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The Influence of Tall Buildings on the Pedestrian Level Micro-Climate in Lujiazui New District, Shanghai

by

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This thesis is dedicated to my beloved families, who have been giving me endless love and absolute support through life.

Abstract

In relation to Chinese cities, both thermal comfort and urban air ventilation have been researched extensively in the past decades while the quality of open urban spaces have received increasing attention in developed countries in recent years. However, there has been relatively little research addressing how microclimatic conditions also contribute to the quality of life.

This thesis aims to obtain the local outdoor thermal comfort criteria, assess the wind environment around the built tall buildings and suggest an approach for urban design. To achieve that, winter outdoor thermal comfort will be determined through a pedestrian thermal comfort questionnaire survey and monitoring of site climatic conditions help to generate local thermal comfort criteria. Summer comfort conditions were determined from an analysis of the literature. After that, the wind environment will be simulated with wind tunnel tests and computational numerical modelling. This will be assessed to improve outdoor wind comfort in urban areas and to build more comfortable and healthier open spaces for pedestrians. Nevertheless, after the creation of the Lujiazui Financial Centre in the Pudong district of Shanghai, a high-density area, with a huge number of tall buildings and the core of the economic development, further improvement has been planned. According to the questionnaire on thermal comfort and the meteorological data retrieved from the monitoring of the site, the majority of participants were satisfied with the outdoor thermal environment found in Lujiazui during the winter and a series of findings demonstrated that microclimate is a very important parameter for outdoor thermal comfort. For instance, it was observed that: (a) the mean neutral air temperature is 14.7℃ and the accepted temperature range is 7.7℃ to 21.8℃; (b) the neutral global radiation is 856W/m^2; (c) the neutral air humidity is 67%;

and (d) the neutral wind velocity is 0.55m/s with an accepted wind velocity range of 0-3.2m/s in winter. Furthermore, the application of wind tunnel tests and computational numerical modelling simulations revealed that the microclimate of an environment would be affected every time a new building is erected. This is why, especially in rapidly developing areas characterised by high-density, generating high-speed winds at the pedestrian level in order to increase air circulation and therefore create a healthier environment in terms of air quality is not uncommon, although these man-made air flows may be perceived as distressful or unsafe. In the light of such conditions, when designing a new building its morphology, its influence on the interior environment, and its impact on the outdoor environment should be equally taken into account. Furthermore, some suggestions for optimised urban design methods about building more skyscrapers in the extended area of Lujiazui are provided, which could become a guideline for the government and the urban designers with the aim to create better, more comfortable and healthier urban open spaces in a sustainable city.

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Nomenclature

U	mean wind speed (m/s)
U_r	reference mean wind speed (m/s)
$U_{(z)}$	mean wind speed at height z (m/s)
U_{ref}	mean wind speed at reference height z_{ref} (m/s)
α	exponent, dependent on the range of height being covered and the surface roughness
a_n	azimuth (º)
$R(a_n)$	velocity ratio
V_g	point air velocity at ground level (m/s)
$V(a_n)$	velocity at reference height (m/s)
M	metabolic rate (W/m^2)
W	physical work output
R	net radiation of the body
C	convective heat flux (W/m^2)
ED	latent heat flux diffusing through the skin
ER_e	heat flux by the respiration
ES_w	heat flux due to evaporation of sweat (W/m^2)
S	storage heat flow for heating or cooling the body
ρ	fluid density (kg/m^3)
t	time (s)
φ	flow variable (mean velocity, for example)
Γ_φ	diffusion coefficient (N s/m^2)
T_g	globe temperature (℃)
T_a	air temperature (℃)
T_{mrt}	mean radiant temperature (℃)
D	globe diameter (m)
ε	emissivity of globe
RH	relative humidity (%)
G	global radiation (W/m^2)
WV	wind velocity (m/s)

I_{clo}	heat resistance of clothing
U	horizontal wind speed at the height of Z (m/s)
U_0	horizontal wind velocity at the reference height of Z_0 (m/s)
α	exponent affected by the roughness of the ground
TSV	thermal sensation vote
MTSV	mean thermal sensation vote
MRSV	mean radiation sensation vote
MWV	mean wind velocity (m/s)
MWSV	mean wind sensation vote
MHSV	mean humidity sensation vote
OCV	overall comfort vote
MOCV	mean overall comfort vote
RBS	ratio of built-up area to site area (%)
TNBH	total new building heights (m)
TBH	total building heights (m)
ABH	average building heights (m)
RCS	ratio of wind comfort area to site area (%)

CHAPTER 1 INTRODUCTION

1.1 Background

The population, economy and used urban land size of many countries have been increasing rapidly, particularly in developing countries. However, the growth rates vary due to local cultures, social requirements, governments and other influencing factors. The urban population of the world rose dramatically throughout the latter half of the 1900s. More specifically, during the 1950s, the number of urban residents did not exceed 200 million; however, by the end of the 20th century, the total number was close to 3 billion and is expected to increase to approximately 9.2 billion by 2050 (United Nations Population Fund Annual, 2006). For example, China has been one of the most populous countries in the world for several decades. Based on recent online statistical data, the Chinese population has reached more than 1.37 billion by 9 June 2016 (Countrymeters, 2016). More than half of China's population (51.2%) lived in urban locations in 2012 (Chan, 2012) and this is predicted to rise to 60% by 2020 and 70-75% by 2030 (Han, 2013). The migration of people to cities has primarily taken place in less-developed regions, which may be due to increased economic and social opportunities offered in urban areas and the degradation of rural economies and societies (Francis et al., 2010).

When cities grow to become highly dense, they will inevitably face a number of serious problems. One of these problems is that the horizontal expansion of cities is hindered due to restrictions implemented to preserve optimum functionality. Thus, these cities are forced to grow vertically and farming and other agricultural production can even be developed using this method. Urban design will gradually focus more on the three-dimensional (3D) space of cities because cities should no longer be viewed as a plain but as a tri-dimensional display of multiple horizontal and vertical aspects.

Focusing on the positive side of this modification, some developing countries will have the opportunity to take advantage of the positive implications of globalisation, such as the benefits of a growing economy followed by increasing employment opportunities and salaries. Indeed, some mega cities in Asia are already flourishing and building upwards to establish 3D dense skyscraper cities, such as Hong Kong and Shanghai, as well as Singapore.

However, focusing on the negative aspects, developing countries may acquire a "failed city" status because some are inadequately planned, dysfunctional and out-of-balance. Inadequate pre-consideration of transportation gridlock on city streets can also lead to unbearable pollution, water supply issues, power shortages and other serious issues (Ali and Al-Kodmany, 2012). Therefore, as developing cities become more urbanised and a continuing number of tall buildings are constructed in dense urban zones, the micro-climatic crisis is likely to deepen.

Wherever people stay, whether in indoor or outdoor environments, thermal comfort is an extremely important element that could affect their physiological and psychological comfortableness and ultimately their decision to stay. As warm-blooded animals, a person's body temperature should be maintained around 37°C (Hensen, 1990), a constant temperature based on the equation of heat balance. Heat exchange takes place due to evaporation, radiation, convection and conduction, so apart from impaired physiological functions, a diverse external environment temperature could also lead to a change of body temperature (Jendritzky et al., 2011). In light of this, based on the principles of heat balance, thermal comfort refers to when a balance is achieved between heat flows in and out of the body and when skin temperature and sweat levels are maintained at a comfortable rate (Höppe, 2002:661).

Based on the statistical survey performed by Hakim et al. (1998), outdoor recreational activities, such as walking and cycling, have benefits both in terms of human physiological and psychological health. However, many city residents often prefer to stay indoors rather than enjoy the natural environment, especially in winter and summer due to extreme climatic conditions. Indeed, the development of air conditioning to create comfortable indoor spaces for living has also encouraged people to stay inside rather than endure extreme weather conditions outdoors. Under these conditions, with the passing of time, the human's active adaptive capacity to the natural environment has been suppressed and the human's ability to resist disease has also been reduced. Fortunately, these drawbacks have been acknowledged and people have begun to participate in healthy outdoor environments and lifestyles and prefer to exercise outside because of the polluted indoor air. At the same time, the more time people spend outdoors, the less energy is consumed for indoor heating/cooling.

