al. (2021), air temperature (*Ta*), mean radiant temperature (*Tm*rt) were important microclimate parameters, and have been always used to validate the ENVI-met model. Hence, *Ta*, *Tm*rt and PET data were used to validate the ENVI-met model. The measured PET values were calculated by Rayman software (Matzarakis et al., 2007). In line with the 5-min recording period of individual measured mobile points, 5-min average values were computed from both the measurement and simulation data. Figure 5.9 shows the comparison of the data values of the simulation model and the field measurement. According to Willmott (1981), results are considered more accurate if the Root-mean-square deviation (*RMSE)* value is close to 0 and the R^2 value approaches 1. The calculated RMSE values of *Tmrt, Ta* and *PET* were 0.91, 4.70 and 2.22°C respectively. These deviations between the measured and simulated values may be due to the assumptions of static cloud and wind conditions in the simple forcing method (Liu et al., 2021; Morakinyo et al., 2019; Ouyang et al., 2020). The anthropogenic heat released by motor vehicle and air conditioning units was not considered in ENVI-met model, which would also contribute to the deviations (Liu et al., 2021; Morakinyo et al., 2018; Ouyang et al., 2020). Besides, the use of default values of the properties of wall and roof material (i.e. emissivity, thermal conductivity) due to the lack of measurement of these properties was also a reason of the deviations (Liu et al., 2021; Morakinyo et al., 2019). Nonetheless, the RSME values obtained in the current study were comparable to those in previous studies summarized by Salata et al. (2016) and Yin et al. (2019) (cf. RSME values for *Ta* ranged from 0.66 to 4.83°C respectively, for *Tmrt* ranged from 5.49 to 7.98°C, and for *PET* ranged from 2.93 to 3.45°C respectively). In addition, the R^2 values of the measured and simulated *Ta, Tmrt and PET* values were 0.82, 0.81 and 0.79 respectively, suggesting that the measured and simulated values were highly correlated. These suggested that the ENVI-met could be used for simulation of street microclimate in Hong Kong.





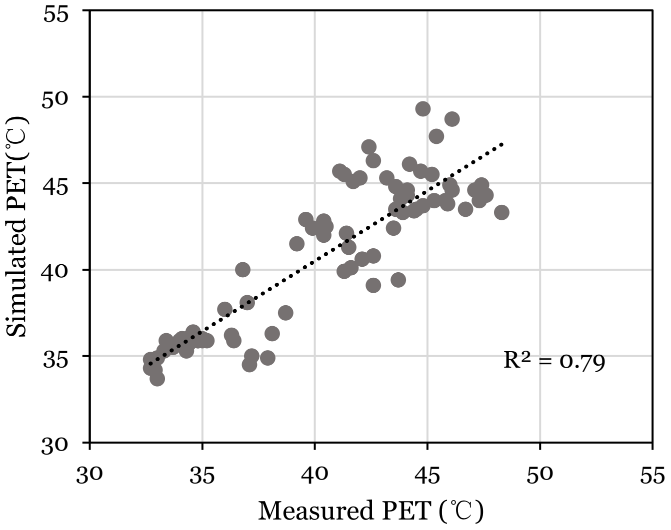


Figure 5.9 A comparison between the simulated and measured *Ta*, *Tmrt* and PET values

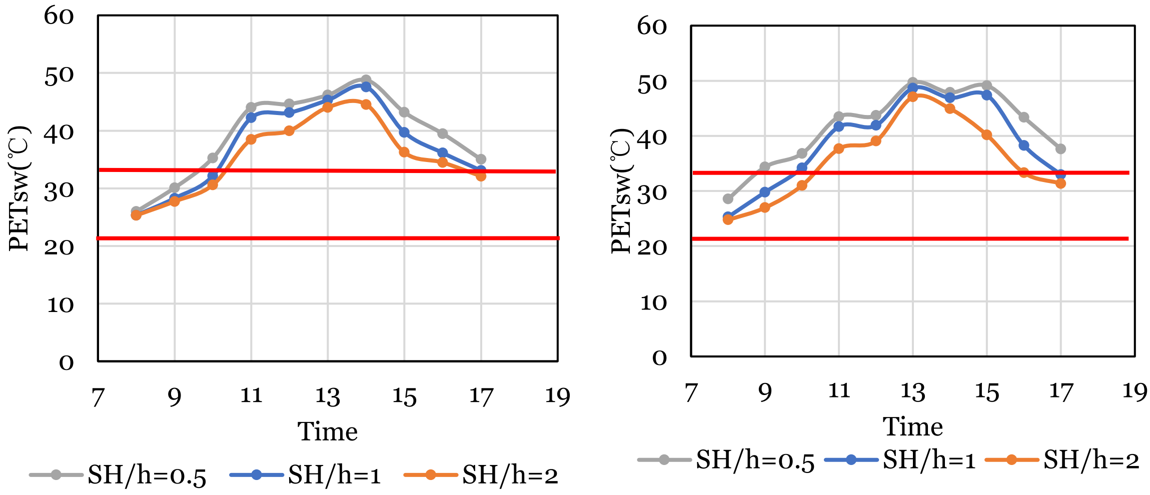
5.3.2 Effects of neighborhood morphological attributes on thermal comfort of a street segment

In this section, the effects of neighborhood morphological attributes on thermal comfort of a street segment under different orientations are going to be discussed. For a more comprehensive thermal comfort evaluation, variation analyses of important thermal comfort factors (Deng and Wong, 2020; Sözen and Koçlar Oral, 2019) including air temperature (Ta), wind speed (v) and mean radiation temperature ($Tmrt$) were also performed alongside the examination of variations of PET_{SW} for different street orientations at different periods.

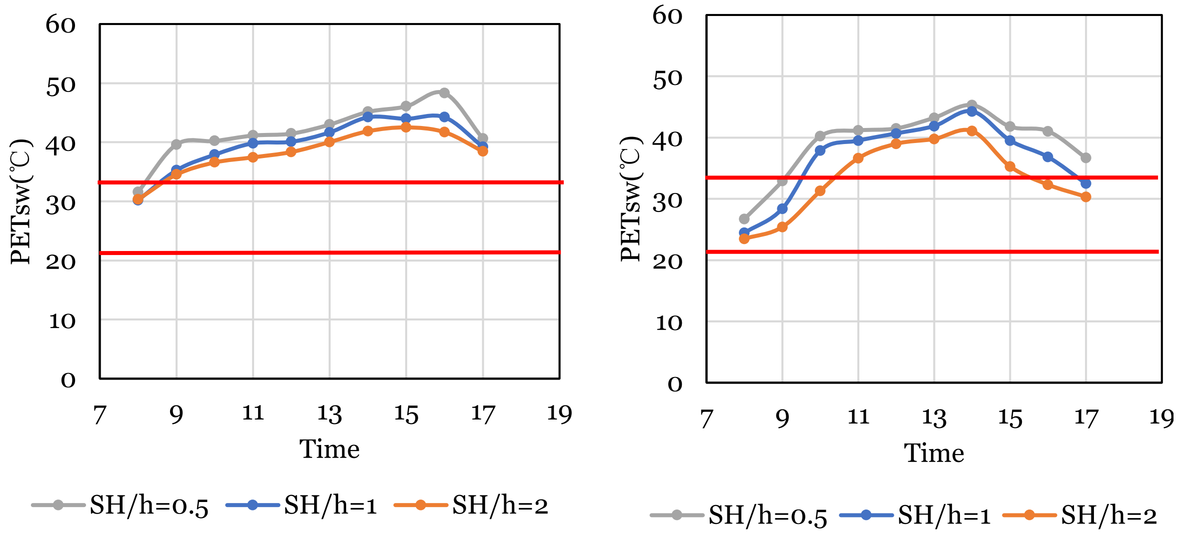
5.3.2.1 Surrounding Building Height Configuration

To facilitate understanding of the relationship between pedestrian thermal comfort and SH/h ratio in detail, the temporal PET_{SW} profiles for different SH/h ratios were examined. Figure 5.10 shows the temporal PET_{SW} profiles for different SH/h ratios from 08:00 to 17:00. The temporal PET_{SW} profiles were similar for various SH/h ratios but varied considerably with orientations. Obviously, the extents of temporal fluctuations of PET_{SW} values for non-E-W Streets (i.e. N-S, NE-SW and NW-SE Streets) were larger and more easily observed than that for E-W Street. The rates of change of PET_{SW} were smaller for E-W Street.

Generally, the pedestrian thermal comfort could be improved by increasing SH/h ratio. The configuration with SH/h = 2 could produce the best thermal comfort conditions for pedestrians. Significant differences in PET_{SW} values were observed between SH/h=2 and 0.5 for non-E-W Streets. Raising SH/h ratio from 0.5 to 2 would lower the PET_{SW} values up to 5.5°C at 11:00, 7.4°C at 09:00 and 8.9°C at 10:00 in N-S, NE-SW and NW-SE Streets respectively during the morning period, and up to 6.9°C at 15:00, and 10.0 and 8.7°C at 16:00. Meanwhile, the average PET_{SW} values were lowered by 4.0, 5.8 and 5.6°C in N-S, NE-SW, and NW-SE Streets respectively, which corresponds to an increase of the comfort duration by 2, 3 and 3 hours (see region inside the red line boundary in Figure 5.10). In contrast, there was no significant increase in comfort duration in E-W Street despite its average PET_{SW} value being increased by 3.5°C. In short, E-W Street had the shortest comfort duration among the four orientations with only 1 comfort hour for all SH/h ratios.



(a)N-S **(b)NE-SW**

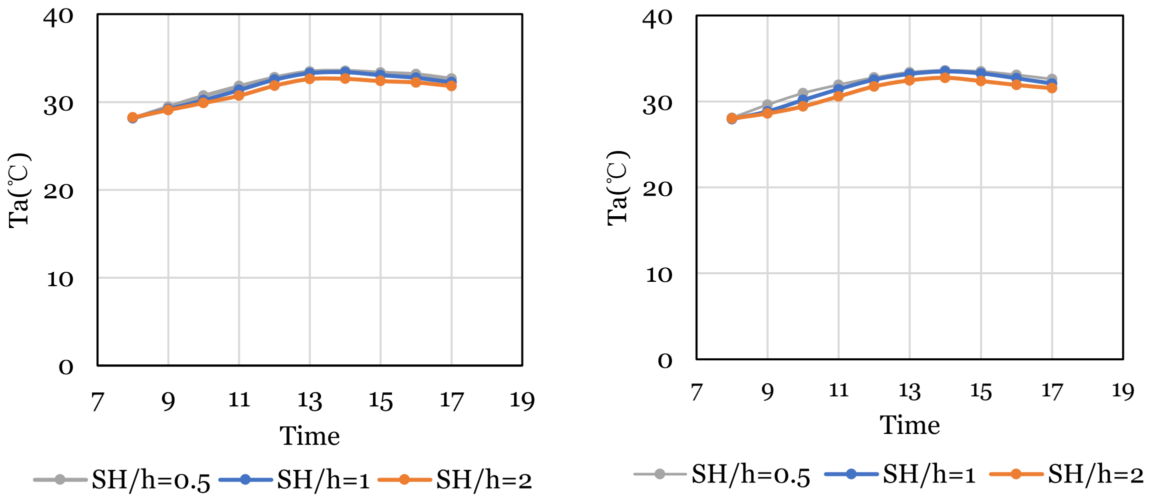


(c) E-W **(d) NW-SE**

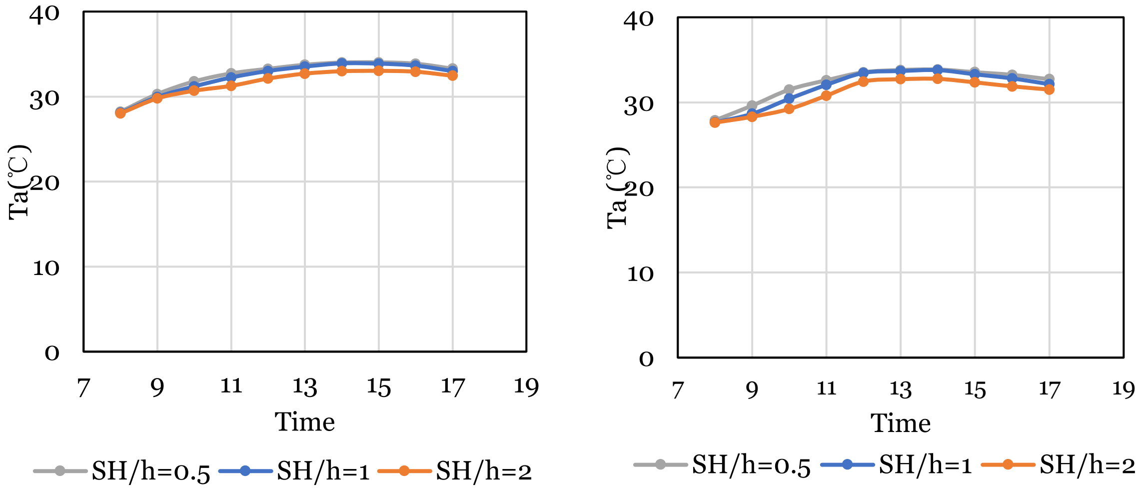
Note: Red lines denote the boundary values of comfort expressed with PET values of 21°C and 33°C

Figure 5.10 The temporal PET_{SW} profiles for different SH/h ratios and orientations

Figure 5.11 shows that the temporal *Ta* variation profiles were similar for all SH/h ratios and orientations, and the lowest *Ta* values were observed at SH/h = 2 for the whole period. During this period, the SH/h = 2 could yield up to 1.1, 1.5, 1.5 and 2.3°C lower than the SH/h = 0.5 for N-S, NE-SW, E-W and NW-SE Street respectively. This was probably because taller Surrounding Buildings could intercept more sunlight incident on the Street and Street Buildings. Noticeably, only small variations of air temperature would be induced by varying SH/h ratio, which echoed earlier field findings that geometrical changes could only induce small *Ta* variations (Ali-Toudert and Mayer, 2007; Nakamura and Oke, 1988; Sözen and Koçlar Oral, 2019). *Ta,* as a climatic value, was slightly affected by built environment as the air circulation could dissipate the heat quickly (Sözen and Koçlar Oral, 2019) .



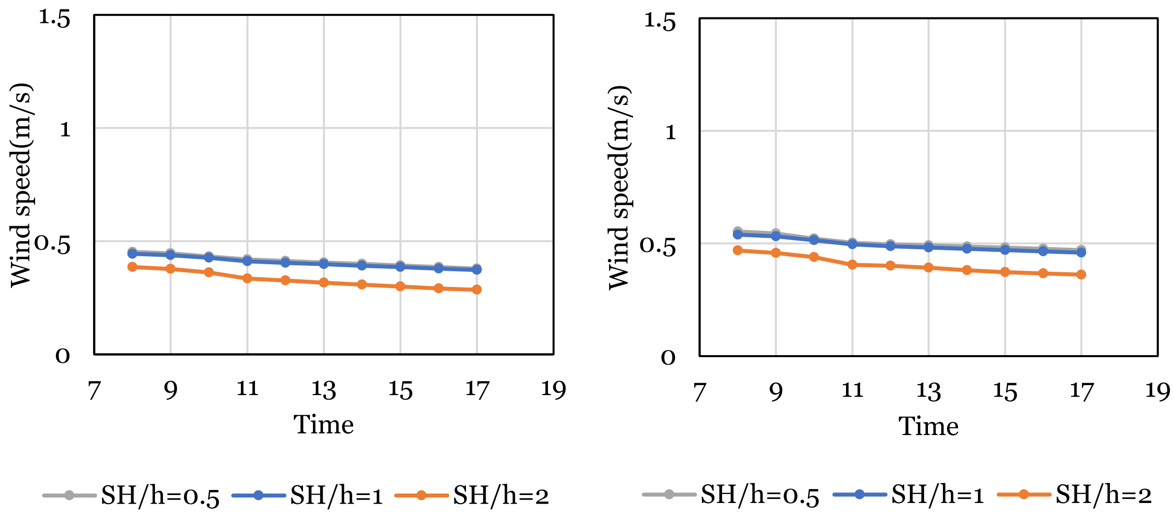
(a)N-S **(b)NE-SW**



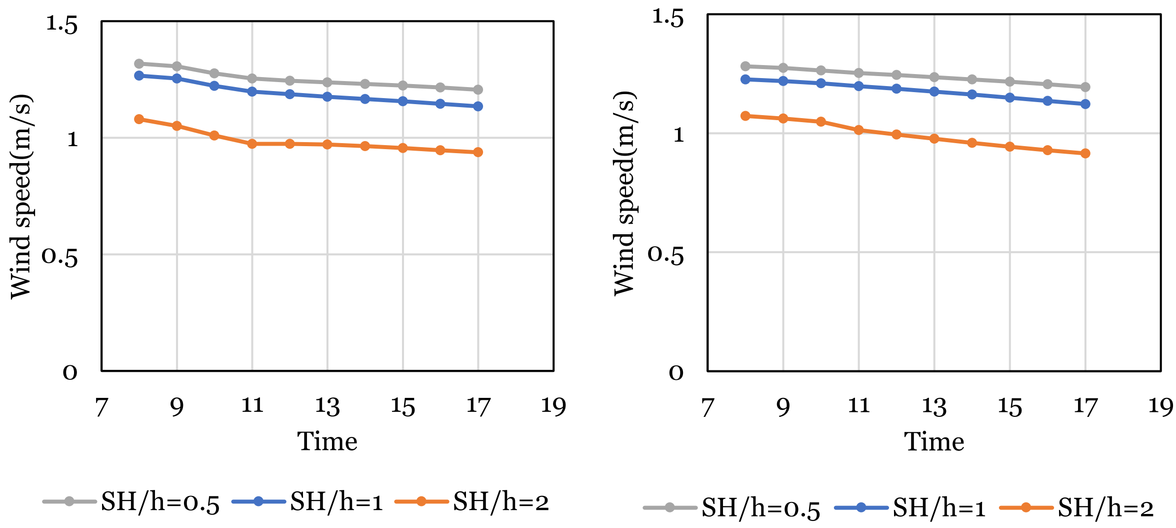
(c) E-W **(d) NW-SE**

Figure 5.11 The temporal *Ta* profiles for different SH/h ratios and orientations

Figure 5.12 shows that wind speed decreased as SH/h ratio increased for all street orientations. The wind speeds of SH/h=0.5 were around 0.1-0.3 m/s higher than that of SH/h=2. Taller surrounding buildings would obstruct the airflow and thus reduce the wind speeds. Noticeably, the wind speeds were very similar between E-W and NW-SE Streets, and between N-S and NE-SW Streets despite the wind speeds of the former pair being always higher by an approximate range of 0.6 to 0.8 m/s. This can be explained by higher wind speed for E-W and NW–SE Streets due to its axis being nearly parallel to the wind direction, and lower wind speeds for N-S and NE-SW Streets due to their axes being nearly perpendicular to prevailing wind direction.