People's lives are closely linked with urban outdoor thermal conditions. This refers not only to residents' living conditions and health, but also to the development of industry, agriculture and tourism. Outdoor thermal comfort has become more and more important in high-density cities because the quality of thermal conditions has the ability to influence the safety and comfort of pedestrians' outdoor behaviour significantly (Grimmond et al., 2010).

Many cities have limited land available as a resource for expansion and with the rapid development of the economy and urbanization, tall buildings are increasingly encouraged within existing central business districts (CBD). In developing countries in particular, a number of new CBDs have been proposed in mega cities. The impact of these dense tall buildings on the pedestrian level environment - open spaces between and around tall buildings - is an important factor that must be taken into consideration by architects and urban designers and those in charge of regulations and policies. People who work, shop and live in these skyscrapers will use the outdoor public area and visitors will also make use of these spaces to get closer to noteworthy buildings and landmarks. For example, many tourists may have visited The Oriental Pearl TV Tower and Shanghai Tower (currently the tallest building in China and also the 3rd tallest in the world) in Lujiazui New District when they travelled to Shanghai. Thus, a healthy and comfortable outdoor environment at pedestrian level is extremely beneficial and desirable for residents and visitors in Lujiazui.

It is easy to see how high-density living may bring advantages in many regards, including the more efficient utilisation of land, more effective public transport systems and more convenient access to necessary amenities. However, one negative result of dense urban design might be the implications for the natural environment. As two main factors of micro-climate, daylight and natural air ventilation are important to sustaining human life and energy saving, but can be easily influenced by objects/buildings.

In recent years, the economy and urban structure of Shanghai has developed at a significantly high speed, and the Lujiazui district has been designed to become one of the most dominating international financial centres in the world, a development model that has been copied by many other Chinese cities. Therefore, urban and architectural design are accepted as effective methods of easing the UHI (urban heat island), which reduces indoor energy consumption by offering a better and healthier outdoor environment (Ng and Cheng, 2012, Wu and Kriksic, 2012).

Thus, environmentally aware urban planning and building designs are definitely important. The unique urban fabric of Shanghai, in terms of its street patterns, building heights, open spaces, density, features, landscape and so on, should inform and determine the environmental quality both within buildings and outside of them.

1.2 Research aims and objectives

Existing Chinese building codes limit the maximum building height for developments based on the predicted impact on the surrounding buildings, including the amount of solar exposure time per day on the ground floor of neighbouring properties and the distance between the proposed building and the road. As such, such codes do not realise the importance of building morphology upon outdoor comfort or simply do not consider it important, most likely the former. At the same time, architects tend to only consider indoor comfort rather than the effect of their building's design upon the outdoor public realm. If the government, urban planners and architects acquire a better understanding of this issue and give greater consideration to the impact of high-rise buildings upon pedestrian comfort and the surrounding buildings, we may begin to see improved urban and building designs that lead to healthier and more comfortable urban environments.

Environmental parameters have a considerable impact on people's behaviour and thermal comfort in outdoor spaces, in a similar way to indoor environments. The complexity, however, is far greater on account of environmental inconsistency and the temporal and spatial activities engaged in by pedestrians, which is the main reason why we must acquire a deeper understanding of comfort conditions in the urban outdoor micro-climate.

There are three main research aims of this theses: 1) to obtain local pedestrian thermal comfort criteria in Shanghai; 2) to determine the wind environment through the assessment of high-density tall buildings in Shanghai; 3) the outdoor wind environment will be assessed in an existing case to enable urban design methods to create comfortable natural wind environments for pedestrians in both the existing and extended site. Therefore, the objectives are: 1) to apply site micro-meteorological measurements and questionnaire survey data to generate the local outdoor pedestrian thermal comfort standards; 2) to implement wind tunnel tests using new computational simulation software (FlowDesigner) to validate findings according to a real site in Hong Kong; 3) to simulate and assess the wind environment around tall buildings in Lujiazui; and 4) to propose appropriate design methods for more tall buildings in the extended site controlled by the urban morphology and building arrangement.

Therefore, this thesis will focus on addressing the following key research questions:

- What are the key factors that affect the urban microclimate? Also, how do these factors influence the local area?
- How to determine outdoor thermal comfort?
- In high-density zones, what is the relationship between urban buildings, the microclimate and outdoor thermal comfort?
- In terms of wind comfort, low wind speed causes poor air circulation while strong wind speed can be dangerous. Thus, what is the healthiest and most comfortable wind velocity range in Lujiazui?
- Using the results of a questionnaire survey, thermal comfort criteria in Lujiazui district, Shanghai will be obtained. In light of these criteria, why are there differences between and variations between

Shanghai and other regions (e.g. Europe, Singapore and even other cities in China)?

- How can tall buildings extending Lujiazui district be designed to improve surrounding outdoor comfort?

Improved urban design methods which take pedestrian wind comfort into account will be recommended in this research. Hopefully, in the near future, the government, urban planners and architects can then understand and give greater consideration to the impact of high-rise buildings upon pedestrian comfort in surrounding public spaces. We may then begin to see more effective urban and building designs leading to healthier and more comfortable urban environments.

1.3 Structure of the thesis

Following a brief introduction of the research background, the key aims and research questions are presented. Chapter 2 will review literature and research on three main aspects, namely: (a) airflow around buildings; (b) thermal comfort criteria; and (c) experimental technology and computational fluid dynamics (CFD) applications in ventilation studies. In Chapter 3, the methodologies applied in this thesis will be introduced and explained, including the questionnaire survey, wind tunnel modelling as well as CFD applications, procedures and modelling. This methodology has also been informed by an exchange study period at the University of Hong Kong in 2014. Indeed, with the help of Dr. Jianxiang Huang's research group, my understanding of outdoor ventilation has been enhanced and studied using site measurements, weather data recordings, wind tunnel tests and CFD simulation for wind environments in high-density tall building zones in a pilot study Sai Wan, Hong Kong. These procedures and results will be presented in Chapter 4 and the results generated by experimental tests and new CFD software FlowDesigner will validate their accuracy. Next, a primary case study on a high-density tall building zone in Lujiazui will be examined in Chapter 5. An outdoor thermal questionnaire survey was completed in winter with more than 1,000 interviewees from 2013 to 2014, and the results of SPSS analysis of the data will be explained in the same chapter. The thermal comfort criteria in Shanghai will be established and will also be compared with other cities. In Chapter 6, the development of urban morphology and tall buildings in the typical CBD will be described. Therefore, by simulating the outdoor wind environment with prevailing wind directions for different years in CFD and referencing the pedestrian wind comfort criteria generated in the previous chapter, past and recent air flow around these tall buildings can be analysed to better understand the influence of different urban morphologies on the neighbouring wind environment at the pedestrian level. Then, in Chapter 7, based on the alteration of building heights, arrangements and construction completion time, different urban and high-rise building morphology designs in the extended area of Lujiazui will be proposed and the outdoor ventilation will be simulated and discussed. Finally, in Chapter 8, a summary of this research work will be given and conclusions on the research contributions will also be drawn. Furthermore, the limitations of this research study will be discussed and suggestions for areas of improvement and recommendations on possible areas of future research will be presented.

The Chinese government has not paid enough attention to the quality of outdoor environment, resulting in many problems in recent years. The urban heat island, increasing indoor energy consumption, polluted air and other drawbacks could be could be overcome through greater understanding of thermal comfort in urban areas. Each city has its own climatic condition, terrain and urban design, based on the comfort range of ventilation from the results of local thermal comfort criteria, the wind environment in the case study will be clarified and understood. Then, according to the buildings arrangement, building heights and completion time, some optimized urban design will be proposed by considering the outdoor wind comfort in the surrounding open areas.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The quality of the available open spaces can influence the quality of life within cities, and isolation and social exclusion may be exacerbated if the quality of such spaces is poor or unacceptable (Boumaraf and Tacherift, 2012). This relates to the physical properties of the space (including microclimates, thermal properties, visual and acoustic comfort levels, and urban morphology) as well as the social environment. According to recent research, the microclimate of a given outdoor urban space is therefore of significance to the way the space is used and the activities that are carried out, because thermal, and by implication comfort, conditions affect people's decisions and behaviours in terms of utilising outdoor spaces (Boumaraf and Tacherift, 2006).

In different weather conditions, people's responses to microclimate will vary, even if only subconsciously, leading to a different uses of these open spaces. For example, people may prefer to stay in shaded spaces in hot days and avoid walking in the streets facing down high-velocity winds on cold days. Obviously, such decision-making varies not just in relation to the actual microclimatic conditions but also in response to socio-cultural and regional variations and preferences (Nikolopoulou and Lykoudis, 2006). As such, the future development of urban locations is likely to be enhanced by detailed knowledge of microclimatic attributes in outdoor environments and how they affect the comfort of users.

This chapter will review current knowledge and techniques relating to airflow around buildings in urban open space, human thermal comfort and the applications of wind tunnel technique and CFD in the field of ventilation studies.

2.2 Air flow around buildings in urban public open spaces

Urban land use planning, in general, features two aspects: the built-up urban environment and the non-built areas. A variety of structures with uses such as residential, industrial, commercial, and infrastructure are established in the former, while parks, gardens, recreational areas are constructed in the latter; these areas are what is commonly referred to as open space in terms of urban land use (Maruani and Amit-Cohen, 2007).

In urban planning, public open space plays an important role in daily public life, and adequate and well kept open public spaces can promote health by relieving mental fatigue (Kaplan, 2001), decreasing mortality rates (Mitchell and Popham, 2008), promoting physical activity levels (Koohsari et al., 2015) and reducing stress levels (Nielsen and Hansen, 2007). In recent Chinese urban design, landscape design of large-scale urban public spaces has received far more attention than previously, including focus on its more complex components and functions (Chen et al., 2016).

Two conflicting methods have been devised with the increase of public planning in open urban spaces. The first method is conventionally used by urban planners and landscapers as it concentrates on satisfying user requirements in terms of environmental quality, comfort and access to amenities or recreational services. The second method is most commonly employed by conservationists and ecologists and concentrates primarily on how to safeguard the existing natural environment and natural resources (Maruani and Amit-Cohen, 2007). It is often argued that the former reflects demand requirements while the latter reflects supply requirements.

In general, size, location, landscape characteristics, accessibility, etc. are the measures used within research on such spaces to gauge the advantages and disadvantages of particular public spaces in the landscape (Chen et al., 2016). In light of these approaches, it is obvious that the distinctions between each method are born from the conflicting goals of conservationists and developers in the design of urban spaces and the conflicting planning principles that are adhered to in each case. An overview of the key distinctions between each method in terms of planning principles and focus is provided in Table 1 (Maruani and Amit-Cohen, 2007). However, improving outdoor natural ventilation to a certain extent can meet the demand of wind comfort and safety at pedestrian level, while it could also reduce the negative effect of increasing indoor energy consumption on outdoor heat island and air pollution, because more residents will spend time in the open spaces.

Planning aspect	**Examples of guiding planning principles**	
	Demand approach	**Supply approach**
Site selection	Proximity to users Accessibility (e.g. mild topography, no obstructions) Visibility Relation to other open spaces	Presence of high-quality natural values Uniqueness of natural values Sensitivity or vulnerability of natural values Visual quality Integrity of ecosystem Vital ecological processes
Quantitative measures	Size of each open space unit Total number of open spaces	Preferably defined by natural features or ecosystem boundaries (e.g. drainage basin)
Types of activities	A variety of recreational activities Activities fit for different groups Suitability to special needs and preferences	Limited outdoor recreation (e.g. hiking) Activities compatible with conservation goals
Site design	Designed for intensive use High maintenance Wide selection of facilities	Minimal intervention Limited access Few facilities Low maintenance

Table 1: Approaches to open space planning - a comparison of guiding planning principles (Maruani and Amit-Cohen, 2007:4)

2.2.1 Importance of urban outdoor spaces

In many studies, urban outdoor spaces have been proved that they are extremely important to the surrounding environment and the quality of the residents' life. (Froot, 1992, Naveh, 1997, Thompson, 2002, Chiesura, 2004). Indeed, in many countries, ensuring the presence and quality of urban open spaces is regarded as an integral part of land use planning decisions by the governments.

In terms of sustainable urban design, outdoor open spaces can play an important role in supporting a pleasant thermal comfort experience for pedestrians and thereby promoting a satisfying urban life, because they can accommodate pedestrians' psychology and their outdoor behaviours, which contributes significantly to urban liveability and vitality (Nikolopoulou and Lykoudis, 2006, Chen and Ng, 2012). Indeed, Chen and Ng (2012) suggest that the more people stay on the streets and in outdoor spaces, the more benefits cities will obtain, and this applies to numerous aspects including physical, environmental, economical, and social perspectives. Under the background of urbanisation, an increasing number of people are encouraged and desire to live in central cities, such as Beijing, Shanghai and Guangzhou in China. However, the extended available urban land is limited and this is leading to people having to live and work in higher buildings. A consequence is that this high-density living in cities is making people extremely vulnerable to the weather and environmental conditions in the global context of climate change. In view of this, pedestrians should be well protected and served by the urban outdoor spaces necessary to high-quality urban living. More and more researchers (Gehl and Gemzøe, 2004, Maruani and Amit-Cohen, 2007) have recognized the importance of urban open spaces to people and their societies, in particular the need to make open spaces attractive to inhabitants and therefore ensure that they are used by those inhabitants.

Outdoor microclimate is a crucial element in determining the quality of outdoor spaces. Pedestrians have to be exposed to momentary surrounding environments including sun and shade, unpredictable wind environment, and other climatic characteristics. The thermal comfort experience is largely influenced by the vicinal microclimate, so pedestrians' feelings and experiences are generally quite different from those of car commuters (Nikolopoulou and Lykoudis, 2006). The urban micro-climate also affects decisions on whether and how to utilize public spaces initially (Chen and Ng, 2012).

2.2.2 Urban planning to local climate

In any serious planning discussions, urban climate results have to be translated into general planning aims that support the well-being of the people in the area. For example, one question to consider is to what extent dense building sites affect the heat island and thermal conditions of open spaces, and what potential does this effect have to improve thermal conditions and air mass exchanges around facilities such as roads and parks? (Katzschner, 2010)

Positive climate effects	**Negative climate effects**
Ventilation paths	Urban heat islands
Downhill air movement	Anthropogenic heat
Air mass exchange	Reduced ventilation
Bioclimatic effects from vegetation	Lack of air path effects
Neighbourhood effects	
Altitude and elevation	

Table 2: Positive and negative influences upon urban climate (Schiller et al., 2001:46)

In tropical and subtropical regions, such as Hong Kong and Singapore, more wind with higher speed is to a certain level demanded, particularly during the hot seasons. According to that, Schiller et al. (2001) consider both positive and negative effects on urban climate, as shown in Table 2. This demonstrates very clearly that the urban environment and buildings should be designed carefully to enhance positive climate effects that are beneficial to microclimates in neighbourhoods, such as healthy and safe natural air movement.

In highly dense districts, especially in those with cold winters and/or hot summers, designing for wind conditions has become an increasingly important urban and building morphology design issue in recent years. However, inappropriately planned cities rely solely on architects to design and establish their own structures, and this cannot encourage people to stay outside in an unhealthy and uncomfortable environment. Indeed, a short distance between two buildings may generate extremely high wind speed in that area which can be dangerous for pedestrians. On the other hand, different building arrangements and their angle to inlet wind direction can create adverse air flow with stagnant wind or high speed ventilation that refers to the problems of pollutant dispersion and wind safety respectively.

For high-density city design, the following design parameters should therefore be considered (Ng and Wang, 2005, Anisha et al., 2010):

- *Air paths;*
- *Deep street canyons;*
- *Street orientations;*
- *Ground coverage ratio; and*
- *Building height differentials.*

In attempting to define an urban environment, the urban canyon climate is crucial. The importance of this element has been addressed at length in the literature (Oke, 1988, Hunter et al., 1992, Ca et al., 1995). Despite this, however, a huge number of cities still suffer from poor quality ventilation and air quality issues on account of inadequate urban planning. Furthermore, increases in traffic due to the rapid development of urban zones have led to the deterioration of local air quality. The interaction of incoming wind flows with urban buildings is the primary factor in determining canyon flow. Thus, the shape and placement of buildings has a strong influence over canyon flow and many research studies have focused on the creation of models to facilitate the consideration of this during the planning and design process (Theurer, 1999, Chan et al., 2001). That being said, it is very difficult to design a universal model that will generate wind field measurements for a specific urban landscape as there are a huge number of influencing variables. For example, strong winds may be irritating to the users of a public space but are more beneficial for the dispersion of pollutants. At the corners of canyons, self-circulating eddies can form that collect pollutants and urban debris. This means that there is a consistent emission of pollutants from the canyon. However, further investigations are required on this matter to become more familiar with the different factors involved and to generate advanced reference data to facilitate those involved in urban planning (Chan et al., 2003).