(a)N-S **(b)NE-SW**

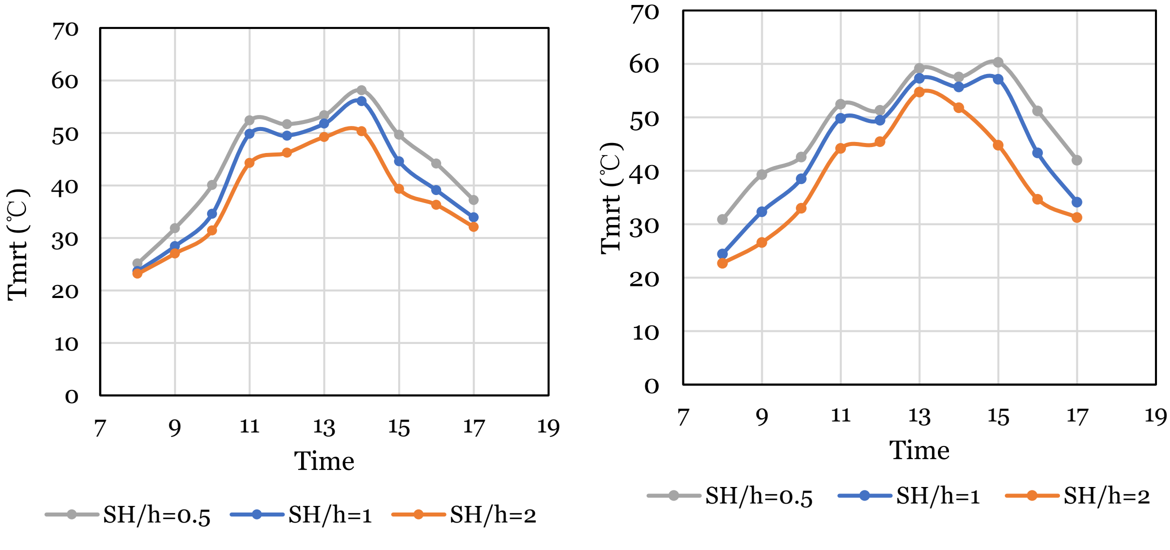


(c) E-W **(d) NW-SE**

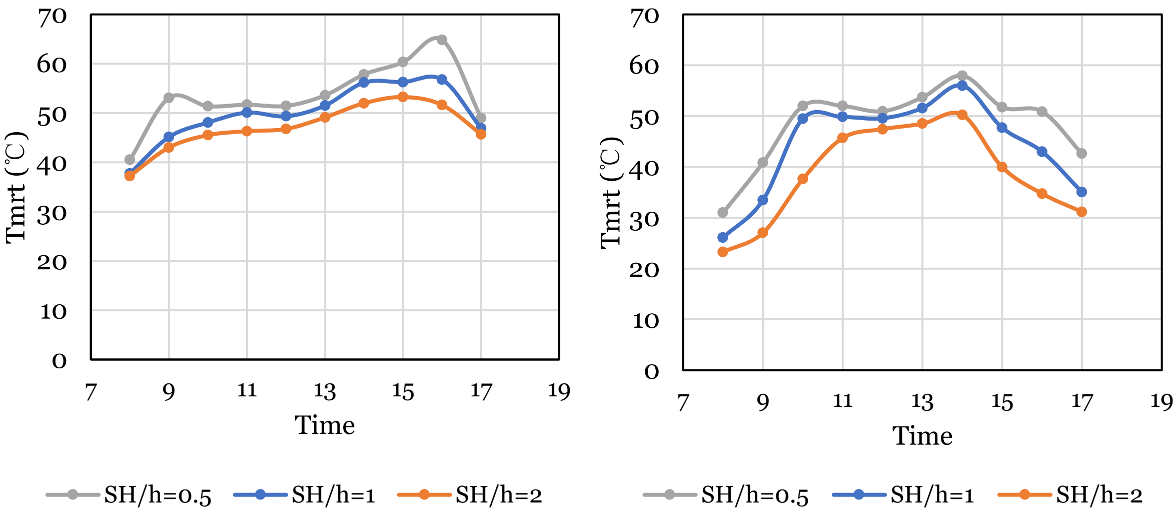
Figure 5.12 The temporal wind speed profile for different SH/h ratios and orientations

Figure 5.13 shows that the temporal *Tmrt* profiles were similar for different SH/h ratios and orientations. Similar to PET, a higher SH/h ratio would produce a lower *Tmrt* value. The temporal PET_{SW} and *Tmrt* profiles were very similar, implying that they were highly correlated.

Over the whole period, the lowest *Tmrt* values were observed at SH/h = 2, while the highest *Tmrt* values were observed at SH/h=0.5. For N-S Street, the differences in *Tmrt* values could be up to 8.6°C for SH/h ratio between 0.5 and 2 during the morning periods (8:00-11:00). The differences were found to be smaller (i.e. around 4°C) at 12:00-13:00, and rose up to 10.3°C between 14:00 and 17:00. This was probably due to the situation that sunlight was largely blocked at lower solar altitudes. Similarly, it was also observed that, for NE-SW, E-W and NW-SE Streets, the SH/h=2 yields *Tmrt* values up to 12.7, 10.1 and 14.4°C at 10:00 and up to 16.5, 13.2 and 16.2°C at 16:00 lower than SH/h=0.5.



(a)N-S **(b)NE-SW**



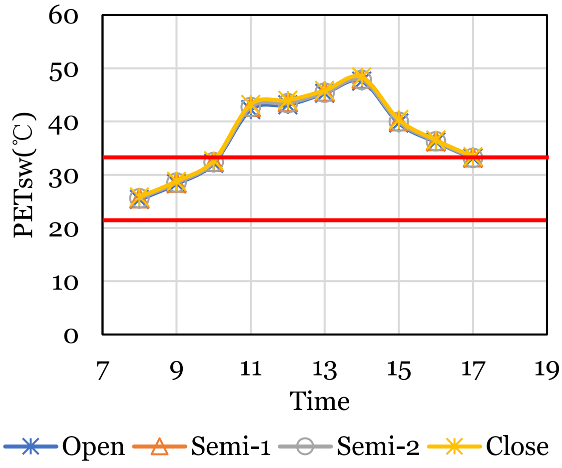
(c) E-W **(d) NW-SE**

Figure 5.13 The temporal *Tmrt* profiles for different SH/h ratios and orientations

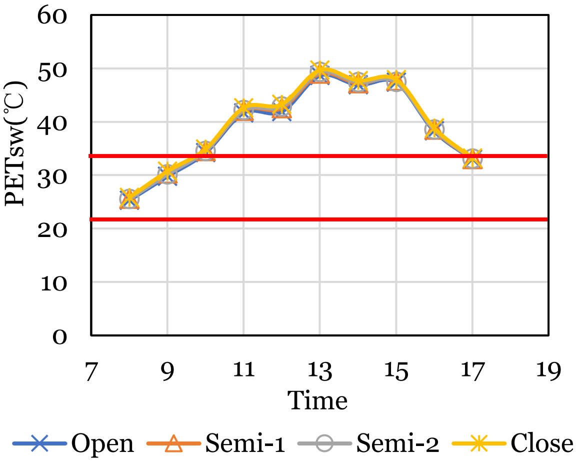
5.3.2.2 Surrounding Building Layout Form

Figure 5.14 shows the temporal PET_{SW} profiles for various building layout forms and street orientations at other periods. It was observed that the PET_{SW} profiles were similar among the four building layout forms for non-E-W Streets over the whole period. Variations of layout forms could only lead to changes in average PET_{SW} of 0.6, 0.8 and 0.5°C in N-S, NE-SW and NW-SE Streets respectively.

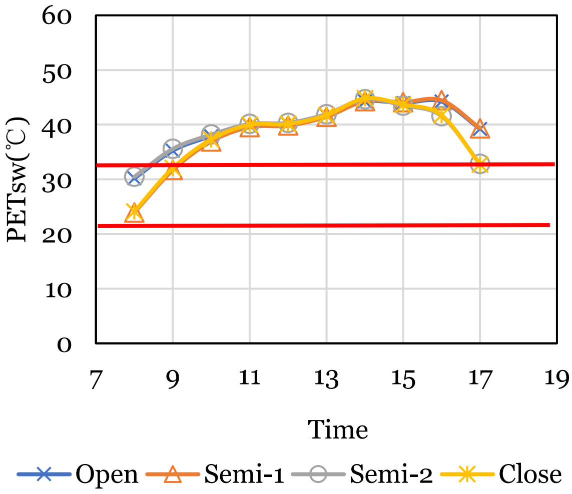
In contrast, for E-W Street, significant differences in PET_{SW} values were observed among different building layout forms at 8:00-10:00 and 15:00-17:00, while similar values were observed from 11:00 to 14:00. At 8:00-10:00, the PET_{SW} profiles were similar between the semi-1 and close layout form, and between the semi-2 and open layout form. The close/semi-1 layout form yielded 6.0°C lower in PET_{SW} values than the open/semi-2 layout form at 8:00. On the other hand, at 15:00-17:00, the semi-2 layout form shared similar profiles with the close layout form, while the semi-1 form shared similar profiles with the open layout form. The close/semi-2 layout form yielded 6.5°C lower in PET_{SW} values than the open/semi-1 layout form at 17:00. In addition, a drop in the average PET_{SW} value of 1.8°C and an increase of comfort duration by 2h were observed by changing the layout form from open to close. Despite so, the shortest comfortable duration was always observed in E-W Street irrespective of layout forms.



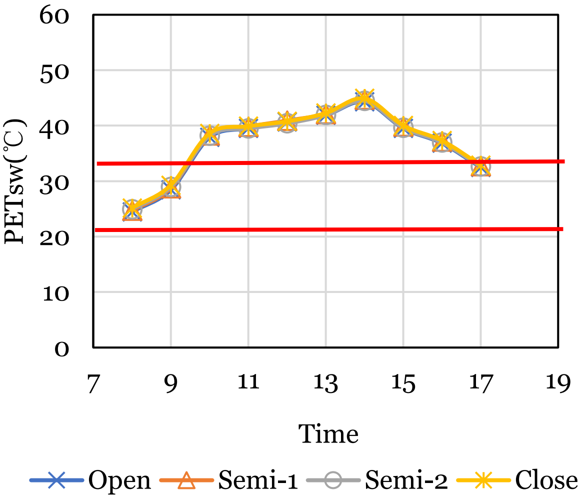
(a)N-S



(a) NE-SW



(c) E-W

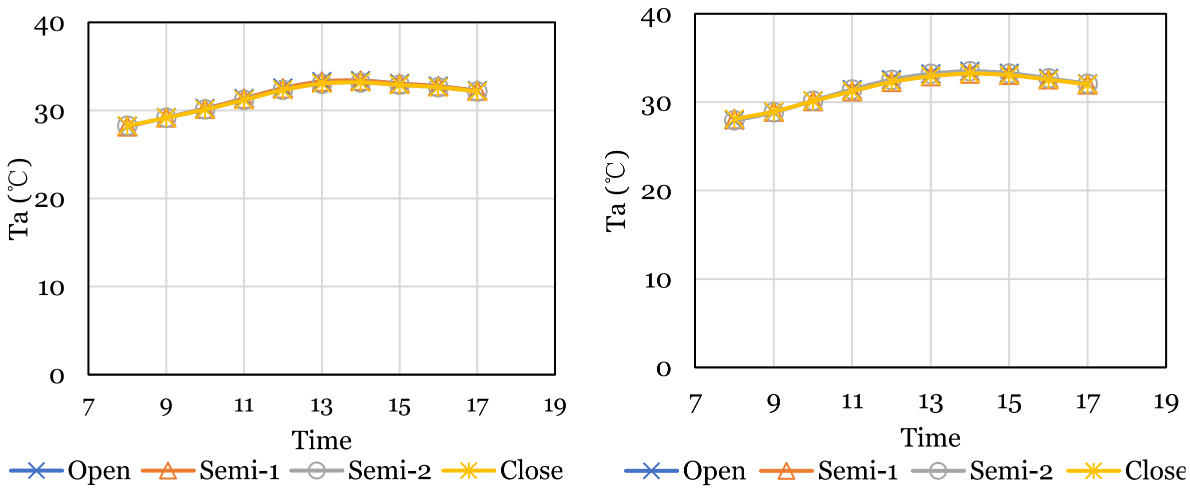


(d) NW-SE

Note: Red lines denote the boundary values of comfort expressed with PET values of 21°C and 33°C

Figure 5.14 The temporal PET_{SW} profiles for different layout forms and orientations

Meanwhile, as shown in Figure 5.15, the *Ta* profiles attributed to the four layout forms were also similar in N-S, NE-SW, E-W and NW-SE Streets despite only small differences in *Ta* values being found among different layout forms. The largest differences in *Ta* values observed in non-E-W Streets were only 0.25 ℃. For E-W Street, a slightly larger *Ta* difference of up to 0.8℃ was observed between the semi-1/close and semi-2/open layout forms. The *Ta* values were similar between the semi-1 and close layout forms, as well as between semi-2 and open layout forms. This was probably because the close and semi-1 layout form protected the Street from the sunlight being penetrated from East direction on the Street and wall in the mornings, which might lower air temperature over a long period.



(a)N-S **(b)NE-SW**

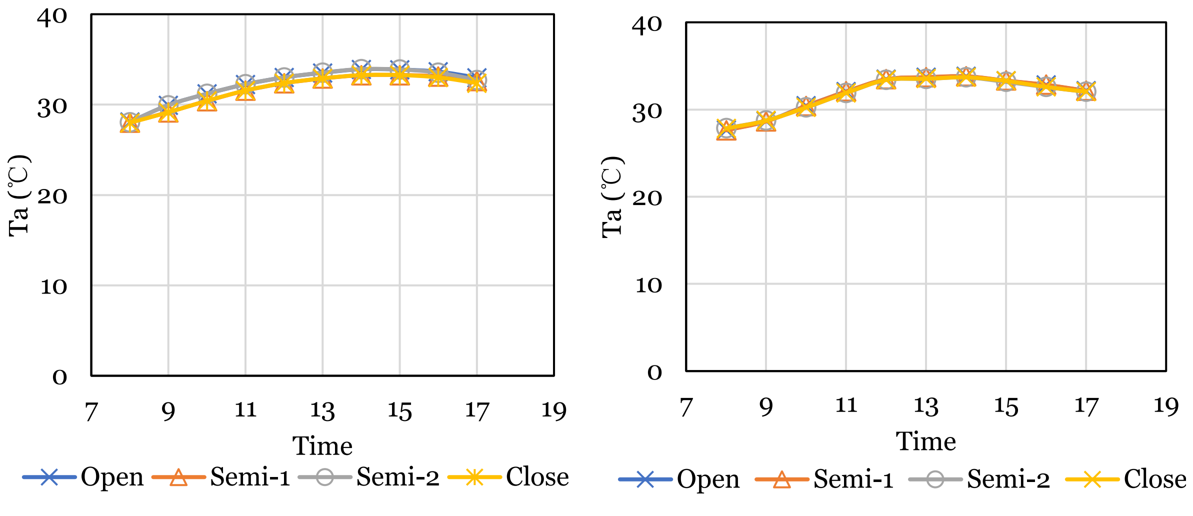
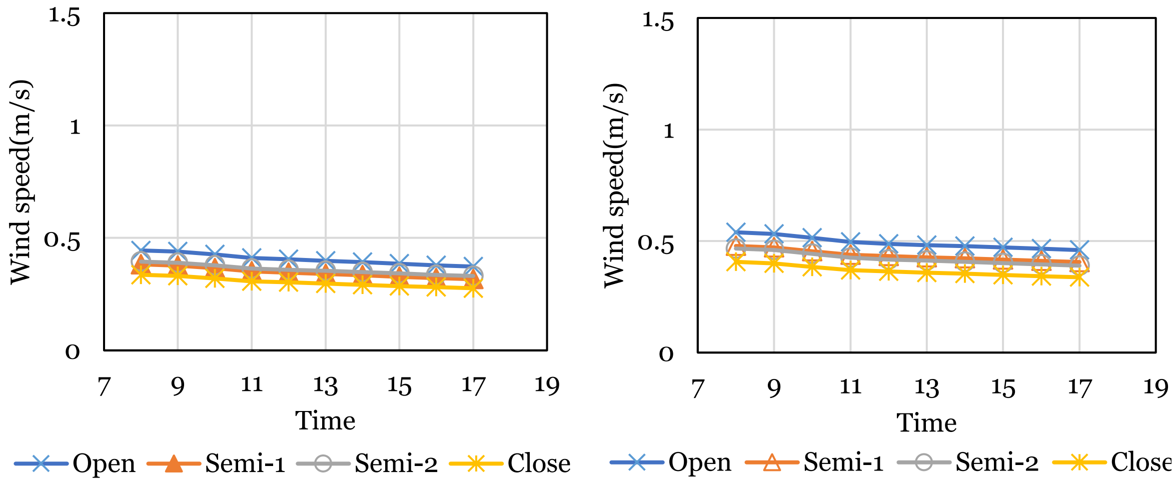
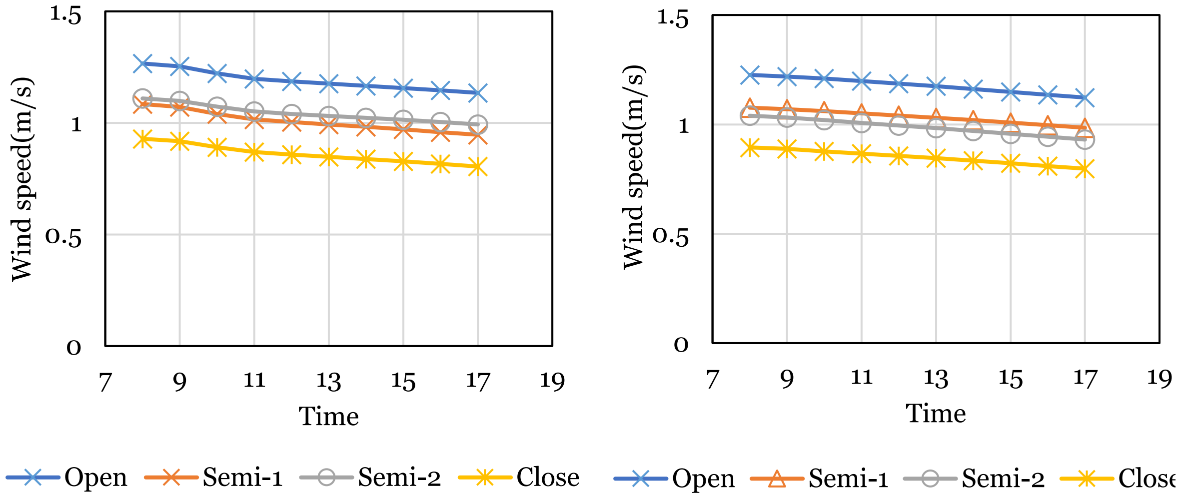


Figure5.15 The temporal *Ta* profiles for different layout forms and orientations

Figure 5.16 shows the wind speeds of the four street orientations due to different building layout forms. Among all the forms, the open layout form yielded the highest wind speed while the close layout form yielded the lowest irrespective of street orientation. The wind speeds of open layout form were around 0.1-0.3 m/s higher than that of close layout form. The lowest wind speed attributed to the close layout form was probably because the airflow was obstructed by the surrounding buildings on two sides. In comparison, the wind speeds of the semi-1 and semi-2 layout form were higher than those of the close layout form but lower than those of the open layout form as the airflow was obstructed by the surrounding buildings on one side only. Furthermore, NW-SE and E-W Streets generally produced higher wind speeds than N-S and NE-SW Streets.



(a)N-S **(b)NE-SW**

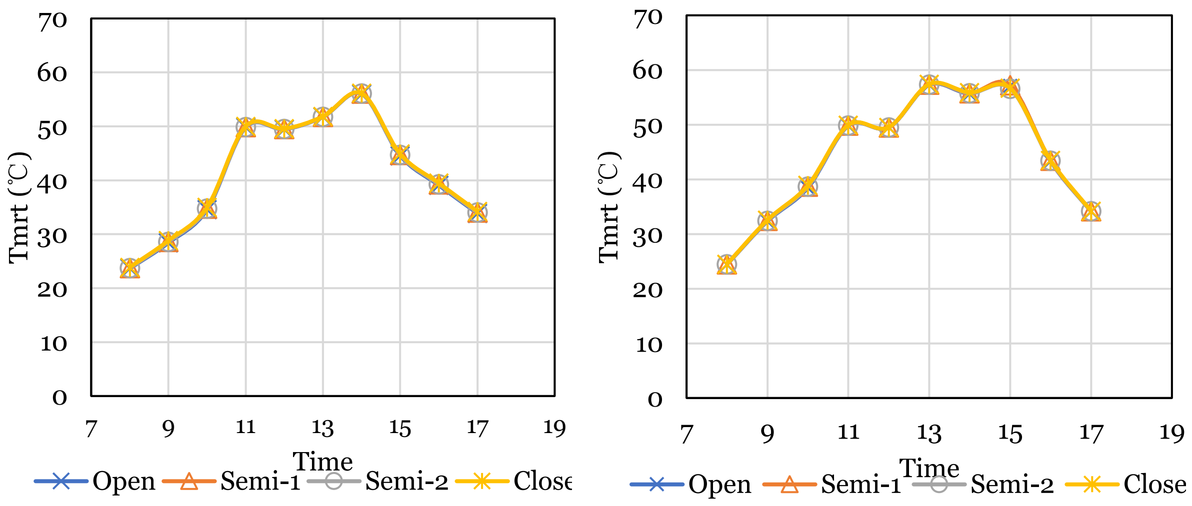


(c) E-W **(d) NW-SE**

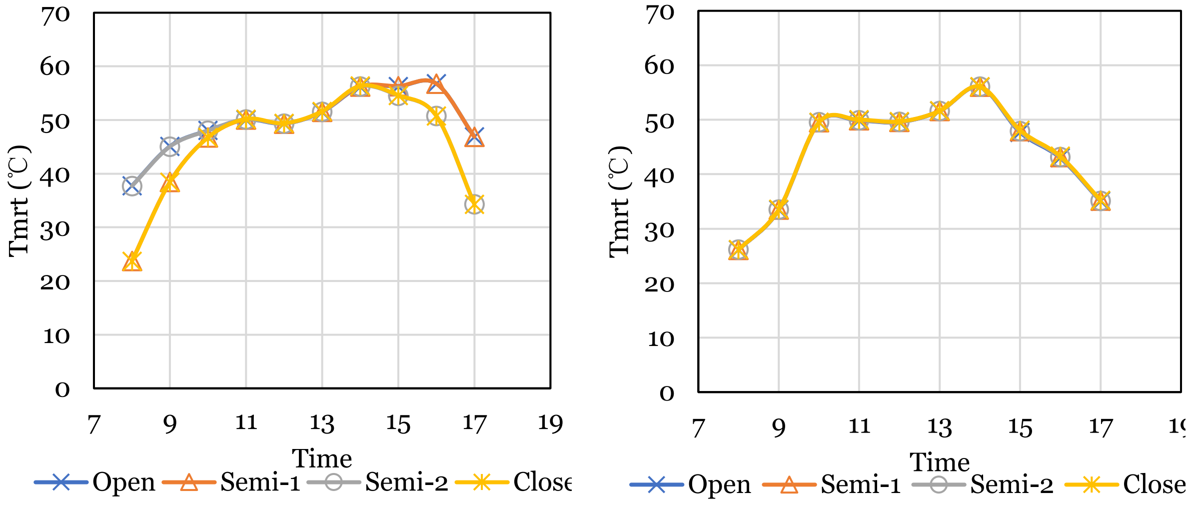
Figure 5.16 The temporal wind speed profile for different layout forms and orientations

As in the case of PET$_{SW}$, the *Tmrt* profiles associated with the four layout forms, as shown in Figure 5.17 (a), (b) and (d), were also very similar in non-E-W Streets. The differences in *Tmrt* values among different layout forms were less than 0.5°C despite the *Tmrt* values attributed to the open layout being always slightly lower than others for all four orientations. This could be explained by the highest wind speed attributed to the open layout form.

Figure 5.17 (c) shows that the *Tmrt* values of layout forms differed among different periods in E-W Street. Between 8:00-10:00, the close/semi-1 layout form yielded up to 14 °C lower in *Tmrt* values than the semi-2/open layout forms. Between 11:00-14:00, all building layouts yielded similar *Tmrt* values with maximum differences of only 0.2°C. This was probably due to direct sunlight penetrating through the street without obstruction at high solar altitudes. On the contrary, between 15:00-17:00, the semi-2/close layout forms yielded up to 12°C lower in *Tmrt* values than the semi-1/open layout forms. This was because the semi-2 and close layout form prevented the afternoon sunlight from the west direction.



(a)N-S **(b)NE-SW**



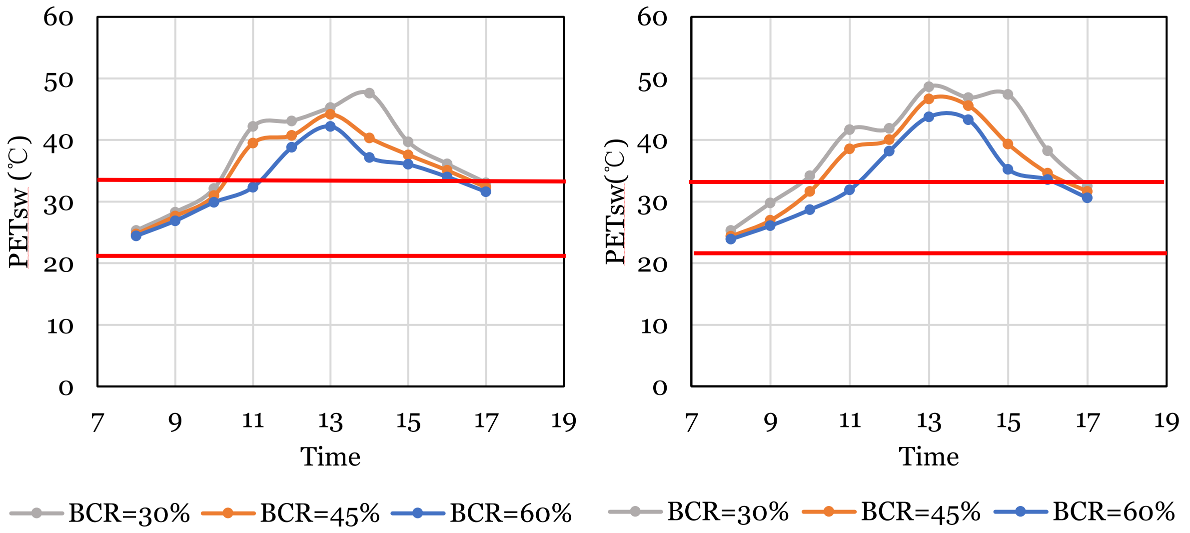
(c) E-W **(d) NW-SE**

Figure 5.17 The temporal *Tmrt* profiles for different layout forms and orientations

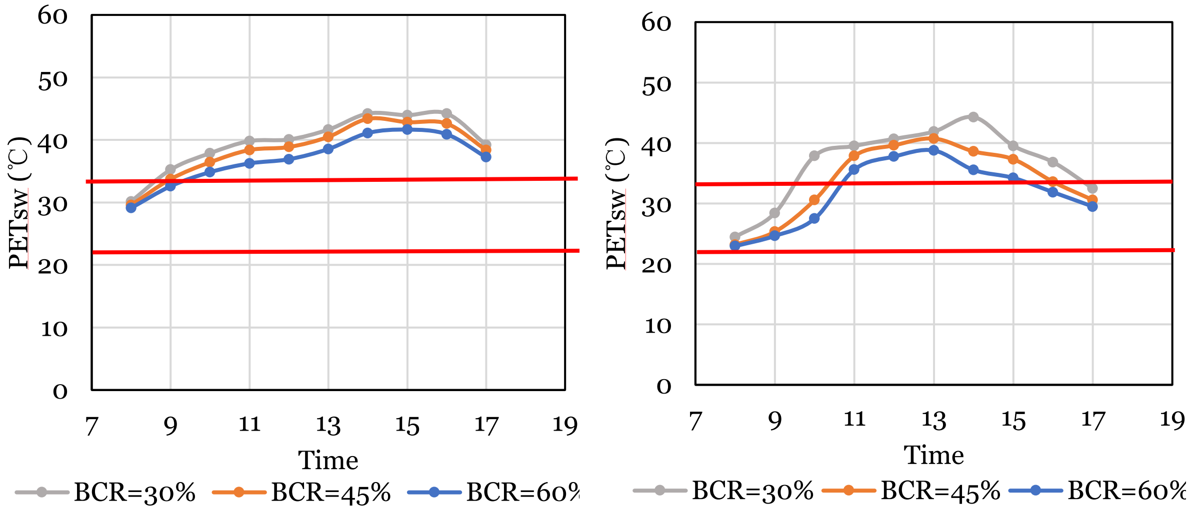
5.3.2.3 Neighborhood Compactness

Figure 5.18 shows the temporal PET_{SW} profiles for various BCRs and street orientations from 08:00 to 17:00. Similar to the SH/h profiles, the extents of temporal fluctuations of PET_{SW} values were much larger and more easily observed for non-E-W Streets (i.e. N-S, NE-SW and NW-SE Streets) than for E-W Street.

Notably, a higher BCR could produce better pedestrian thermal comfort during daytime for all street orientations as the PET_{SW} values decreased. The differences in PET_{SW} values between BCR=30 and 60% were quite significant in non-E-W Streets (i.e. up to 9.9°C at 11:00, 9.8°C at 11:00 and 10.4°C at 10:00 in the morning, and 10.4°C at 14:00, 12.1°C at 15:00 and 8.8°C at 14:00 in the afternoon in N-S, NE-SW and NW-SE Streets). In fact, raising BCR from 30 to 60% would lower the average PET_{SW} values by 4.0, 5.1 and 5.8°C in N-S, NE-SW, and NW-SE Streets respectively, which corresponds to an increase of their comfort duration by 2 hours. In comparison with Non-E-W Streets, the drop in the average PET_{SW} values in E-W Street were smaller with an average value of 2.7°C, which corresponded to an increase of comfort duration by 1 hour. The E-W orientation has the shortest comfort duration regardless of BCRs.



(a)N-S **(b)NE-SW**

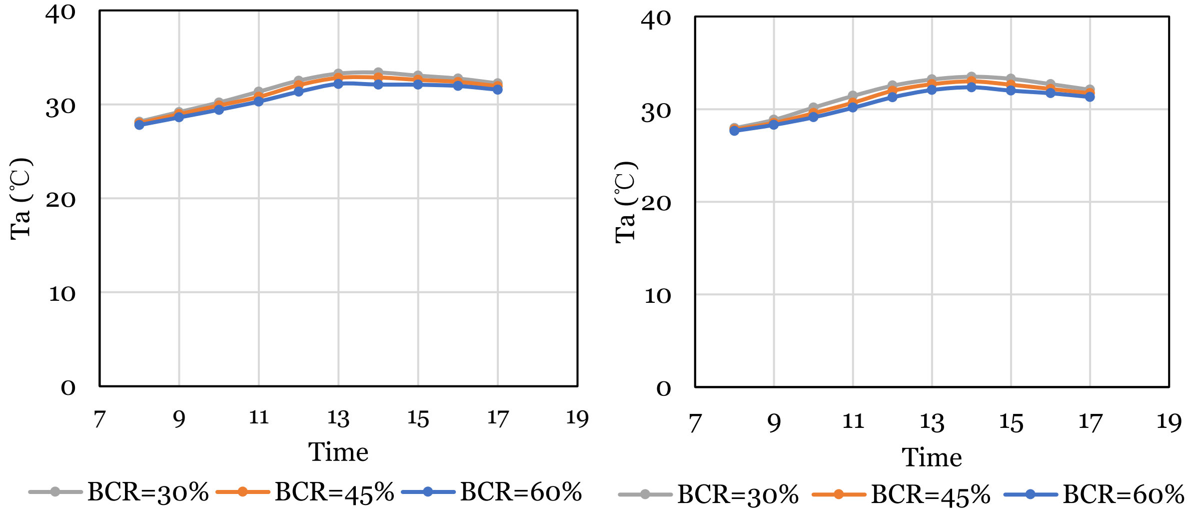


(c) E-W **(d) NW-SE**

Note: Red lines denote the boundary values of comfort with PET values of 21°C and 33°C

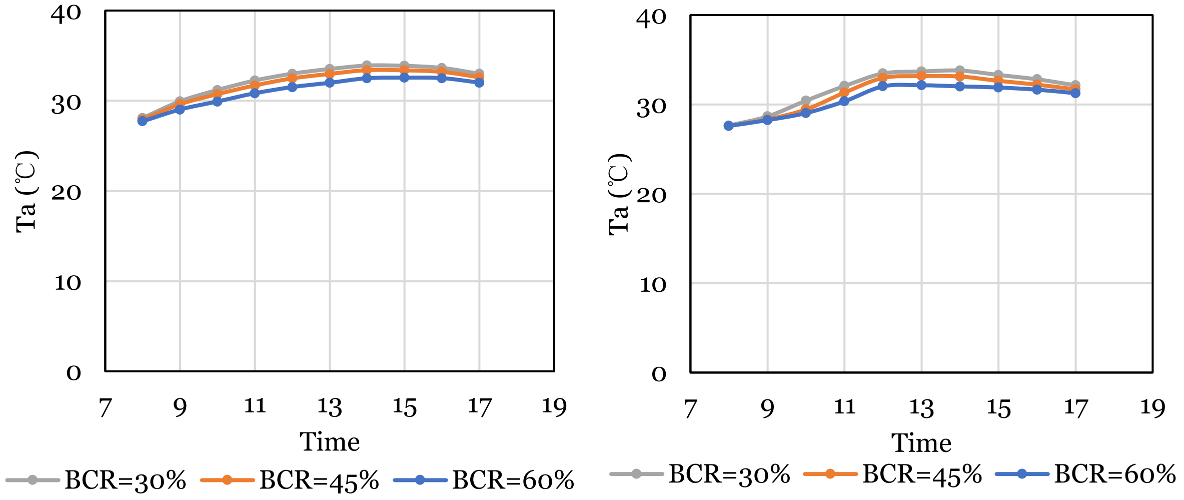
Figure 5.18 The temporal PET_{SW} profiles for different BCRs and orientations

As shown in Figure 5.19, the temporal *Ta* profiles were similar for different BCRs and orientations. The *Ta* values also only slightly decreased as BCR increased over the whole period. The maximum *Ta* difference was only 0.6, 0.7, 0.5 and 1.0°C at 10:00 or 11:00 for N-S, NE-SW, E-W and NW-SE Streets. This was probably due to smaller solar exposed areas in narrower street configurations.