During recent decades, large energy resources have been expended in many cities to make residents feel more comfortable in both winter and summer, but successful urban open public spaces can help to reduce indoor energy consumption. They encourage people to spend more time outdoors, which also helps to add life to a city. A great deal of social interaction takes place between buildings as people perform daily activities such as sitting on park benches, waiting for buses, walking by, planning, meeting friends, and so on. These outdoor activities are affected by a number of conditions, but particularly by the physical environment including air flow, temperature, solar access, and other comfort factors (Wu and Kriksic, 2012).

Katzschner (2010) therefore assumes that ideal thermal conditions could be derived by following specific guidelines:

1) The use of open space is more frequent in the centre of a heat island and increases with high values of thermal indices;
2) Streets are seen as more comfortable for pedestrians if there is a choice between sun and shadow; and
3) Ventilation areas have to be assessed in terms of their affect throughout the whole city in order to have an appropriate influence on planning.

Tsang et al. (2012) note that the creation of low air velocity spaces surrounding tall buildings may give rise to a poor outdoor wind environment in summer conditions. In these conditions, the wind velocity not only has a desirable maximum but also a minimum condition in order to create the acceptable and comfortable wind velocity range that allows better urban life at the pedestrian level.

With this in mind, Ferreira et al. (2002) suggest that the modification of wind patterns in a built-up area due to neighbouring buildings could be quite significant. Interference effects depend on several conditions: (a) upstream obstacles and terrain conditions; (b) the morphology and arrangement of adjacent constructions; and (c) the angle between structures' orientations and the prevailing wind direction. As well wind velocity being impacted by the level of aerodynamic interference, the effects may extend to affect the efficiency of building ventilation systems, wind loads, air quality, and pedestrian comfort.

2.2.3 Urban ventilation in high-density cities

Energy and mass exchange regulates urban weather conditions in the urban boundary level, which is generally deemed to the atmosphere space between the ground to a height of 1000m (Oke, 1987). The urban canopy layer (UCL) underneath the urban boundary layer has been studied by many researchers such as Yang (2004), Mayer et al. (2008), Chen and Ng (2012). The more numerous and taller the typical buildings established in the UCL, the higher the volume of building mass, and the more complex the microclimate changes that ensue. These include a reduced solar radiation at the ground level, higher air temperatures, weaker wind fields, and more frequent turbulence. With regard to highly dense cities in tropical and subtropical zones, these effects lead to residents having to live in dangerous conditions with a poor urban thermal comfort environment. Encouraging natural elements such as wind to penetrate the city can be an essential and important method to ease such negative effects (Chen and Ng, 2012).

In order to understand the concept of the way wind affects urban ventilation, the wind velocity ratio (VR_w) is a useful and simple model. Figure 1 outlines how VR_w can be schematically conceptualized (Ng, 2010). The wind velocity gradient expresses the vertical gradient of the mean horizontal wind speed in UCL, while it is the rate of increasing of wind strength with unit increase in height above ground level. Wind speed increases with growing height above the ground, which starts from zero to no-slip condition. Therefore, the surface wind slows dramatically from rural to urban areas because of surface friction forces.

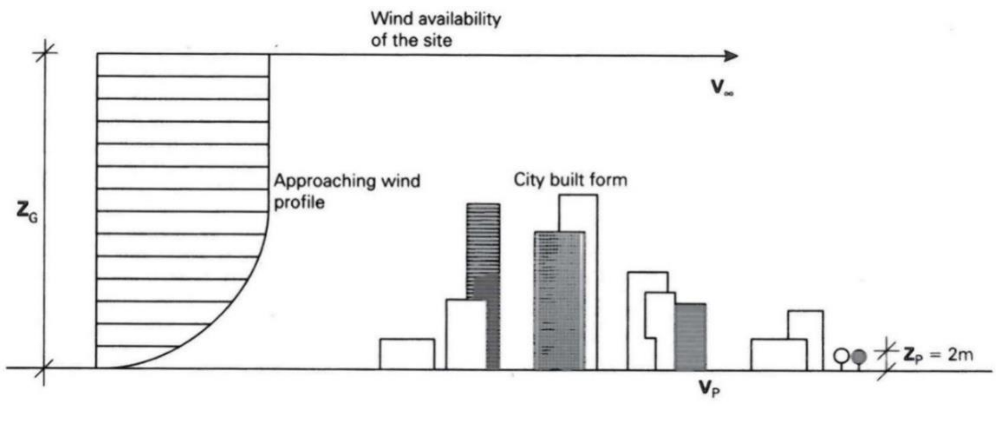


Figure 1: Wind velocity ratio between V_p and V_∞ (Ng, 2010:121)

An empirical power law representation of the mean velocity profile in the outer layer can be given by the following Equation 2.1, which can be applied to estimate wind power potential.

$$\frac{U_{(z)}}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad \text{(Equation 2.1)}$$

Where $U_{(z)}$ is the mean wind speed at height z, U_{ref} is the mean wind speed at reference height z_{ref}, and the exponent, α, depends on the range of height being covered and the surface roughness. The evaluation of wind power potential at a proposed site by extrapolation from measured winds at a reference level is investigated, and the wind speed at 10m height in nearest airport is usually employed by many researchers.

Indeed, considering the wind available to a city coming from the left of Figure 1, the wind profile as illustrated can be calculated using the power law with an appropriate coefficient for the surrounding terrain (Ng, 2010, Ng and Cheng, 2012). At the gradient height of this profile, the wind is assumed to be not affected by friction with the ground. This is commonly known as V_{∞} or V (infinity). For high-density cities, this can be conveniently assumed to be about 500 metres above the ground, so it is also known as V_{500}. City activities commonly take place at the pedestrian level inside the city, roughly 1.5 to 2 metres above ground. The wind speed at this level is V_p or V_2. The ratio between V_2 and V_{500} is known as the wind speed ratio (VR_w). The ratio indicates how much of the available wind within the city is enjoyed by pedestrians on the ground. It is plain from this statement of effects that the buildings and structures between 2 metres and 500 metres indicate the magnitude of this ratio. How well architects and planners design for city ventilation can be assessed by the magnitude of the VR_w; the higher the VR_w, the better the available site wind is captured for pedestrians (Ng, 2010).

The percentage of the gradient wind at pedestrian level (1.5 to 2 metres above ground), as related to ground roughness, can be summarized from Table 3 (Ng, 2010):

α	Description	Height of gradient wind (m)	Wind speed % of gradient wind
0.10	Open sea	200	63
0.15	Open landscape	300	47
0.3	Suburban	400	20
0.4	City with some tall buildings	500	11
0.5	High-density city	500	6

Table 3: Height of gradient wind versus wind speed based on the power law with various coefficients (Ng, 2010:120)

The size and morphology of the objects can influence wind velocity and direction dramatically, while wider and taller buildings facing the wind have ability to generate larger covering effect in leeward. (Tsang et al., 2012). However, under these conditions, the natural air flow around the structure is also influenced adversely. On the other hand, the pedestrian level obtains more air and the near-field wind environment is improved when higher buildings redirect more upper-level wind downwards. Building separation effects can be considered by taking an example of a row of buildings (Figure 2). Here, more air passes across the gaps to the rear of the front set of buildings, so the wind velocity in the near-field space is improved. When the wind encounters such objects, the air flows located on the downstream side of the buildings divide into two separate flows: the backflow, and the air flow passing through the gaps between buildings. Without this separation, the backflow will be much stronger. In these conditions, there may be high air speed zones generated downstream a long way away from the initial impact point, and the wind direction will generally oppose the initial inlet wind direction. On the contrary, the wind direction is equivalent to the inlet flow when the space between buildings is more than half their width. Wind speed then increases in far-field and near-field zones (Tsang et al., 2012). On the other hand, if the space between buildings is no more than half their width, air flow is likely to be turbulent, which means that low average wind flow speed zones will eliminate natural ventilation (Ng and Cheng, 2012).