(a)N-S

(b)NE-SW

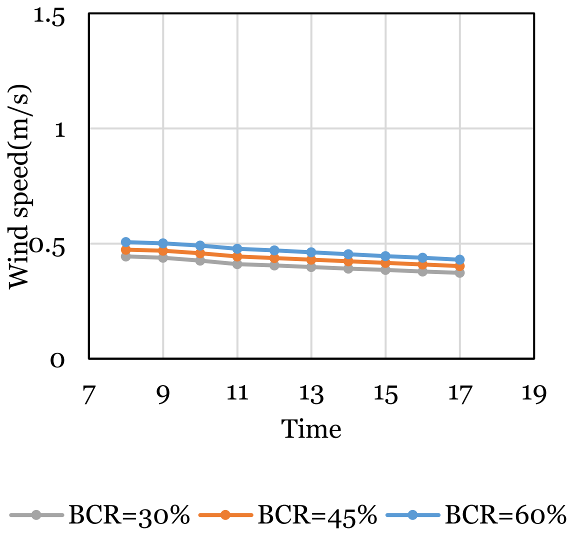


(c) E-W

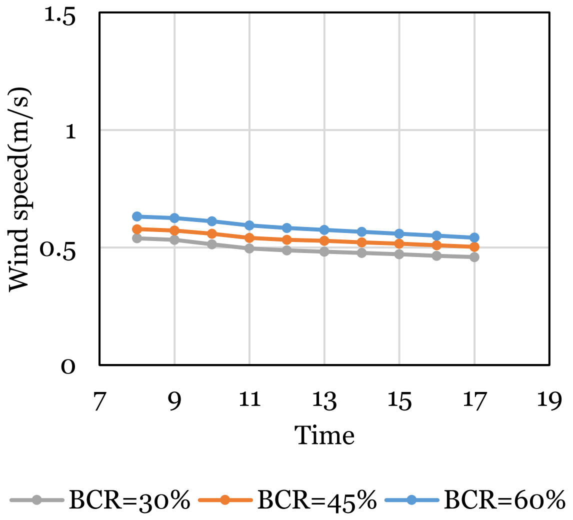
(d) NW-SE

Figure 5.19 The temporal *Ta* profiles for different BCRs and orientations

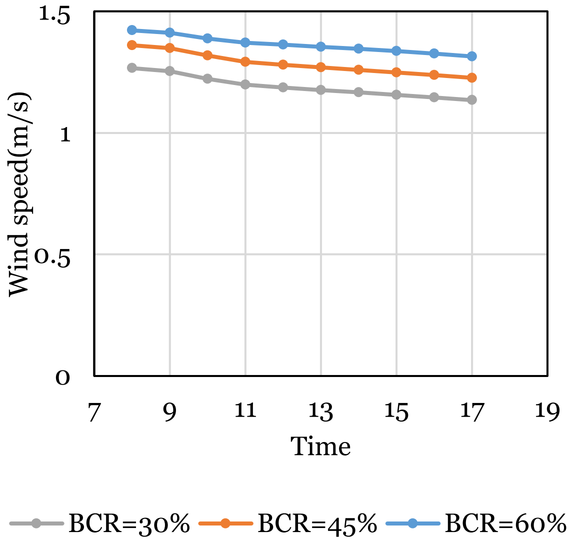
Figure 5.20 shows that the wind speeds at BCR=60% were 0.1-0.2 m/s higher than those at BCR=45 or 30%. This was probably due to the channeling effect in narrower street configurations. For different orientations, the wind speeds of all the studied BCR scenarios were found to be higher in E-W and NW-SE Streets than NE-SW and N-S Streets.



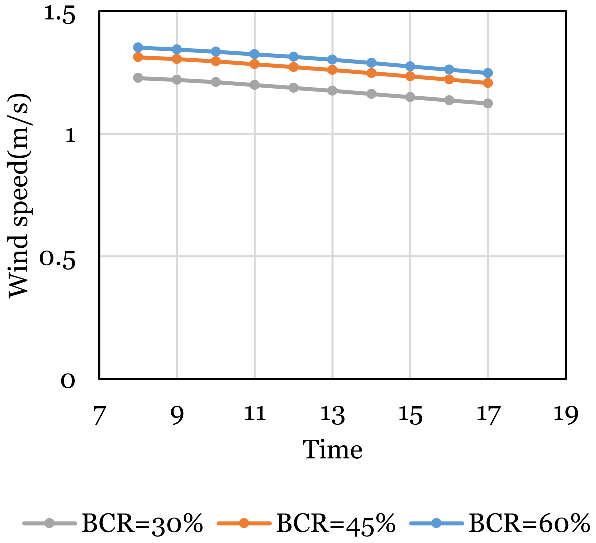
(a)N-S



(b)NE-SW



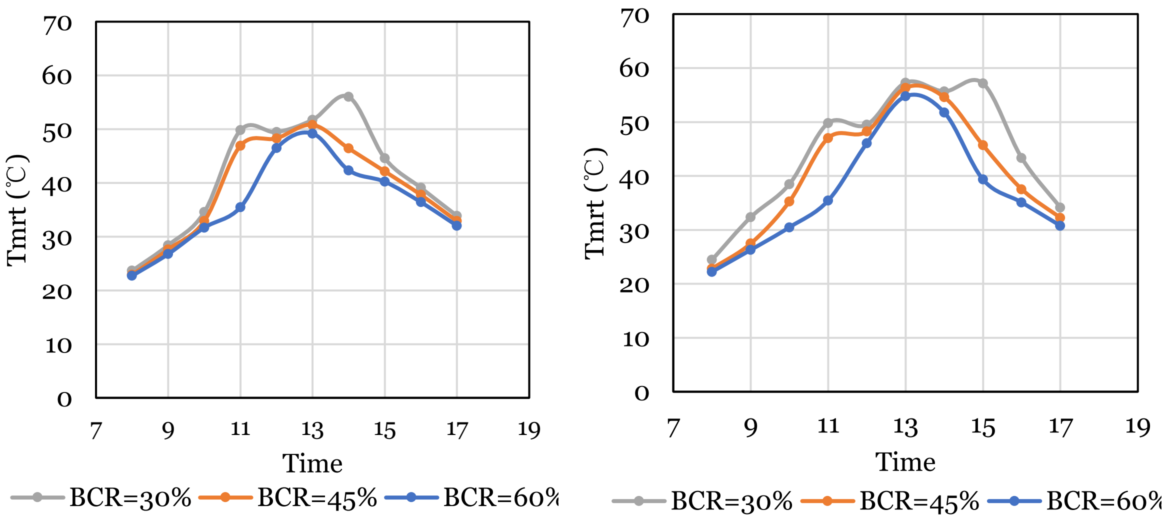
(c) E-W



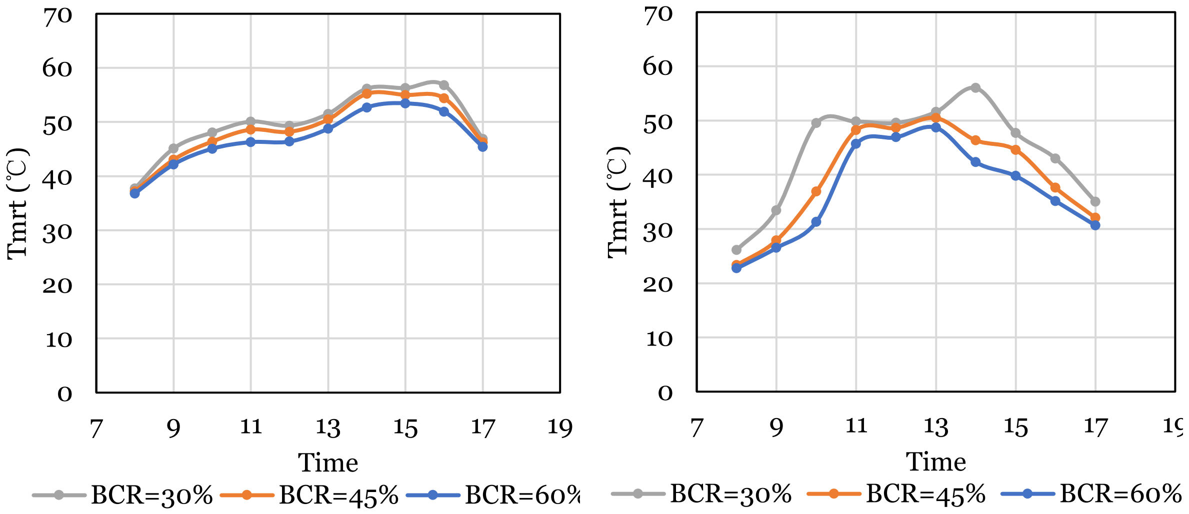
(d) NW-SE

Figure 5.20 The temporal wind speed profile at different BCRs for four orientations

The temporal *Tmrt* profiles of different BCRs and street orientations were found to be similar to their temporal PET_{SW} profiles. As seen in Figure 5.21, a higher BCR would lead to a lower *Tmrt* value. If the BCR increased from 30 to 60%, significant drops in *Tmrt* values were found to be 14.3, 14.4 and 18.2°C for N-S, NE-SW and NW-SE Streets respectively at 10:00 and 11:00, and 13.7, 17.8 and 13.7°C at 14:00 or 15:00. Smaller drops in *Tmrt* values (i.e. 1°C - 8.0°C) were observed at the other periods. As for E-W Street, the maximum *Tmrt* drop was 4.9°C at 16:00, which was much lower than those of non-E-W Streets.



(a)N-S **(b)NE-SW**



(c) E-W **(d) NW-SE**

Figure 5.21 The temporal *Tmrt* profiles for different BCRs and orientations

5.3.3 Prediction Models of Thermal Comfort of a Street Segment

In addition to reveal the effect of neighborhood morphological attributes, multivariate regression models have been constructed to predict the $\mathrm{PET}_{\mathrm{SW}}$ values of a street segment from the microclimatic conditions and neighborhood morphological attributes. Separate models have been constructed for E-W and non-E-W Streets in view of substantial differences being observed in temporal $\mathrm{PET}_{\mathrm{SW}}$ profiles for SH/h ratios and BCRs and $\mathrm{PET}_{\mathrm{SW}}$ variations among building layout forms between E-W Street and non-E-W Streets.

The studied factors include the computed PET_{SW} values as the dependent variable, and hourly microclimate factors (i.e. air temperature (AT), relative humidity (RH), solar radiation (SR) and solar altitude (SA), which were the input meteorological conditions), and neighborhood morphological attributes (i.e. BCR, SH/h ratio, and BL) as independent variables. Only the main effects of these factors were studied in the model. The formulated models bear the following form:

$$PET_{SW} = B_0 + B_{SA}X_{SA} + B_{AT}X_{AT} + B_{RH}X_{RH} + B_{SR}X_{SR} + B_{BCR}X_{BCR} + B_{SH/\hbar}X_{SH/\hbar} + \left\{\begin{array}{c} B_{semi-1}X_{semi-1} \\ B_{semi-2}X_{semi-2} \\ B_{close}X_{close} \end{array}\right. \tag{5.3}$$

where X_{SA}, X_{AT}, X_{RH}, X_{SR}, X_{BCR} and $X_{SH/h}$ are the values of solar altitudes, air temperature, relative humidity, solar radiation, BCR and SH/h ratio; $X_{semi\text{-}1}$, $X_{semi\text{-}2}$ and X_{close} denote various building layout forms (semi-1, semi-2 and close respectively), which are dummy variables with values of 0 and 1; *B*'s are the coefficient estimates of the independent variables.

Prior to the model formulation, assumptions regarding normality, linearity, homoscedasticity and the absence of multi-collinearity had been thoroughly checked (Poole and O'Farrell, 1971; Uyanık and Güler, 2013; Vaus, 2002). The variables of relative humidity and solar radiation were omitted due to multi-collinearity with air temperature and solar altitude respectively (Pearson correlation *R*-value between air temperature and relative humidity = 0.973; Pearson correlation *R*-value between solar radiation and solar altitude = 0.926). Table 5.4 lists the unstandardized and standardized coefficient estimates (B and β) of all the significant factors for E-W and non-E-W orientations ($p<0.05$). Only those significant factors ($p < 0.05$) were included in the model formulation. The R^2 values of regression models for E-W and non-E-W orientations were 0.77 and 0.87, suggesting that all the formulated models can portray the PET_{SW} values reasonably well. All the studied microclimatic factors and urban morphological factors were found to be significant predictors for both models.

Table 5.4 The unstandardized and standardized coefficient estimates (*B and β*) of the PET_{SW} prediction models

	Orientation	**Non-E-W Streets**		**E-W Street**	
		B	*β*	*B*	*β*
	Constant (B_o)	-39.0		-32.57	
Microclimate	SA	0.174	0.505	0.047	0.171
	AT	2.355	0.516	2.43	0.663
Neighborhood morphological attributes	BCR	-14.05	-0.259	-9.483	-0.218
	SH/h	-2.718	-0.255	-3.295	-0.385
	BL(Base-Open)				
	Semi-1	0.357	0.023	-0.956	-0.078
	Semi-2	0.298	0.019	-0.769	-0.062
	Close	0.706	0.046	-1.697	-0.138

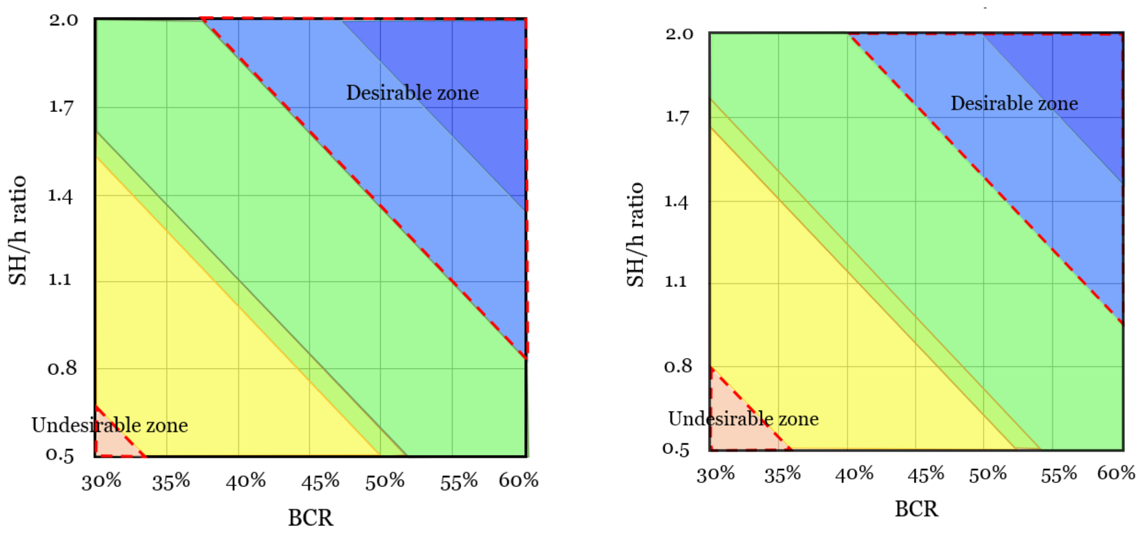
A positive sign of the coefficient estimate in the prediction model implies that the value of the independent variable varies directly with the value of the dependent variable. Conversely, a negative coefficient sign implies that the value of the independent variable varies inversely with the value of the dependent variable. Generally, PET_{SW} varied inversely with BCR and SH/h ratio. The higher the BCR or SH/h ratio, the lower the PET_{SW} values, and vice versa. In line with the findings in Section 5.3.2, the open and close layout form would produce lower PET_{SW} values in non-E-W Streets and E-W Street respectively.