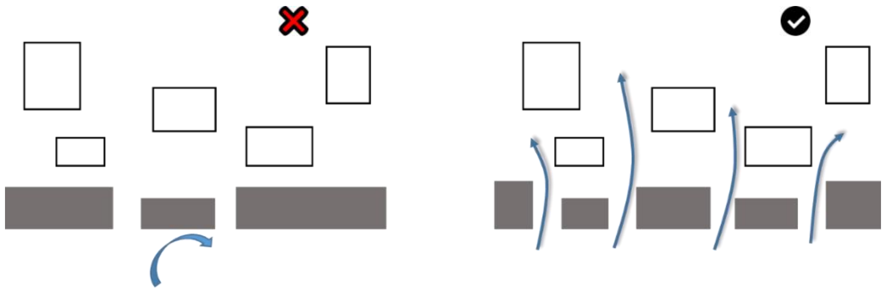


Figure 2: Air path to a row of buildings (adapted from Ng, 2009: 1485)

Whether a building podium should be applied has caused extensive concern. Tsang et al. (2012) found that such constructions had an adverse influence on the wind environment at a downstream level in areas both far away and nearer, because the wind is blocked at the pedestrian level. Applying podiums in areas where natural ventilation is required at the pedestrian level is therefore not advisable.

Nonetheless, Ng (2009) argues that a terraced podium would be beneficial in guiding downward air flow, which would in turn enhance wind conditions on the pedestrian level, as shown in Figure 3. Pollutants, including those produced by vehicles, are also dispersed by this kind of podium. When considering the effects of podiums, it is important to recognise that sometimes one tall building integrates with a single podium while in other cases, several tall buildings are designed to integrate with the same podium. To improve the surrounding natural air ventilation at pedestrian level, any podium should be divided into several parts and integrated with each building separately at the design stage.

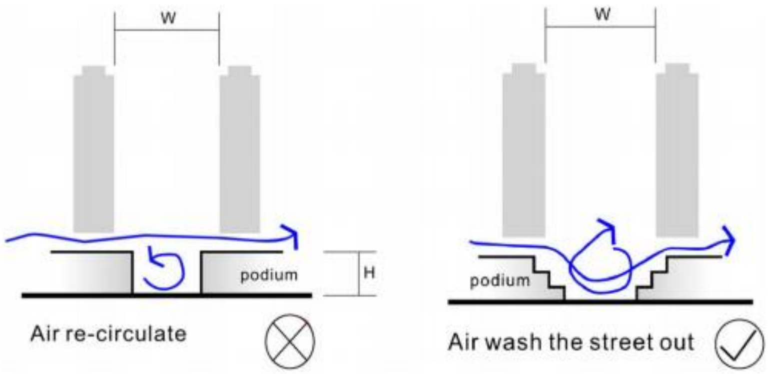


Figure 3 : Air flow in podium (Ng, 2009: 1487)

2.2.3.1 Flow patterns

According to Santamouris et al. (1999), air path refers to the movement of air around people and objects in a specific location. Particularly in terms of air velocity, air ventilation is a key criterion for thermal comfort as people prefer to live in comfortable, a safe and healthy wind environment.

Within the medium humidity range of 40-50%, air movements can cause increased skin evaporation. That being said, physical exertion also generates air flow and this must be taken into account along with air velocity (Santamouris et al., 1999).

To further understand the parametric studies of wind flow in canyons, larger building heights and width ratios (H/W) should be researched. Many researchers have proved that air reaches the ground level with highest speed when the ratio is 2:1 or less (Nakamura and Oke, 1989, Santamouris et al., 1999), but a few researchers suggest exceeding that ratio with deeper street canyon. This is likely because of the additional complexity increasing this ratio introduces (Kovar-Panskus et al., 2002). Figure 4 summarizes several air flow conditions with their primary and secondary vortexes in canyons with different H/W ratios. When the ambient wind blows in a perpendicular direction to the canyons, the wind becomes weaker towards the bottom once secondary vortexes are created (DePaul and Sheih, 1986). In highly dense districts with high buildings, the H/W ratio is likely to go well beyond 5:1, sometimes as high as 10:1. Thus, in some canyons with an extremely high H/W ratio, even if the ambient wind velocity away from buildings is much higher, it may reduce to an extremely low level at the ground.

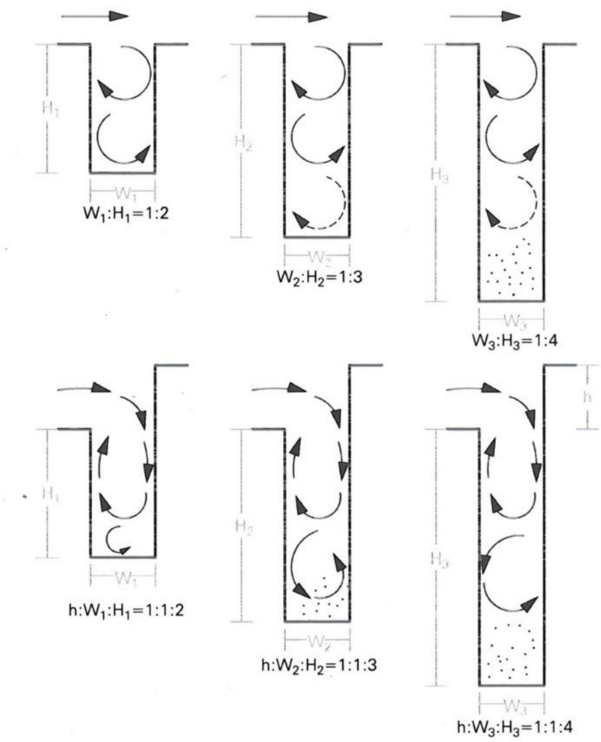


Figure 4: The ambient wind blowing perpendicular to the canyon (Ng, 2010:123)

2.2.3.2 Street orientations

To most urban designers, determining the street orientation is likely to be the first decision for any new development project. According to previous literature reviews of air paths and canyon wind flows, streets should be placed parallel to the prevailing wind direction (Figure 5), as this can significantly benefit inner city ventilation on extremely hot days (Wu and Kriksic, 2012). More wind along the streets can improve thermal comfort and wind environment in high temperatures and humid summers. In contrast, buildings can block air paths directly to create a much lower wind velocity zone in the rear streets, which may be desired on extremely cold days.

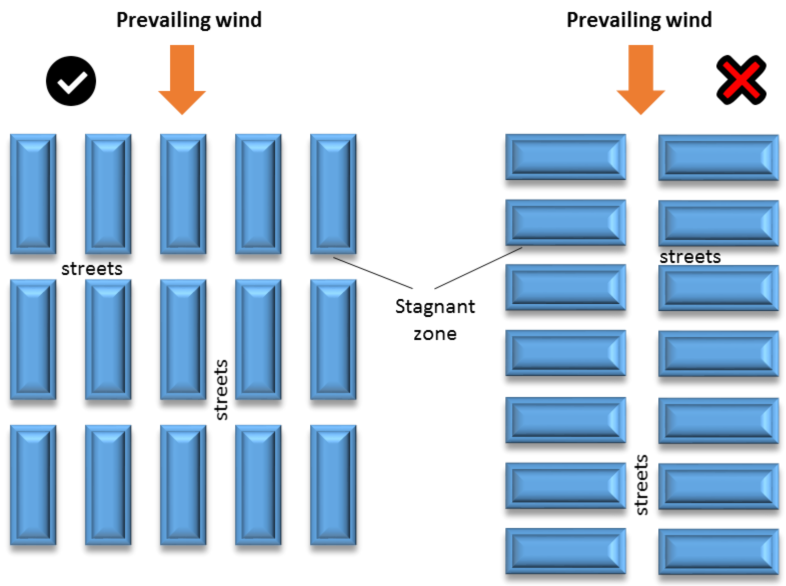


Figure 5: Orientation of street grids (adapted from Ng, 2009: 1484)

However, sometimes streets cannot be placed directly parallel to the prevailing wind direction; in these instances, controlling the deviation to be less than 30° is advantageous (Ng, 2010, Chen and Ng, 2012). In reality, the feasible orientation of the street must also consider many other factors such as local terrain and sunshine conditions. Metje et al. (2008) have shown a relationship between street orientation and solar access and note that people on north/south-orientated streets are much more likely to feel thermally comfortable than those on east/west-orientated streets.