In addition, the relative influence of individual factors can be determined by comparing the absolute values of standardized coefficients (Uyanık and Güler, 2013; Vaus, 2002). The most influential factor is the one having the highest absolute value. For non-E-W Streets, BCR was slightly more influential than SH/h ratio, and building layout was the least influential (i.e. 0.259>0.255>0.046). For E-W Street, the most influential factor was SH/h ratio, followed by BCR, and the least was building layout (i.e. 0.385>0.218>0.138).

5.3.4 Effects of combinations of neighborhood morphological attributes on the thermal comfort of a street segment

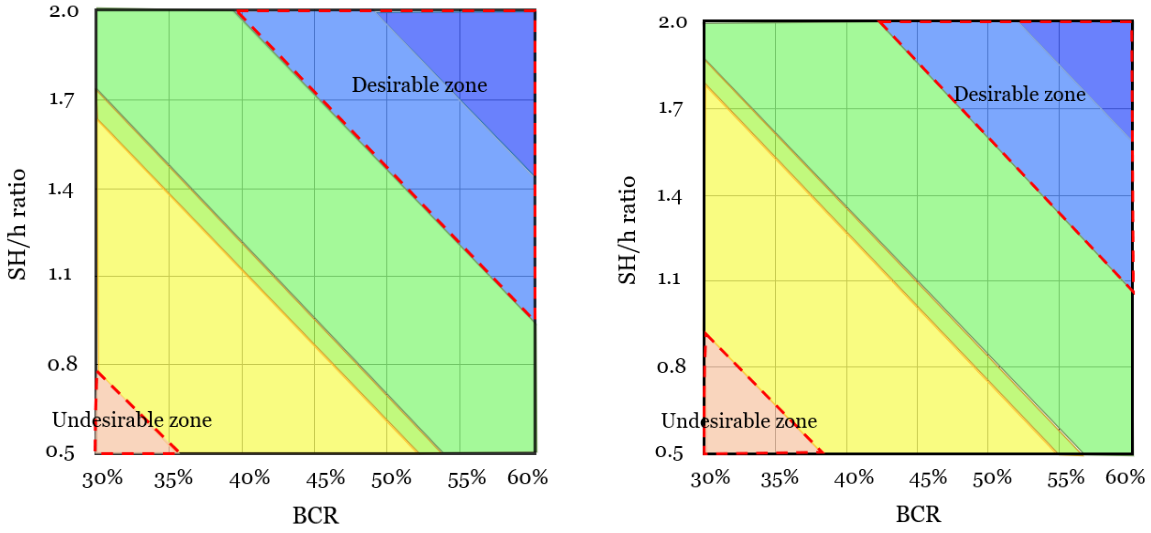
All the different combinations of the investigated ranges of BCR and SH/h ratios, layout forms and street orientations were input to the formulated models to predict the corresponding hourly PET_{SW} values during daytime. The input ranges of values of BCR and SH/h were 30 to 60% and 0.5 to 2.0 respectively, while the layout forms and street orientations were open, semi-1, semi-2 and close, and non-E-W and E-W respectively. The total numbers of comfort hours (i.e. PET_{SW} = 21 - 33°C) and very hot hours (i.e. PET_{SW}>41 °C) obtained during daytime were then determined for all the combinations of neighborhood configurations. Figure 5.22 depicts the charts showing the total number of comfort and very hot hours yielded by various combinations of BCR, SH/h ratios and layout forms for (a) non-E-W and (b) E-W Streets. In the following context, we only confined our discussions to "comfort conditions" (i.e. with at least 3 comfort hours and no very hot hours), and "highly discomfort conditions" (i.e. with 5 or more very hot hours). It can be observed that a number of configurations within specific ranges of BCR and/or SH/h ratios could yield comfort conditions (i.e. within the "zone of desirable thermal perception"), while the others would lead to highly discomfort conditions (i.e. within the "zone of undesirable thermal perception").

For non-E-W Streets, the open layout form was the most favorable (with the largest favorable and smallest undesirable zone areas), while the close layout form was the least desirable (with the smallest desirable and largest undesirable zone areas). In contrast, for E-W Streets, the close layout form was the most favorable (with the largest desirable and smallest undesirable zone areas), while the open layout form was the least favorable (with the smallest desirable and largest undesirable zone areas). It should be noteworthy pointing out that all the non-E-W Street configurations lying within the desirable zone could provide 4 - 5 comfort hours and no very hot hours, while most of the E-W Street configurations lying within the desirable zone could yield only 3 comfort hours and no very hot hours. Exceptions were found in E-W Street with the close layout form when BCR > 57% and SH/h ratio > 1.9, which could produce 4 or 5 comfort hours and no very hot hours.



(i) Open

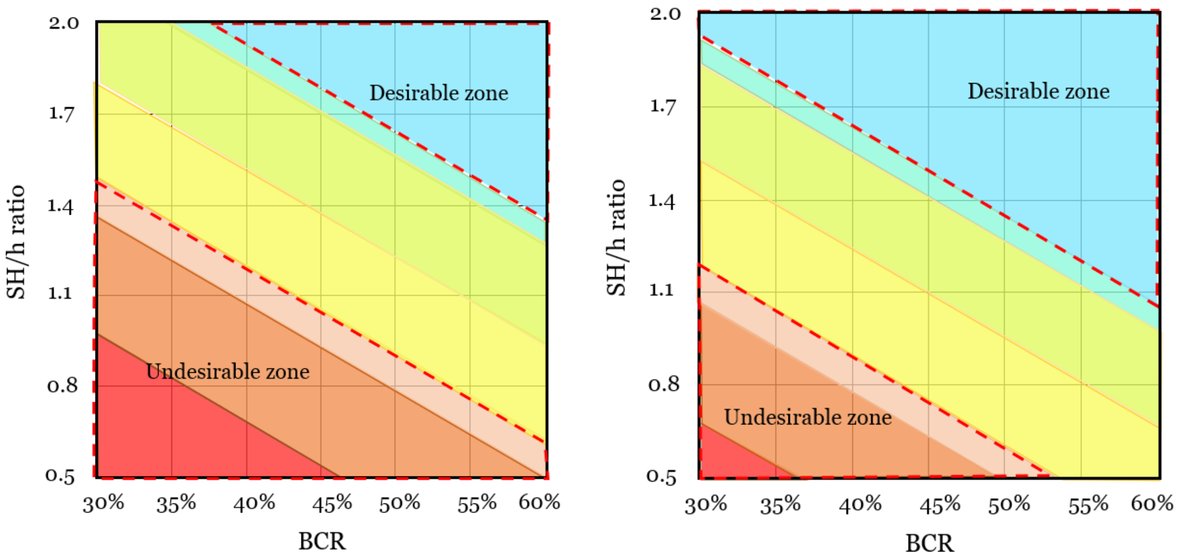
(ii) Semi-1



(iii) Semi-2

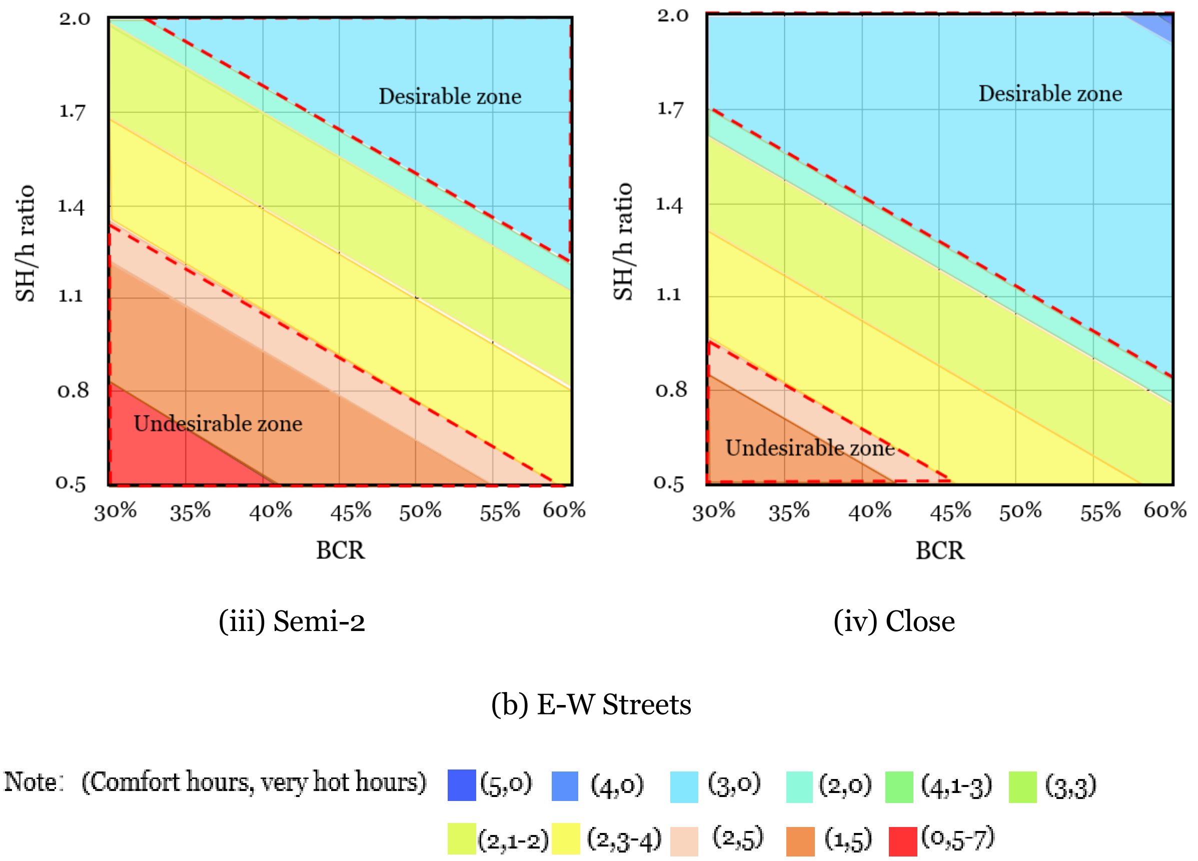
(iv) Close

(a) Non-E-W Streets



(i) Open

(ii) Semi-1



(iii) Semi-2

(iv) Close

(b) E-W Streets

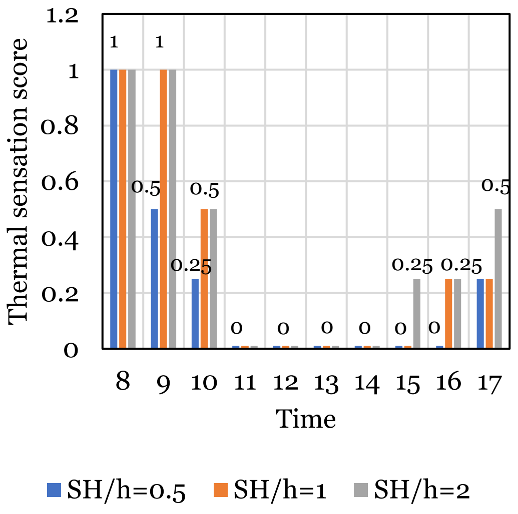
Figure 5.22 Charts showing the total number of comfort and very hot hours yielded by different combinations of neighborhood morphological attributes for (a) non-E-W and (b) E-W Streets

5.3.5 Effects of neighborhood morphological attributes on pedestrian comfort of a street segment

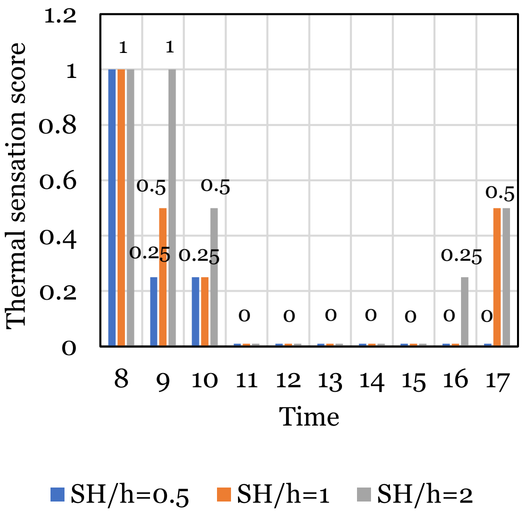
Based on the comprehensive thermal comfort analysis in previous sections, this section further analyzed how neighborhood morphological attributes affected pedestrian comfort of a street segment.

5.3.5.1 Surrounding Building Height Configuration

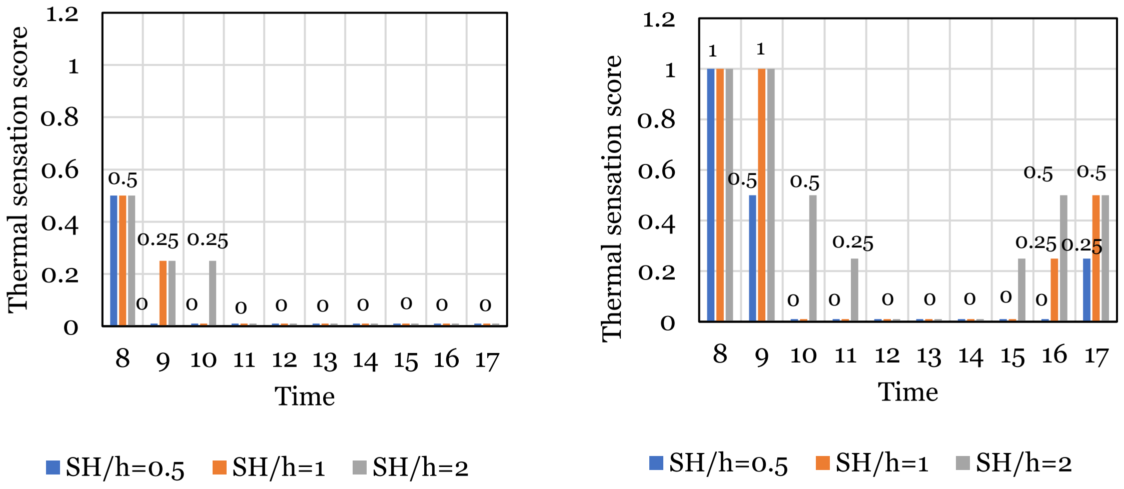
Thermal sensation and PAQ of a street segment are expected to vary with SH/h ratio. SH/h=2.0 generally yielded the highest thermal sensation scores at four orientations. (i.e. the average thermal sensation scores=0.35, 0.3, 0.20 in N-S Street; 0.33, 0.23, 0.15 in NE-SW Street; 0.10, 0.08, 0.05 in E-W Street; 0.40, 0.28, 0.18 in NW-SE Street (See Figure 5.23 and 5.10)). However, the PAQ scores did not vary with SH/h ratio (i.e. the PAQ scores=0 with the highest wind speed of 0.45, 0.55, 1.32, 1.28m/s, for N-S NE-SW E-W NW-SE Streets (See Figure 5. 12)).



(a)N-S



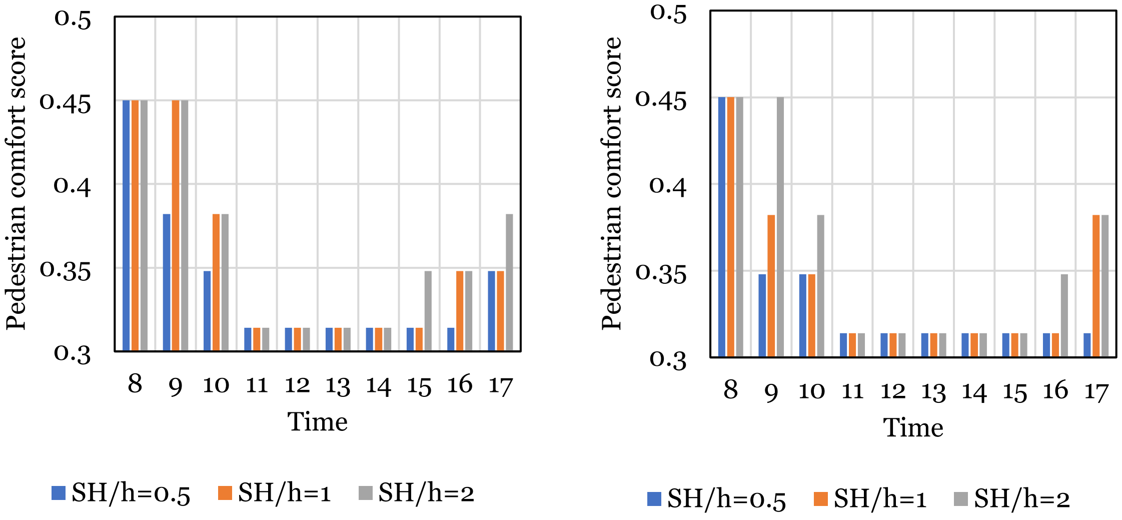
(b)NE-SW



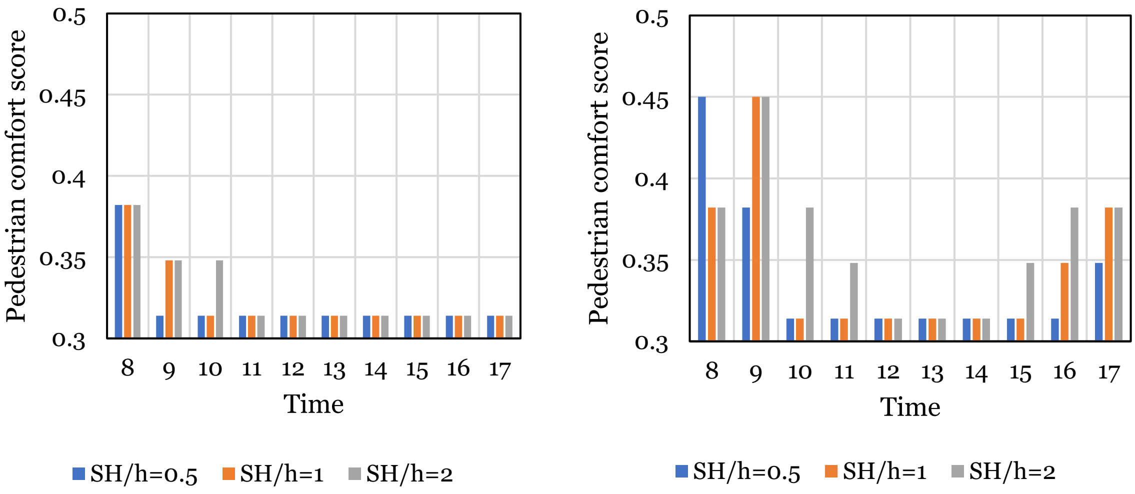
(c) E-W **(d) NW-SE**

Figure 5.23 The hourly thermal sensation scores for different SH/h ratios and orientations

Due to the thermal sensation score variation with SH/h ratios, it was found that SH/h=2 produced the higher pedestrian comfort level than SH/h=1 and 0.5 for all orientations. (i.e. average pedestrian comfort scores=0.36, 0.35, 0.34 in N-S Street; 0.36, 0.34, 0.33 in NE-SW Street; 0.33, 0.32, 0.32 in E-W Street; 0.37, 0.35, 0.34 in NW-SE Street (See Figure 5.24)). When SH/h ratio increased from 0.5 to 2, the maximum hourly pedestrian comfort score increases would be 17.8% (0.07/0.38 at 9:00) in N-S Street, 29.3% (0.10/0.35 at 9:00) at NE-SW Street, 10.8% (0.03/0.31 at 9:00 and 10:00) in E-W Street and 21.6% (0.07/0.31 at 10:00 and 16:00) in NW-SE Street



(a)N-S **(b)NE-SW**

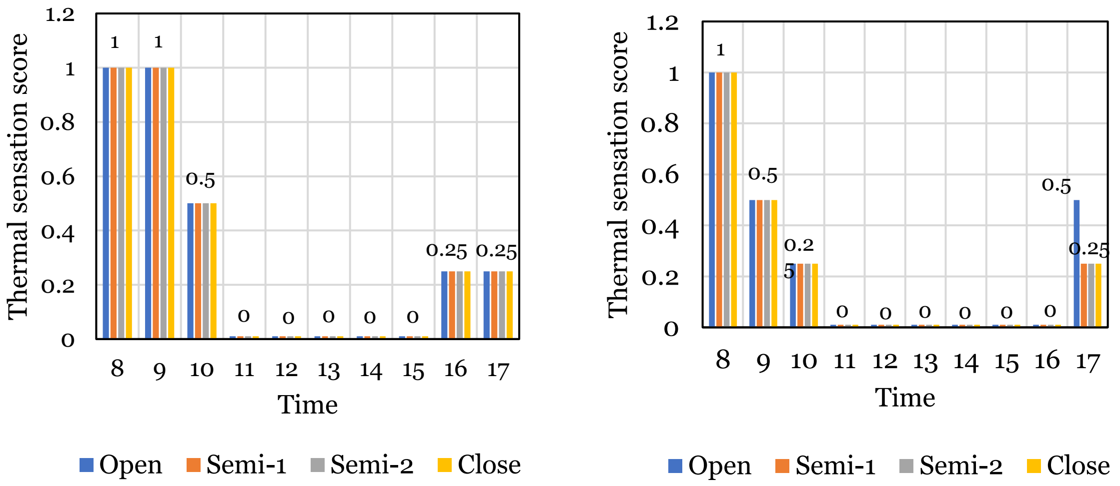


(c) E-W **(d) NW-SE**

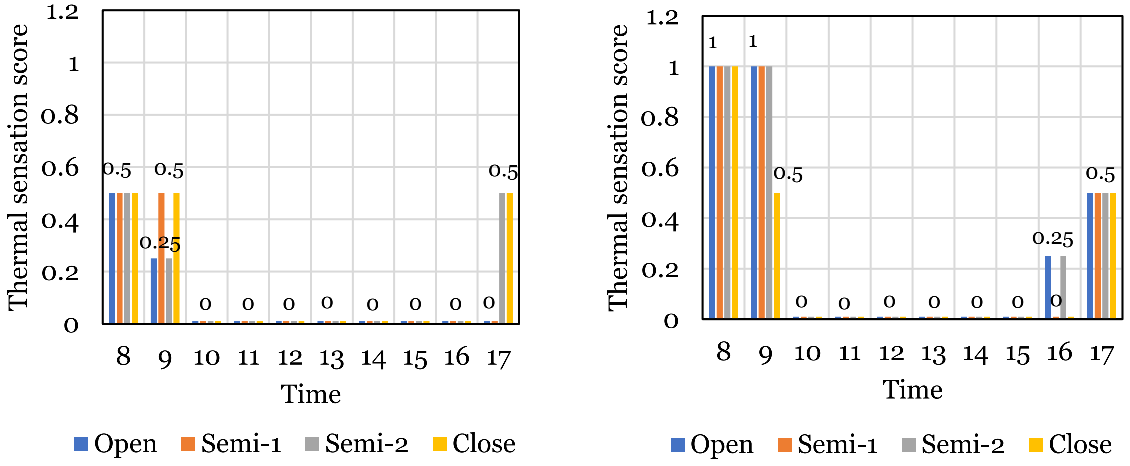
Figure 5.24 The hourly pedestrian comfort scores for different SH/h ratios and orientations

5.3.5.2 Surrounding Building Layout

Surrounding building layout is expected to bring changes in both thermal sensation and PAQ at a street segment. At non-E-W orientations, open layout form always yielded the highest thermal sensation scores (i.e. the average thermal sensation scores= 0.3 for four layout forms in N-S Street; 0.23, 0.20, 0.20, 0.20 in NE-SW Street; 0.28, 0.25,0.28, 0.20 for open, semi-1, semi-2 and close layout form in NW-SE Street (See Figure 5.25 and 5.14)). However, at E-W orientation, close layout form produced better thermal sensation than other three layout forms (i.e. the average thermal sensation scores= 0.08 ,0.1, 0.13 0.15 for open, semi-1, semi-2 and close layout forms). However, the PAQ scores of surrounding building layouts were similar for all orientations (i.e. the PAQ scores=0 with the highest wind speed of 0.44, 0.54, 1.27, 1.23 m/s for N-S, NE-SW, E-W, NW-SE Streets (See Figure 5. 16).



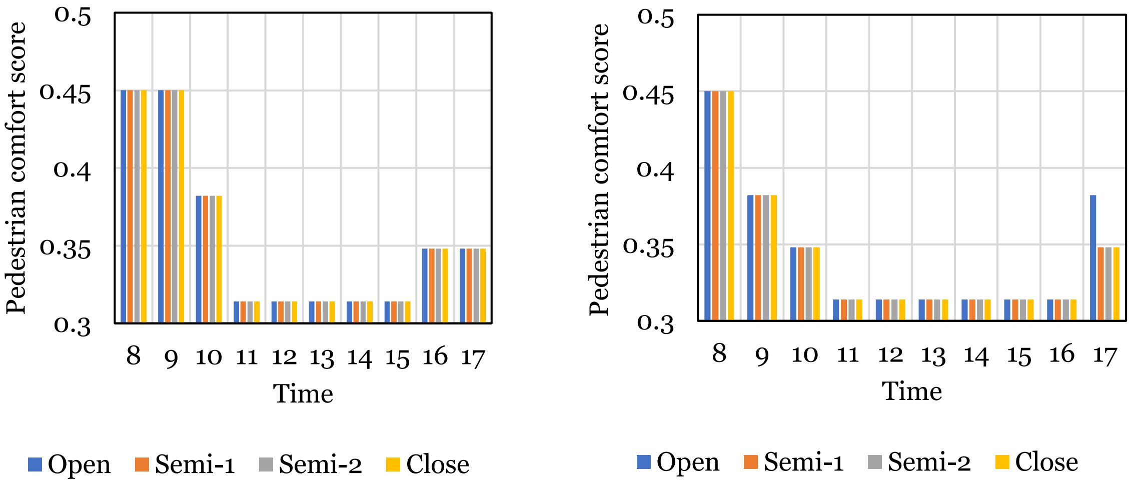
(a)N-S **(b)NE-SW**



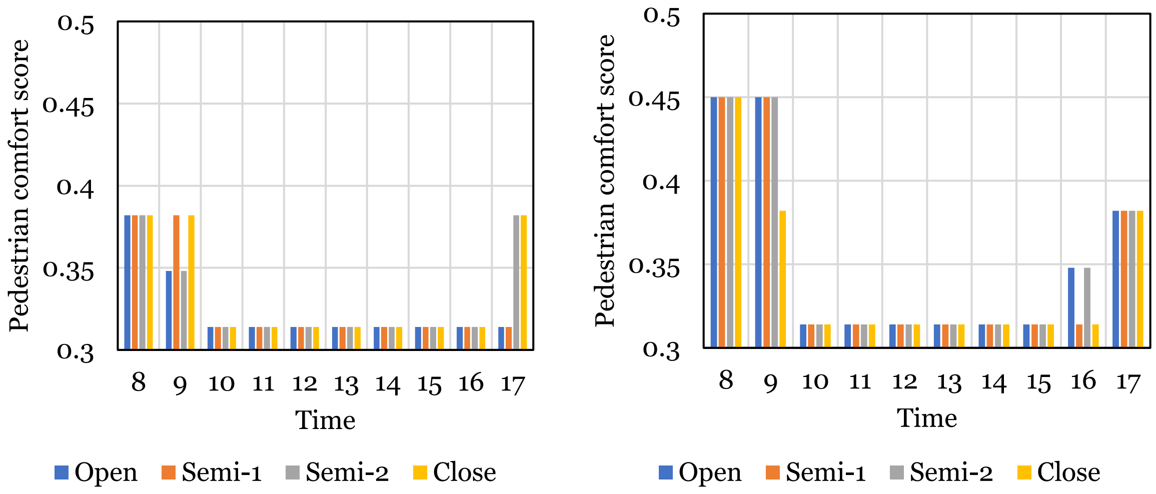
(c) E-W **(d) NW-SE**

Figure 5.25 The hourly thermal sensation scores for different surrounding building layouts and orientations

As shown in Figure 5.26, open layout form always yielded the highest pedestrian comfort level in non-E-W Streets, while close layout form always yielded the highest pedestrian comfort level in E-W Street (i.e., the average pedestrian comfort scores= 0.35 for four layout forms in N-S Street; 0.35, 0.34, 0.34, 0.34 in NE-SW Street; 0.32, 0.33, 0.33, 0.34 in E-W Street; 0.35, 0.35, 0.35, 0.34 in NW-SE Street for open, semi-1 and semi-2, and close layout form). When building layout varied, the hourly pedestrian comfort score would vary by up to 9.7% (0.03/035 at 17:00) in NE-SW Street, 21.6% (0.07/0.31 at 17:00) in E-W Street and 17.8% (0.07/0.38 at 9:00) in NW-SE Street. Most importantly, the pedestrian comfort score variations due to the change of building layout form were only attributed to variations of thermal sensation scores.



(a)N-S **(b)NE-SW**

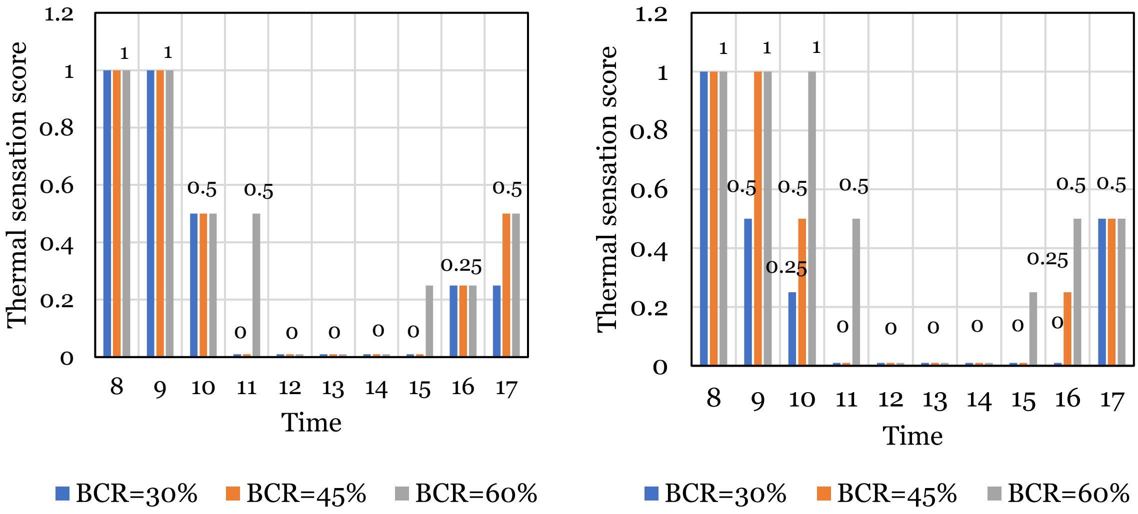


(c) E-W **(d) NW-SE**

Figure 5.26 The hourly pedestrian comfort scores for different surrounding building layouts and orientations

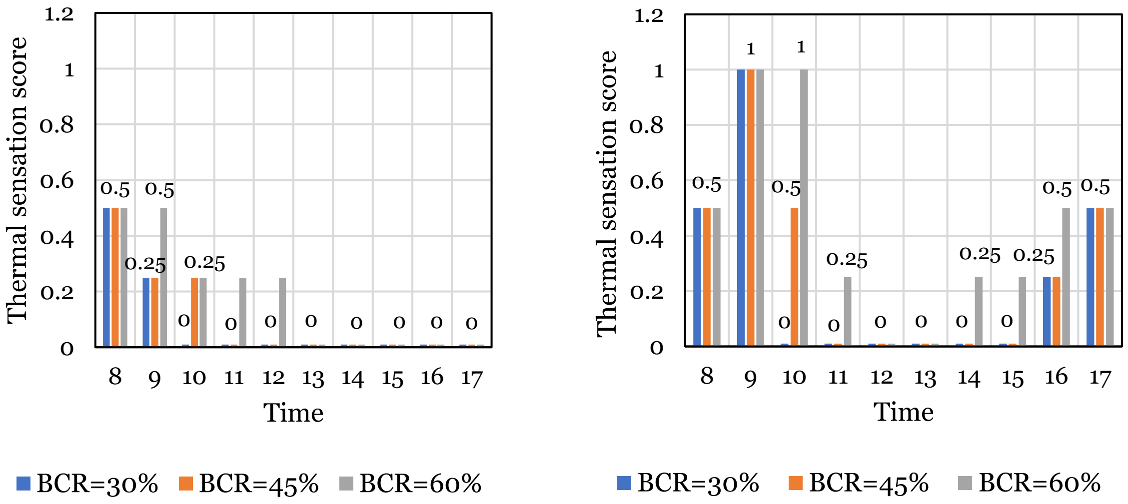
5.3.5.3 Neighborhood Compactness

Thermal sensation, PAQ and noise annoyance of a street segment are expected to vary with BCR. BCR=60% always produced the better thermal sensation than BCR= 45% and 30% at four orientations (i.e., the average thermal sensation scores= 0.40, 0.33, 0.30 in N-S Street; 0.48, 0.33, 0.23 in NE-SW Street; 0.18, 0.10, 0.08 in E-W Street; 0.43, 0.28, 0.23 in NW-SE Street (See Figure 5.27 and 5.18)). Conversely, the noise annoyance scores of BCR=30 and 45% were similar, but higher than that of BCR=60% (i.e. the average noise annoyance scores= 0.4, 0.4, 0.33 (See Figure 5.28(a)). In addition, the PAQ scores did not vary significantly with BCRs for all orientations (i.e. the PAQ scores=0 with the highest wind speed of 0.51, 0.63, 1.42, 1.35m/s for N-S, NE-SW, E-W, NW-SE Streets) (See Figure 5.20).