2.2.3.3 Increased building heights

According to the International Code Council (2006:26), building height means "*...the vertical distance from grade plane to the average height of the highest roof surface. Moreover, the height of buildings of different* *construction types generally shall be governed by the intended use of the building and shall not exceed some limits."*

Building height is one of the most important urban and building design parameters, and it can influence urban thermal climate significantly (Anisha et al., 2010). The effects of height of buildings are also independent from those of district density. Deosathali (1999) has completed some research in Pune, India, and found that increasing building heights could decrease residents' reported discomfort levels. However, research comparing the thermal comfort levels of Colombo, Sri Lanka showed that wide streets surrounded by low-rise buildings with less shade from trees can worsen outdoor conditions, while narrow streets with high buildings help to generate the most comfortable conditions in cities of this nature, especially in places shaded by trees (Johansson and Emmanuel, 2006). It may be mainly because Colombo is quite near to the equator and pedestrians prefer to stay in the shadow to avoid too much direct solar radiation

The thermal comfort in an existing urban canyon was compared with the conditions resulting from increased building height in the same canyon by Anisha et al. (2010). This research found that the ambient air temperature reduced in the canyon when higher building heights were introduced. This demonstrates that increasing building height is condutive, to some extent, to obtaining better thermal climates in high-density districts, an effect that is badly needed given the pressure from rapid urbanization found especially in tropical and sub-tropical regions.

2.2.3.4 Building height differentials

As mentioned above, increasing building heights is conducive to obtaining better thermal conditions in high-density zones. However, only improving each building height to the same level may be non-effective. The large differences between taller and lower buildings are required to improve urban outdoor ventilation (Ng and Wang, 2005, Ng, 2010). Besides, in some areas with the same height buildings, there are about 10.5 times of air change per hour, while with the higher of height contrast, the number of air changes per hour has upward trend overall (Table 4).

Height contrast	Height difference Max:Min	Air changes per hour
0	4:4	10.5
3	3:6	10.8
4	3:7	11.9
6	2:8	13.8
7	2:9	11.2
8	1:9	13.3
10	1:11	13.4
10	0:10	17.9
14	0:14	17

Table 4: Relationship between height contrast and air change per hour performances (Ng, 2010:124)

(Note: height contrast means the difference value between the maximum and minimum building height)

On the other hand, taller buildings are easy to capture more inlet horizontal wind and induce it down to the street level, and the air speed will increase in the windward area. (Figure 6.a). On the other hand, some wind moves upwards, and the speed will rise extremely at the top the buildings, where wind turbines can be installed. Furthermore, Figure 6.b describes the positive and negative pressures are generated on the two sides of buildings because of the various building heights, which encourages more air move parallel to the building facades. Thus, higher air change rate and better urban ventilation in urban open spaces can improve thermal, including the wind, comfort (Ng and Wang, 2005, Berkovic et al., 2012).

Furthermore, Ng (2010) also determined that building height should descend towards the prevailing wind direction (Figure 7). Tall buildings with stepped heights in urban design are conducive to capturing wind and downwash to the bottom level of canyons, which optimizes the natural ventilation at the pedestrian level.

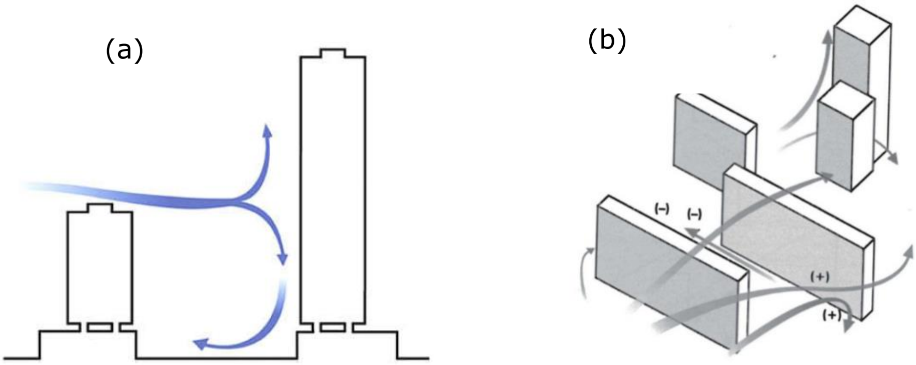


Figure 6 : Different building heights (Ng, 2009, Ng, 2010:124)

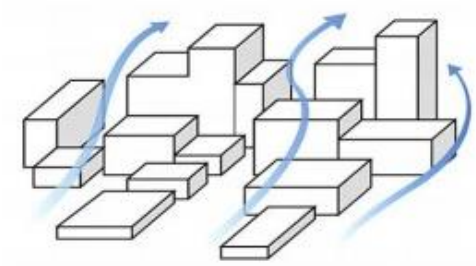


Figure 7 : Optimal urban ventilation applying stepped building heights (Ng, 2010:134)

2.2.4 Air ventilation assessment

The first systematic research on wind influence in the world was conducted by Admiral Sir Frances Beaufort (Penwarden, 1973), who devised the scale of wind force in 1806; this scale is still applied in modern research. The initial purpose of applying the Beaufort scale was to facilitate research of wind effects at sea. After that, it was revised to assess wind velocities on land. Beaufort numbers, the corresponding wind speed ranges and their respective wind influence descriptions are shown in Table 5. According to these criteria, urban designers must work to improve wind safety and comfort in and around buildings (Penwarden, 1973). Furthermore, Penwarden (1973) has also pointed out that people cannot walk steadily when the wind speed exceeds 10.8m/s, and they should avoid staying outside if the wind speed rises above 17.2m/s.

Based on the research by Murakami and Deguchi (1981), large-scale experimental simulations and field observations have been applied to research the influence of turbulent wind on wind comfort at street level. The non-uniformity of air velocity over time and space influences human walking significantly. Walking is much more difficult to control in greatly turbulent wind, even at ambient wind velocities as low as 3m/s. New wind criteria have been proposed that take a more rigorous definition of these effects into account (Table 6).

Beaufort Number	Speed (m/s)	Effects
0, 1	0.0 - 1.5	Calm, no noticeable wind
2	1.6 - 3.3	Wind felt on face
3	3.4 - 5.4	Wind exteds light flag Hair is distured Clothing flaps
4	5.5 - 7.9	Raises dust, dry soil and loose paper Hair disarrange
5	8.0 - 10.7	Force of wind felt on body Drifting snow becomes airborne Limit of agreeable wind on land
6	10.8 - 13.8	Umbrellas used with difficulty Hair blown straight Difficult to walk steadily Wind noise on ears unpleasant Windborne snow above head height (blizzard)
7	13.9 - 17.1	Inconvenience felt when walking
8	17.2 - 20.7	Generally impedes progress Great difficulty with balance in guests
9	20.8 - 24.4	People blown over by gusts

Table 5: Effects of wind force – the Beaufort Scale (Penwarden, 1973: 260)

Category	Speed *(m/s)	Effects*
1	< 5	No Effect in case of female, minor effect on hair and skirt
2	5 - 10	Some Effect footsteps sometimes irregular, hair and skirt considerable disturbed
3	10 - 15	Serious Effect walking irregular, walking difficult to control, upper body bends windward
4	> 15	Very Serious Effect dangerous for elderly person, walking impossible to control, body blown sideways or leeward

*Wind speed is the instantaneous averaged over 3s.
*For highly turbulent wind, downward revision is required.

Table 6: Criteria proposed by Murakami and Deguchi (1981:291)

According to the Beaufort scale, the research results from Murakami and previous research findings during the last few decades, Soligo et al. (1998) have established a single wind force criterion (Table 7) to evaluate outdoor comfort, which is applied in RWDI (Rowan Williams Davies & Irwin Inc.). By employing frequency of occurrence rather than the maximum wind velocity during a short period of time, this comfort index can also reflect mean wind speeds.