(a)N-S

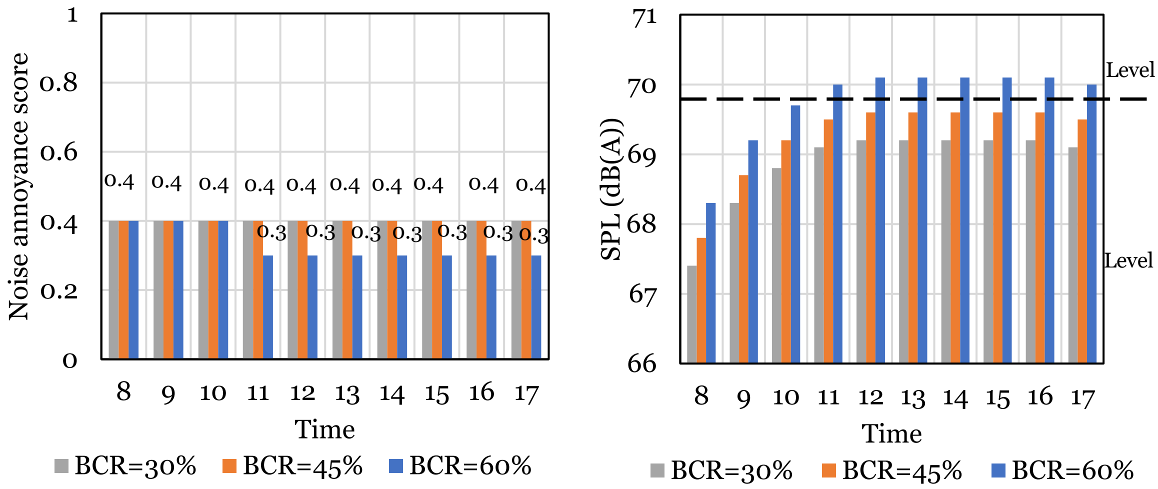
(b)NE-SW



(c) E-W

(d) NW-SE

Figure 5.27 The hourly thermal sensation scores for different BCRs and orientations



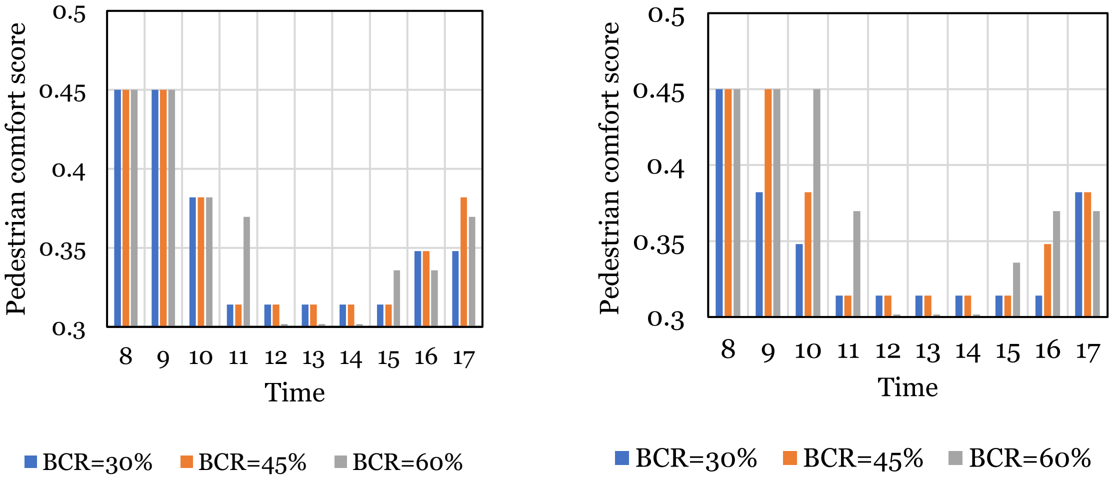
(a) Noise annoyance scores (b) SPL values

Figure 5.28 The hourly (a) noise annoyance scores and (b) SPL values for different BCRs and orientations

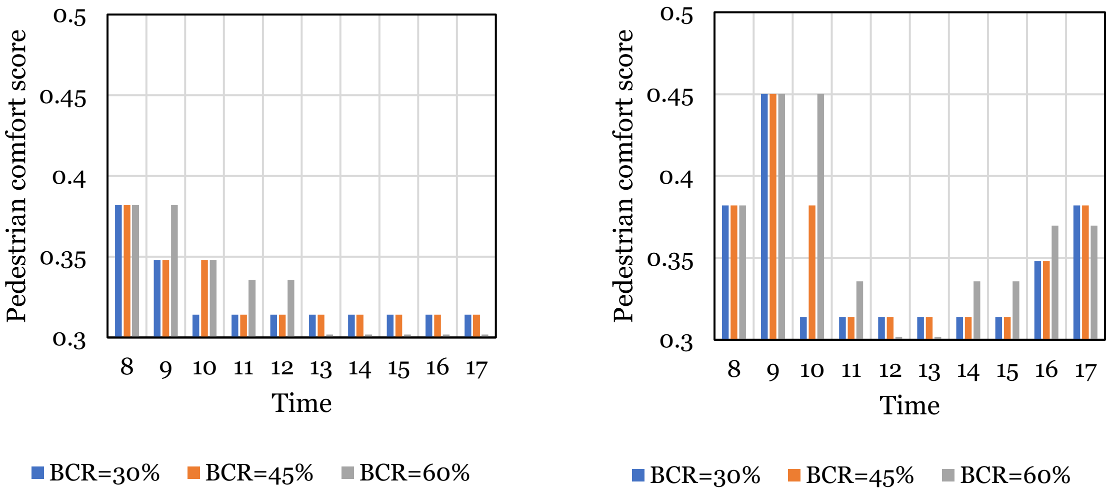
In Figure 5.29, it was found that the BCR yielding the highest pedestrian comfort score was different at different periods. At N-S orientation, BCR=60% produced the most comfortable walking environment at 8:00-11:00 and 15:00 (i.e. the average pedestrian comfort scores= 0.40, 0.38, 0.38), while BCR=45 and 30% produced the more comfortable walking environment than BCR=60% at 12:00-14:00 and 16:00-17:00 (i.e. the average pedestrian comfort scores= 0.33, 0.33, 0.32). At NE-SW orientation, BCR=60% yielded the best pedestrian comfort at 8:00-11:00 and 15:00-16:00 (i.e. the average pedestrian comfort scores=0.40, 0.38, 0.35), while BCR=45 and 30% yielded the best overall comfort at 12:00-14:00 and 17:00 (i.e. the average pedestrian comfort scores= 0.33, 0.33, 0.32). At E-W orientation, BCR=60% produced the best pedestrian comfort at 8:00-12:00 (i.e. average pedestrian comfort scores=0.36, 0.34, 0.33), while BCR=45 and 30% produced better pedestrian comfort at 13:00-17:00 (i.e. the average pedestrian comfort scores= 0.31, 0.31, 0.30). At NW-SE orientation, BCR=60% exerted the highest pedestrian comfort score at 8:00-

11:00 and 14:00-16:00 (i.e. the average pedestrian comfort scores= 0.38, 0.36, 0.35), while BCR=45 and 30% exerted higher pedestrian comfort score at 12:00-13:00 and 17:00 (i.e. the average pedestrian comfort scores= 0.34, 0.34, 0.32).

When BCR varied, the hourly pedestrian comfort scores would vary by up to 17.7% (0.06/031 at 11:00) in N-S Street, 29.3% (0.10/0.35 at 10:00) in NE-SW Street, 10.8% (0.03/0.31 at 10:00) in E-W Street and 43.3% (0.13/0.31 at 10:00) in NW-SE Street. Noticeably, the variations of pedestrian comfort score due to changes in BCR were attributed to the combined variations of thermal sensation and noise annoyance scores. Hence, thermal sensation played a more significant role on pedestrian comfort than noise annoyance (i.e. the average pedestrian comfort score due to thermal sensation and noise annoyance would increase by up to 0.014, 0.034, 0.014, 0.027 for N-S, NE-SW, E-W, NW-SE, respectively, and 0.004 for all four orientations).



(a)N-S **(b)NE-SW**



(c) E-W **(d) NW-SE**

Figure 5.29 The hourly pedestrian comfort scores for different BCRs and orientations

5.4 Summary of this chapter

This chapter investigates the effects of neighborhood morphological attributes on the thermal comfort as well as pedestrian comfort of a street segment. The findings provide urban planners with suggestions to create comfortable streets. Some interesting findings are going to be discussed in detail as follows:

First, thermal comfort and pedestrian comfort of a street segment would vary considerably with the neighborhood morphological attributes. The maximum PET reductions achieved by changes in SH/h ratio, BCR and building layout form were found to be 10.0°C, 12.1°C and 6.5°C respectively, while the maximum pedestrian comfort score increases were observed to be 29.3%, 43.3% and 21.6%.

Second, the effects of neighborhood morphological attributes on the thermal comfort of a street segment under different street orientations were revealed. (i) A higher SH/h ratio would lead to a lower PET value for all orientations, which was in line with Chen et al. (2021)'s finding that the thermal comfort conditions in center area would be poorer for the configuration with the surrounding building height being lower than the center area as compared with the uniform building configuration. (ii) Higher BCR would improve the thermal comfort for all orientations, which was also in line with the earlier findings which revealed that the thermal comfort of the whole neighborhood or center area would be improved with a more compact building form (Perini and Magliocco, 2014; Xuan et al., 2016). (iii) The close layout form, which was a variant of the courtyard layout, would produce better pedestrian thermal comfort in E-W Street, while open layout form performed better in non-E-W Streets. This was in line with the earlier findings reported by Taleghani et al. (2015), and Othman and Alshboul (2020) that courtyard layout form yielded lower PET values than E-W linear layout/Street, while N-S linear layout/Street yielded lower PET values than courtyard layout.

Of paramount value of our findings is the capability to quantify the effects of neighborhood morphological attributes on the PET values of a street segment. The findings revealed that the amounts of PET variations due to changes in BCR and SH/h ratio were larger in non-E-W Streets than E-W Streets, but the trend was reversed for layout forms. The average PET value dropped by 4.6°C by raising BCR from 30 to 60% in non-E-W Streets, which was larger than 2.7° C in E-W Streets (with maximum drops of 12.1 vs 3.6°C). The average PET value also dropped by 5.1°C by raising SH/h ratio from 0.5 to 2 in non-E-W Streets, which was larger than 3.5°C in E-W Street (with maximum drops of 10.0 vs 6.6°C). Conversely, the amounts of average PET variations due to changes in layout form were slightly larger in E-W Street than non-E-W Streets (i.e. 1.8°C in E-W Street vs only 0.6°C in non-E-W Streets). Although the difference in the average values appealed to be small, the difference in the PET values due to variations in layout forms could amount to 6.5°C in E-W Street vs only 1.0 °C in non-E-W Streets.

Besides, upon closer examination, the amounts of hourly PET variations influenced by layout form in E-W Streets should not be overlooked. The variation of layout forms exerted much stronger impacts on the PET values during the early morning (08:00-10:00) and late afternoon periods (15:00-17:00) than midday (11:00-14:00) (i.e. the average PET variations of 3.1 and 3.3°C for morning and afternoon vs 0.2°C for midday). On the contrary, not many differences in the hourly PET values were observed due to a change of layout forms in non-E-W Streets throughout the daytime periods (i.e. average PET variation of 0.6°C). Noticeably, the revelation on considerable differences in the amount of PET variations between E-W and non-E-W Streets is not unique to the influences of neighborhood morphological attributes. Indeed, a similar phenomenon was also observed for the influences of a street geometry feature, i.e. H/W ratio (Ali-Toudert and Mayer, 2006; Galal et al., 2020; Srivanit and Jareemit, 2020).

Third, the models formulated in this part also allow the orders of relative influences of individual neighborhood morphological attributes on thermal comfort of a street segment to be compared. The orders were found to vary between E-W and non-E-W Streets. For E-W Streets, SH/h ratio was found to be more influential than BCR, followed by building layout.

This is generally in line with the previous findings derived from neighborhood or area-scale studies that building height and density/compactness exerted stronger influences than building layout on the thermal comfort of a neighborhood (Yang et al., 2017), and building height in a neighborhood exerted stronger influences than neighborhood compactness (Chen et al., 2021). However, for non-E-W Streets, BCR was found to be slightly more influential than SH/h ratio, and building layout was the least influential, which disagrees with the most dominant role of building height as concluded by Chen et al. (2021). Such divergences in conclusions between E-W and non-E-W Streets cannot be easily determined from the results derived from neighborhood or area-scale studies as orientation effects have often been shadowed in the average values.

A series of charts have been generated from the PET values computed for all the combinations of neighborhood morphological attributes to help visually determine the total number of comfort and very hot hours that will be yielded during daytime for a street segment being surrounded by different combinations of neighborhood morphological attributes (i.e. with specific BCR, street orientation, building layout form and SH/h ratios). The charts possess three key characteristics that can facilitate a quicker and more direct way of identifying the comfort and highly discomfort conditions caused by combinations of different neighborhood morphological attributes. (i) The proposed chart format enables 2 morphology (BCR and SH/h) and 1 time–scale factor (daytime hours) with continuous scales to be presented in the same chart as opposed to the format of line charts produced by Yin et al. (2019) which only allowed only one morphology factor together with daytime hours with continuous scales to be presented simultaneously. (ii) The total numbers of comfort and very hot hours for different combinations of morphological features can be readily read off from the charts, which should be more easily used by planners or designers than only the hourly comfort conditions yielded by various urban morphologies given by Rodríguez Algeciras et al. (2016) Balogun and Daramola (2019) and Srivanit and Jareemit (2020). (iii) The charts can help identify neighborhood configurations falling within not only zone of desirable thermal perception but also zone of undesirable thermal perception. This can help direct urban designers and planners to focus on identifying and handling configurations, which can provide comfortable thermal environments, as well as those which need to be improved.

Fourth, the information extracted from the charts can also provide valuable insights on improving the thermal comfort of a street segment. It can be determined that the thermal comfort of the street environment could still be substantially improved by increasing the SH/h ratio even if BCR, street orientation and building layout form have been fixed, which is more alike to the constraints faced by an urban street renewal project. In particular, at least 3 comfort hours could be achieved by raising the SH/h ratio to ≥ 1.8 when BCR ≥ 47%, irrespective of the street orientation and layout form. However, same comfort conditions could not be achieved by even raising the SH/h value to 2.0 for non-E-W Streets if BCR was lower than 37%, or for E-W streets with BCR < 32% and open or semi-2 layout. In such cases, supplementary measures like planting of trees, which was previously shown to be able to increase the number of comfort hours (Yang et al., 2017), can be employed to improve the thermal comfort of a street.

Finally, this part of the study successfully revealed the effect of neighborhood morphological attributes on the pedestrian comfort of a street segment. i) A higher SH/h ratio would provide a more comfortable walking environment for pedestrians at four orientations. ii) The open and close layout forms would yield higher pedestrian comfort levels in Non-E-W and E-W Streets respectively. iii) The BCR with the highest pedestrian comfort level varied with time and street orientation. iv) Thermal sensation was the most important criterion affecting pedestrian comfort among different individual neighborhood morphological attributes.

Chapter 6 Conclusions and Recommendations for Future Works

In this chapter, major findings arising from this study are summarized and recommendations for future works will be given.

6.1 Summary of findings and contributions

This thesis has investigated the relationships between street environment and pedestrian comfort for recreational walking and proposed a multivariate index to assess the pedestrian comfort of street environments by embracing built environment criteria (i.e. sidewalks, amenities and landscape) and micro-environment criteria (i.e. thermal sensation, PAQ and noise annoyance). In addition, this study applied the formulated pedestrian comfort index to reveal the composite effects of street and neighborhood morphological attributes, which exerted influences on multiple comfort-related environmental factors, on pedestrian comfort. These findings provide suggestions for urban planners to create comfortable streets.

In the first stage, this study successfully revealed the relationships between pedestrian comfort and street physical environment with the particular focus on recreational walking. A path model was formulated to identify the major built and micro- environmental features affecting pedestrian comfort for recreational walking and provide an integrated view on how various environmental factors affect pedestrian comfort in a street environment within a high-dense city. Next, the assessment framework was formulated by identifying the indicators of major comfort-related environmental criteria and eliciting their importance weightings. In addition, the formulated index was applied to analyze the effects of street morphological attributes on pedestrian comfort. Finally, our study systematically explored the effects of neighborhood morphological attributes on the pedestrian comfort of a street segment, as most previous studies related to neighborhood configuration focused on the scale of an area or neighborhood. Prior to pedestrian comfort, their effects on the thermal comfort of a street segment, which was the significant criterion, were revealed. A string of important findings arising from this thesis are summarized as follows:

(i) Understanding the interrelationships among recreational walking, pedestrian comfort, and street physical environment

A path model has been successfully constructed to acquire a better understanding on the interrelationships among the perceptual and objective micro- and built environmental features, pedestrian comfort, and recreational walk. Pedestrian comfort was identified to be influenced by both objective and subjective built environmental factors as well as micro-environmental factors such as noise, air quality and microclimate. Thermal sensation, perceived loudness and PAQ were found to mediate the associations between objectively measured parameters and pedestrian comfort. Thermal sensation was correlated with air temperature, wind speed and solar radiation, and perceived loudness was positively correlated with SPL values. In particular, PAQ in street canyons was found to be positively correlated with wind speed in our study, which added new knowledge as there are still no fully established relationships between PAQ and specific indicators up to now. Moreover, our findings also revealed that the effect of the satisfaction of built environment on pedestrian comfort was comparable to the aggerated effect of thermal sensation, perceived loudness and PAQ under the normal ranges of conditions, which are more frequently encountered in our daily life situations and more favorable for recreational walking.

(ii) The formulation of pedestrian comfort index

The formulated index in this study embraced several important characteristics, which makes it portray the pedestrian comfort level of street environment for recreational walking more realistically. (a) The index was formulated in a comprehensive scope with both built environment criteria (i.e. sidewalk, amenities and landscape) and micro- environment criteria (i.e. PAQ, noise annoyance and thermal sensation). (b) The scoring methods for all the micro-environmental criteria were formulated by using the absolute comfort performance standards, and the well-established empirical relationships between physical micro-environmental conditions and human sensations. (c) The set of weightings for the major comfort criteria determined from go-along interviews in urban streets should be one of the best approaches to obtain the relative influences of built and micro- environment. (d) The formulated index presents the pedestrian comfort level of street environment on an hourly basis with the consideration of the impacts of fluctuating micro-environmental conditions. The findings from the pedestrian comfort index provide more holistic views and valuable insights for urban planners than that from a single aspect of comfort. Besides, the pedestrian comfort assessment framework can be generalized in other cities over the world.

(iii) The effects of street morphological attributes on pedestrian comfort

4m and 8m tree-planting configurations yielded higher pedestrian comfort levels than the treeless throughout daytime in summer. Besides, the orientation and aspect ratio that produced the most comfortable walking environment varied with time. The most comfortable walking environment at 8:00, 9:00-11:00 and 14:00-17:00 were N-S, NE-SW and NW-SE Streets respectively despite similar pedestrian comfort levels being occurred at 12:00-13:00 for all orientations. At 8:00-11:00 and 17:00, the most comfortable walking environment occurred H/W = 3, and for H/W = 2.5 at 12:00-16:00. The street design strategies related to street orientation and aspect ratio can be determined according to the period that people are most active outdoors. Most importantly, among micro-environment criteria, thermal sensation was found to be the major criterion affecting pedestrian comfort among different street morphological attributes.

(iv) The effects of neighborhood morphological attributes on thermal comfort and pedestrian comfort of a street segment

In view of the significant role of thermal comfort (i.e. thermal sensation) on pedestrian comfort and unrevealed effects of neighborhood morphological attributes on thermal comfort of a street segment, the effects of neighborhood morphological attributes on thermal comfort of a street segment were investigated first before revealing their effects on pedestrian comfort. Thermal comfort and pedestrian comfort of a street segment were found to vary significantly with the type and condition of neighborhood morphological attributes. Specifically, the changes of SH/h ratio, BCR and building layout form varied the hourly PET values by up to 10.0°C, 12.1°C and 6.5°C, respectively. Also, they would vary the hourly pedestrian comfort scores by up to 29.3%, 43.3% and 21.6%, respectively.

For thermal comfort of a street segment, taller surrounding buildings and/or more compact neighborhoods could help improve the thermal comfort conditions of both sides of sidewalks. The close layout form could help improve the thermal comfort for E-W Street only.

As significant differences were observed on the influences of various neighborhood morphological attributes between E-W and non-E-W Streets, multivariate models have been formulated to predict the thermal comfort on an hourly basis based on the studied neighborhood morphological attributes and microclimatic conditions for both E-W and non-E-W Streets. Also, the orders of relative influences of individual neighborhood morphological attributes on thermal comfort yielded by multivariate models of E-W and non-E-W Streets were determined to be different. In addition, a series of charts have been generated to visually help determine the total number of comfort and very hot hours yielded during daytime by different combinations of neighborhood morphological attributes. It was observed that at least 3 comfort hours could be achieved by raising the SH/h ratio to ≥ 1.8 when BCR ≥ 47%, irrespective of the street orientation and layout form.

With regards to pedestrian comfort of a street segment, a higher SH/h ratio would provide a more comfortable walking environment for pedestrian for four orientations. Open and close layout forms would yield higher pedestrian comfort level in Non-E-W and E-W Streets respectively. In contrast, the BCR with the highest pedestrian comfort level varied with daytime period and street orientation. The value of BCR can be determined according to the period that people are most active outdoors. In addition, it was determined that thermal sensation was the major criterion affecting pedestrian comfort among different individual neighborhood morphological attributes.

6.2 Recommendations for future works

In spite of the above useful findings summarized in the above thesis, there are still several aspects about pedestrian comfort and street design strategies that have not been investigated within the scope of this thesis. Recommendations for future works are listed as follows:

(i) The effect of personal characteristics on pedestrian comfort

In our findings arising from the path model, personal characteristics did not exert a significant relationship with pedestrian comfort. However, previous studies have reported that pedestrian comfort was correlated with personal characteristics (Ovstedal and Ryeng, 2002; Peng et al., 2019). These may be due to the limited questionnaires in our study. Further studies will collect more questionnaires to explore whether there existed significant differences in pedestrian comfort among different groups with specific characteristics, e.g. age or gender.

(ii) Explore the potential application in different cities with different morphology and climates

The applicability of the findings is confined to cities in the sub-tropical climate regions during the daytime period. Regardless of this limitation, the findings are useful for many cities around the world, especially those metropolises with a similar densely built environment to Hong Kong, which are confronted with the problem of overcrowded street environments. Hence, further studies would attempt to investigate the condition in other areas with different morphology and climates.

(iii) *Additional noise and air quality studies about neighbourhood morphological attributes*

The effects of neighborhood morphological attributes on pedestrian thermal comfort of a street segment have been investigated systematically. Although our study has made simple analysis of air quality and noise for the calculation of pedestrian comfort scores of various neighborhood morphological attributes, there was still a need for more in-depth investigations on the effect of neighborhood morphological attributes on air quality and noise in the future.

(iv) *Application of the pedestrian comfort index with aid of GIS system*

The analytical unit of this study was street segment. Further studies can extend the application of the pedestrian comfort index by using GIS system to provide instantaneous pedestrian comfort assessments of street segments within neighborhood districts for pedestrians to choose the most comfortable route and for urban planners to improve the worst street segment.

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Appendix 1: Full version of questionnaire (in English)

DATE: ___________
TIME: ___________
REF NO: ___________
SPOT: ___________

THE HONG KONG POLYTECHNIC UNIVERSITY
DEPARTMENT OF BUILDING SERVICES ENGINEERING

Survey on street environment

I am a student from the Department of Building Services Engineering of The Hong Kong Polytechnic University, and I am now doing a survey about Hong Kong people's pedestrian comfort.

Before you start the questionnaire survey, please assume that you are having a leisure walk, and without the limitation of time and space, the concern of safety, crowdedness, and traffic situation.

Part 1 – The perceptions of built environment

Amenities（Bench, rubbish bins）	☐Extremely dissatisfied ☐Dissatisfied ☐A bit dissatisfied ☐Neutral ☐A bit satisfied ☐Satisfied ☐Extremely satisfied
Sidewalks (Cleanliness, quality obstruction, and width)	☐Extremely dissatisfied ☐Dissatisfied ☐A bit dissatisfied ☐Neutral ☐A bit satisfied ☐Satisfied ☐Extremely satisfied
Aesthetics (Trees, building aesthetics)	☐Extremely dissatisfied ☐Dissatisfied ☐A bit dissatisfied ☐Neutral ☐A bit satisfied ☐Satisfied ☐Extremely satisfied

Part 2 –The perceptions of micro-environment

Perceived loudness	☐Very noisy	☐Noisy	☐A bit noisy	☐Neutral	☐A bit quiet	☐Quiet	☐Very quiet
Perceived Air quality	☐Very bad	☐Bad	☐Quite bad	☐Neutral	☐Quite good	☐Good	☐Very good
Wind sensation	☐Very weak	☐Weak	☐Quite weak	☐Neutral	☐Quite strong	☐Strong	☐Very strong
Perceived solar radiation	☐Very weak	☐Weak	☐Quite weak	☐Neutral	☐Quite strong	☐Strong	☐Very strong
Thermal sensation	☐Very cold	☐ Quite cold	☐Cool	☐Neutral	☐Warm	☐Quite hot	☐Very hot
Relative humidity	☐Very dry	☐Dry	☐Quite dry	☐Neutral	☐Quite humid	☐Humid	☐Very humid

Part 3 –Pedestrian overall comfort

1. The pedestrian comfort in the current environment

Pedestrian comfort	☐Very uncomfortable ☐Uncomfortable ☐A bit uncomfortable ☐A bit comfortable ☐Comfortable ☐Very Comfortable

2. Are you willing to walk in the current environment (built environment, microclimate, noise and air quality)?

☐Yes ☐No

DATE: ____________
TIME: ____________
REF NO: ___________
SPOT: ____________

If your answer for Q3 is 'Yes', how long are you willing to walk?

☐ 0-4 minutes ☐5-10 minutes ☐10-20 minutes ☐20 minutes or above

Part 4 – Respondent's activity before the survey and Personal information

1. The aim of this walking:

☐ Go to work ☐ Go home ☐ Leisure ☐Others, please specify:______________

2. Your walking frequency on this road:

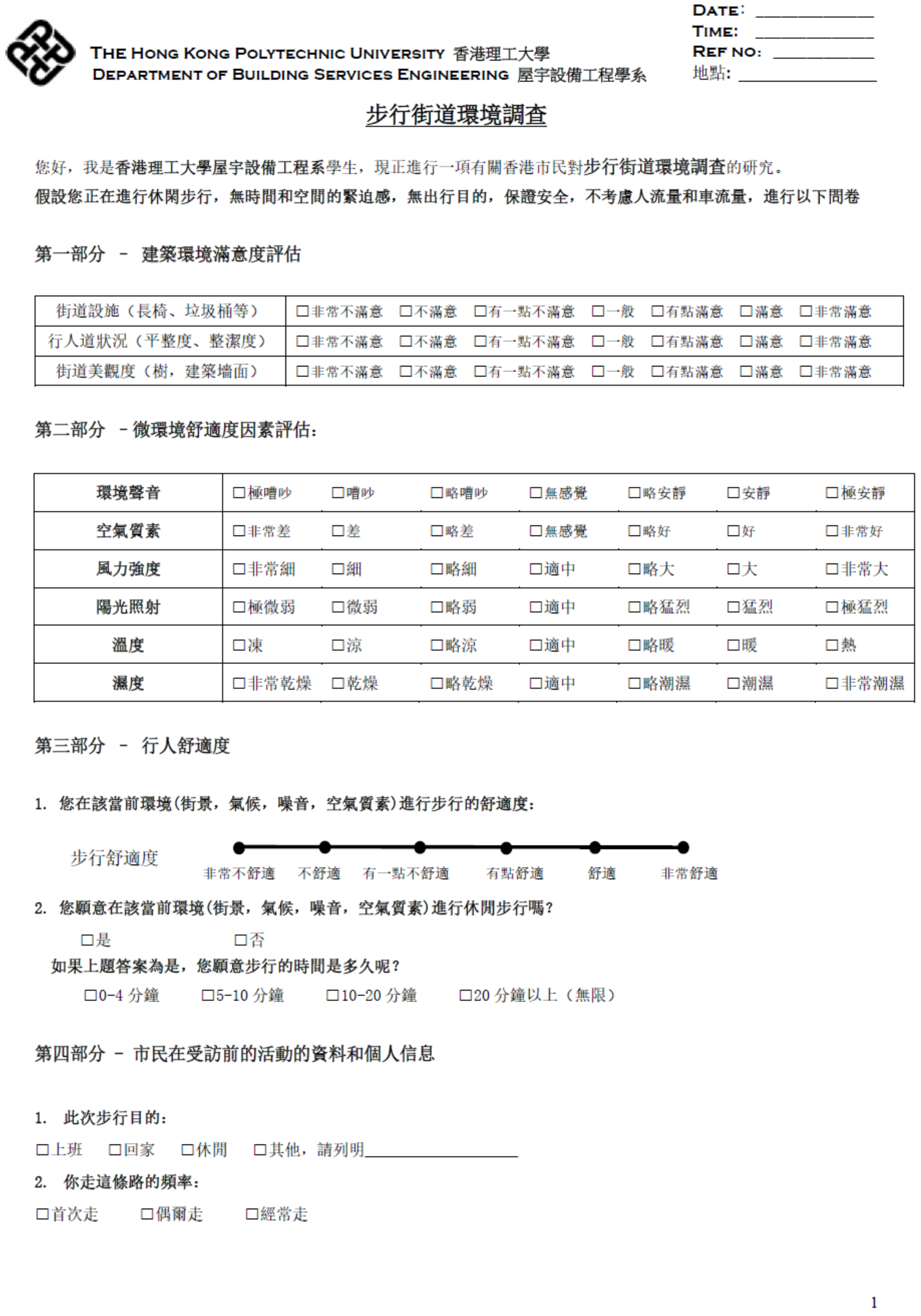
☐ First time ☐ Sometimes ☐ Always

3. Personal information

Gender	☐ Male ☐ Female					
Age	☐ 19 or below ☐ 20-39 ☐ 40-59 ☐ 60-69 ☐ 70 or above					
Place of residence	☐ Non-local ☐ Local					
Education level	☐ Grade school or below ☐Middle school ☐ High school ☐Bachelor or above					
Employment status	☐Self-employed ☐Employed ☐Student ☐Unemployed ☐Homemaker ☐Retired ☐Others					
Thermal sensitivity	☐Very insensitive	☐Insensitive	☐Neutral	☐Sensitive	☐Very sensitive	
Noise sensitivity	☐Very insensitive	☐Insensitive	☐Neutral	☐Sensitive	☐Very sensitive	
Air quality sensitivity	☐Very insensitive	☐Insensitive	☐Neutral	☐Sensitive	☐Very sensitive	
Self-reported health	☐Very unhealthy	☐unhealthy	☐Neutral	☐Healthy	☐Very heathy	

— End Many thanks —

Appendix 2: Full version of questionnaire (in Chinese)



THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學
DEPARTMENT OF BUILDING SERVICES ENGINEERING 屋宇設備工程學系

DATE: ____________
TIME: ____________
REF NO: ____________
地點: ____________

步行街道環境調查

您好，我是**香港理工大學屋宇設備工程系**學生，現正進行一項有關香港市民對**步行街道環境調查**的研究。

假設您正在進行休閑步行，無時間和空間的緊迫感，無出行目的，保證安全，不考慮人流量和車流量，進行以下問卷

第一部分 － 建築環境滿意度評估

街道設施（長椅、垃圾桶等）	□非常不滿意 □不滿意 □有一點不滿意 □一般 □有點滿意 □滿意 □非常滿意
行人道狀況（平整度、整潔度）	□非常不滿意 □不滿意 □有一點不滿意 □一般 □有點滿意 □滿意 □非常滿意
街道美觀度（樹，建築墻面）	□非常不滿意 □不滿意 □有一點不滿意 □一般 □有點滿意 □滿意 □非常滿意

第二部分 －微環境舒適度因素評估：

環境聲音	□極嘈吵	□嘈吵	□略嘈吵	□無感覺	□略安靜	□安靜	□極安靜
空氣質素	□非常差	□差	□略差	□無感覺	□略好	□好	□非常好
風力強度	□非常細	□細	□略細	□適中	□略大	□大	□非常大
陽光照射	□極微弱	□微弱	□略弱	□適中	□略猛烈	□猛烈	□極猛烈
溫度	□凍	□涼	□略涼	□適中	□略暖	□暖	□熱
濕度	□非常乾燥	□乾燥	□略乾燥	□適中	□略潮濕	□潮濕	□非常潮濕

第三部分 － 行人舒適度

1. 您在該當前環境(街景，氣候，噪音，空氣質素)進行步行的舒適度：

步行舒適度 ●—●—●—●—●—●
非常不舒適 不舒適 有一點不舒適 有點舒適 舒適 非常舒適

2. 您願意在該當前環境(街景，氣候，噪音，空氣質素)進行休閒步行嗎？

□是 □否

如果上題答案為是，您願意步行的時間是多久呢？

□0-4 分鐘 □5-10 分鐘 □10-20 分鐘 □20 分鐘以上（無限）

第四部分 － 市民在受訪前的活動的資料和個人信息

1. 此次步行目的：

□上班 □回家 □休閒 □其他，請列明________________

2. 你走這條路的頻率：

□首次走 □偶爾走 □經常走

3. 個人背景資料

性別	□ 男性　□ 女性				
年齡	□ 19 或以下　□ 20-39　□ 40-59　□ 60-69　□ 70 或以上				
現居住地	□ 非本區　□ 本區，於本區居住年期: ______				
學歷	□ 小學或以下　□ 初中或以下　□ 中學或以下　□ 專上或以上				
工作狀況	□自僱　□受聘　□學生　□待業　□家庭主婦　□退休　□其他				
對聲音的敏感度	□ 非常不敏感	□ 不敏感	□ 普通	□ 敏感	□ 非常敏感
對熱的敏感度	□ 非常不敏感	□ 不敏感	□ 普通	□ 敏感	□ 非常敏感
對空氣質素敏感度	□ 非常不敏感	□ 不敏感	□ 普通	□ 敏感	□ 非常敏感
健康狀況	□ 非常不健康	□ 不健康	□ 普通	□ 健康	□ 非常健康

—問卷完　多謝—