Category	Mean wind velocity (m/s)	Frequency (%)
Sitting	0 - 2.5	≥ 80
Standing	0 - 3.9	≥ 80
Walking	0 - 5.0	≥ 80
Uncomfortable	> 5.0	> 20
Severe	≥ 14.0	≥ 0.1

Table 7: Wind force criteria by Soligo et al. (1998:757)

Following the guidance of ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) for indoor comfort criteria, human’s behaviour and perception can be grouped into three levels by the mean wind velocity: (a) environment will be assessed as comfortable if more than 80% (the majority) of people would like to sit, stand or walk; (b) environment will be identified uncomfortable if more than 20% of people refuse to stay in such surrounding wind environment; and (c) frequency of occurrence of the dangerous value exceeds 0.1% in one day (Soligo et al., 1998). Furthermore, both Murakami and Soligo research teams specified that 5m/s of wind speed seems to be a threshold of pedestrian wind comfort. Indeed, people are much more likely to feel comfortable and safe when the wind velocity is under 5m/s, and the ambient wind environment can indeed be extremely dangerous if it exceeds this threshold.

Many people died due to severe acute respiratory syndrome (SARS) in Hong Kong in 2003, which led the government to establish a Government Team Clean Committee to improve local urban design policies. In 2006, all development projects funded by the government had to apply a new system of air ventilation assessment (AVA) (Ng, 2009). Using AVA, urban designers and architects can optimize the natural air ventilation in high-density areas of Hong Kong to avoid stagnant and slow air movement to obtain an appropriate air change rate in urban open public spaces. This is intended to generate a healthy and comfortable outdoor environment. According to previous research focused on Hong Kong, improving air ventilation to create a better wind environment has been demonstrated as the most important consideration in designing and developing sustainable cities (Ng, 2010).

To estimate comfort and calculate a healthy wind environment at the pedestrian level, the average air flow or air exchange rate characterised by a mean wind velocity with an averaging period of 10 minutes to an hour can be utilized (Tsang et al., 2012), which appears to give more accurate results than measuring gusty winds lasting for periods of a few seconds. The mean wind speed, U, can also be applied to evaluate low wind velocity districts. The ratio of mean air speed at any selected point at pedestrian level and the reference mean wind speed, U_r, have been applied in both experimental and numerical technologies with a prototype scale (Visser et al., 2000, Blocken et al., 2007). The value of U/U_r can be integrated to calculate a specific wind environment, enabling the planner to evaluate the statistics of wind velocities according to magnitude and probability of occurrence.

In conditions of strong wind, velocity-based exceedance probability $\mathrm{P}\big(\mathrm{V} > V(a_n)\big)$ criterion can be applied to assess acceptable speeds at the pedestrian level for the urban plan (Wu and Kriksic, 2012). Therefore, Bu et al., (2009:1503) presented that "the velocity ratio $\mathrm{R(a_n)}$ is defined as the ratio between scalar velocity at ground level $\mathrm{V_g}$ and velocity at reference height $\mathrm{V(a_n)}$ for azimuth $\mathrm{a_n}$."

$$\mathrm{R}(a_n) = \frac{V_g}{V(a_n)} \qquad \text{(Equation 2.2)}$$

Therefore, $V(a_n)$ for 16 azimuths, according to a two-parameter Weibull distribution for each wind direction, is shown as

$$\mathrm{P}\big(\mathrm{V} > V(a_n)\big) = \mathrm{A}(a_n)\exp\left\{-\left(\frac{V(a_n)}{C(a_n)}\right)^{K(a_n)}\right\} \qquad \text{(Equation 2.3)}$$

Here, $\mathrm{P}\big(\mathrm{V} > V(a_n)\big)$ describes the probability of exceeding a specified air speed $\mathrm{V}(a_n)$ at reference height for azimuth a_n, while $\mathrm{A}(a_n)$ is the relative frequency of occurrence and $K(a_n)$ and $C(a_n)$ are the two parameters of the Weibull distribution (Wu and Kriksic, 2012).

Most recent research about the influence of micro-climates on pedestrians and their behaviours have been reviewed and summarized in Appendix 1, and most of them have verified that air temperature, solar radiation and wind speed are the most important aspects of these micro-climates. Considering the relationship between urban morphology, thermal sensation and human behaviour also has advantages in terms of designing a more comfortable and sustainable city (Eliasson et al., 2007, Lin, 2009b).

Forty years ago, San Francisco established regulations to optimize the influence of new constructions on its urban open space microclimates. These included limiting wind speeds and controlling shadows cast by new buildings (City & County of San Francisco, 1985). These guidelines were copied by many other North American cities such as Montreal and New York (Chen and Ng, 2012).

In terms of the outdoor wind environment assessment in China, the Ministry of Housing and Urban-Rural Development of the People's Republic of China published Design Standards for Thermal Environment in Urban Residential District (城市居住区热环境设计标准 JGJ286-2013) in 2013. Following on from this, the China Academy of Building Research published The Green Building Assessment Technology Details (绿色建筑评价细则 2015: 23), and its complementary work Green Building Evaluation Standard (绿色建筑评价标准 GB/T50378-2014), which both have recommended building limits:

- That there is no wind vortex or stagnant zone in open active areas at the pedestrian level;
- Outdoor wind environment simulations with typical wind speeds at 1.5m height above the ground are necessary for each project;
- According to the local historical meteorological data, the outdoor wind environment should be simulated and assessed with the prevailing wind at pedestrian level. Therefore, it is necessary to consider about summer or winter conditions if they are typical; and
- The outdoor wind environment at the pedestrian level must be conducive to natural ventilation, users' activities and comfort, and winds speed should be less than 5m/s.

2.2.5 Problem statements

In China and several other countries, many large–scale public open spaces have been built to meet the different requirements of their users. Of these, most are considered well designed because of their adherence to urban design theory. However, the quality of the micro-climates in these open space and the behaviours and feelings of their users have often been neglected.

The flow of wind around buildings is a very complex phenomenon and has been the subject of many studies over the last half century. Blocken and Carmeliet (2004) performed a detailed review of such studies and drew attention to the high level of emphasis that has been placed on thermal comfort in outdoor environments over the past 50 years of research. The main focus of wind studies on the pedestrian level has been the negative impact of high speed winds around buildings (Wiren, 1975, Stathopoulos and Storms, 1986). These studies generate significant data on the impact of wind on the pedestrian level and facilitate the creation of advanced knowledge systems (Thorsson et al., 2004). Nonetheless, the majority concentrate on areas with high wind velocity, which primarily refer to small areas like the corners of buildings.

A study by Tsang et al. (2012) focused on the spaces between a set and row of buildings. However, limited studies have focused on the impact of contemporary building configurations where there may be several rows of structures or buildings with podiums. Similarly, few studies have examined zones of low wind speed that affect a significantly large percentage of downstream areas (Chan et al., 2001, Chan et al., 2003). They simulated air flow around some blocks with different distances, arrangements and various dimensions. Therefore, if those blocks were regular hexahedron then the whole model changed according to the proportion. Finally, the relationship between wind environment and the designed and controlled variable. However, it may be hard to adapt the regular pattern into realistic urban design, because the morphology of buildings are not only hexahedron, and also the plot ratio, transportation, fire protection and many other factors have to be considered when making buildings and urban design. Furthermore, few researchers have studied the outdoor wind environment in high-density tall building district because of its complexity. In this thesis, a large site with lots of tall buildings in Shanghai will be simulated, and the wind environment around these tall buildings will be analysed.

2.3 Human thermal comfort

People display a variety of behaviours in urban open spaces, adding to the complexity of the environment and affecting human thermal comfort conditions, but this has not been effectively researched outside (Ng and Cheng, 2012). A better understanding of human thermal perception is conducive to improving the outdoor thermal environment and creating acceptable and pleasant spaces for residents.

2.3.1 Definition

Thermal comfort can be defined using three different aspects: (a) psychological; (b) thermo-physiological; and (c) the heat balance of human body (Nikolopoulou et al., 2001, Givoni, 2010).

British standard BS EN ISO 7730 and ASHRAE define thermal comfort as: *"…the condition of mind which expresses the satisfaction with thermal environment"* (British Standard, 2004b:1).

It is difficult to evaluate human thermal comfort because of the wide range of factors that affect it, and user psychology is the most complex and important factor in outdoor thermal research. Furthermore, thermo-physiological effects are generated by the effectiveness of thermal receptors in the skin and hypothalamus. Thus, thermal comfort can also be defined as the *"…minimum rate of nervous signals from these receptors"* (Höppe, 2002:661).

Höppe (1999) has noted an equation describing this energy balance (Equation 2.4), and it can be applied when generating thermal comfort criterion.

$$M + W + R + C + ED + ERe + ESw + S = 0 \qquad \text{(Equation 2.4)}$$

In this equation, the various terms are given positive signs where they add energy to the body, and they receive negative signs when they remove energy from the body. M, the metabolic rate, is therefore always positive, while W (physical work output), ED (latent heat flux from the skin) and ES_w (heat flux through sweat evaporation) are always negative. The other terms, R (net radiation), C (convective heat flux), ER_e (heat flux through respiration) and S (storage heat flow) will vary in sign depending on current conditions.

Honjo (2009) notes that each term is affected by some subset of meteorological parameters. Air temperature has a main effect on C and ER_e, while ED, ER_e, and ES_w are particularly influenced by humidity. However, as well as these influences, C and ES_w are also influenced by wind speed. R is the product of a calculation of the exchange of energies between the environment and the human body in terms of both short wave and long wave radiation.

Within the heat balance approach, thermal comfort is defined as *"…when heat flows to and from the human body are balanced and skin temperature and sweat rate are within a comfort range"* (Höppe, 2002:661).

After taking account of these definitions, environmental, human behaviours and other aspects have to be taken into account to improve outdoor comfort to satisfy the majority of people within the environment. Here, "majority" means at least 80%, which is considered a reasonable limit by the Health & Safety Executive (HSE) (British Standard, 2004b). In other words, meteorological data, referring to air temperature, humidity, radiation and wind comfort, have all become important factors to consider when assessing outdoor thermal comfort. Under these conditions, meteorological data, such as air temperature and wind speed, must be considered alongside the number of residents accepting the thermal environment to assess outdoor thermal comfort.

2.3.2 Development of thermal comfort indices

While there have been a large number of studies relating to indoor thermal comfort, there have been far fewer studies into similar outdoor conditions, even though governments and researchers have noted an increase in urban heat islands and uncontrolled climate change in many cities. This may be because the variable climatic conditions that make up the major aspects required to analyse outdoor thermal environments appear to be much more complex than those found in indoor settings (Honjo, 2009).

A number of thermal comfort indices, including Physiological Equivalent Temperature (PET), Predicted Mean Values (PMV) and Standard Effective Temperatures (SET*), are frequently used to measure the thermal comfort of internal and external environments. These are typically applied to determine ambient air temperature, radiant temperature, air humidity and air velocity (Mayer and Höppe, 1987). Gagge et al. (1971) furthered the field of indoor thermal comfort indices by incorporating two additional factors, namely clothing value (Clo) and human's metabolic rate (Met), into the New

Effective Temperature (ET*) and SET* models. Once the Clo and Met variables are taken into account, PMV of thermal comfort or discomfort and PPD (Predicted Percentage Dissatisfied), based on a rating scale from a large number of participants in a thermal comfort questionnaire survey, can be applied as new indices to evaluate the thermal comfort conditions.

However, due to a much more complex climatic environment than indoor areas, SET* has to be applied with modification to assess outdoor thermal comfort (Spagnolo and de Dear, 2003). Using the Munich energy-balance model for individuals (MEMI), Mayer and Höppe (1987) have developed the concept of PET. In the PET index, the effects from thermo-physiological factors and ambient weather conditions are also considered, providing a similar definition to ET*. Both of these scales are measured by temperature in ℃.

PET for multiple grades of thermal perception has been applied in a great deal of European research. Differing PET values for neutral conditions in Taiwan, which is in a subtropical region, have also been reported by Lin and Matzarakis (2011). Table 8 shows that people in Taiwan are more sensitive to thermal environment changes and they always require a higher temperature than western people. For a long time, SET*, PMV, and PET were the most frequently applied thermal comfort indexes. However, outdoor meteorological parameters can be further characterized by less complex criterion such as the discomfort index (Thom, 1959), wind-chill index (Steadman, 1971) and apparent temperature (Steadman, 1979). On the other hand, a more complex heat budget, the Universal Thermal Climate Index (UTCI), has been applied by an increasing number of bio-meteorological researchers recently (Blazejczyk et al., 2011, Jendritzky et al., 2011). Other methods to evaluate human thermal responses to the ambient thermal environment include the Index of Thermal Stress and the

COMFA outdoor thermal comfort model, which have been applied by Givoni (1969) and Kenny et al. (2009).

In addition, as one of the most important parameters in evaluating thermal comfort, mean radiant temperature (T_{mrt}) is defined as the "*uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure*" (ASHRAE, 2001 in Thorsson et al., 2007:1983). T_{mrt} is the sum of the human body's exposure to all short- and long-wave radiation fluxes, including direct, diffuse, reflected and emitted fluxes, in the surrounding environment (Johansson et al., 2014).

PMV	PET range for Taiwan (℃)	PET range for Western/Middle European (℃)	Thermal perception	Grade of physiological stress
			Very cold	Extreme cold stress
-3.5	14	4		
			Cold	Strong cold stress
-2.5	18	8		
			Cool	Moderate cold stress
-1.5	22	13		
			Slightly cool	Slight cold stress
-0.5	26	18		
			Comfortable (Neutral)	No thermal stress
0.5	30	23		
			Slightly warm	Slight heat stress
1.5	34	29		
			Warm	Moderate heat stress
2.5	38	35		
			Hot	Strong heat stress
3.5	42	41		
			Very hot	Extreme heat stress

Table 8: Comparison of PMV and PET for different grades between Taiwan and Western/Middle Europe (Lin and Matzarakis, 2011)

Many of the thermal comfort models have applied T_{mrt} in previous research studies. Thorsson et al. (2007) estimated T_{mrt} using different methods, including the globe thermometer method and the complicated integral radiation measurement method. According to their study results, there is only a small difference in accuracy between the globe method and others. Therefore, a standard black globe has been proven to overestimate the influence of short-wave radiation (Olesen et al., 1989), although lowering the albedo may improve accuracy slightly (Thorsson et al., 2007) based on the outcome of tests using a flat grey globe thermometer. In this study, estimates are made using the globe temperature method with a mobile globe thermometer integrated with a 40mm diameter black table-tennis ball. This method is chosen for its convenience and cost effectiveness.

T_{mrt} can be calculated with measured globe temperature, air temperature and air speed using the equation below (ASHRAE, 2001 in Ng and Cheng, 2012: 53):

$$T_{mrt} = \left[\frac{\left(T_g + 273\right)^4 + 1.10 \times 10^8 WV^{0.6}\left(T_g - T_a\right)}{\varepsilon D^{0.4}}\right]^{1/4} - 273$$

(Equation 2.5)

Here, T_g is the globe temperature (℃), WV is the wind speed (m/s), T_a is the air temperature (℃), D is the globe diameter (m) and ε is the emissivity of the globe that is generally assumed to be 0.95 for a black globe (Ng and Cheng, 2012, Taleghani et al., 2015).

2.3.3 People's clothing insulation level and metabolic rate

Conventional comfort theory relies on a steady-state model that matches the generation of heat with heat losses to the ambient environment. In other words, clothing insulation effects and activity levels that are considered when estimating whether the micro-climate can maintain a human's core body temperature at 37℃ are important factors in terms of estimating thermal satisfaction. However, adaptive opportunity, the effectiveness of the ways that people can naturally adapt to the ambient environment, is part of human thermal sensation that can affect the degree of satisfaction with the environment (Nikolopoulou et al., 2001).

2.3.3.1 Clothing insulation level (Clo)

Clothing offers insulation to prevent the dissipation of body heat into the environment. As such, the insulating qualities of clothing worn by users will have a significant impact on thermal comfort (Humphreys, 1977, Metje et al., 2008). Thus, users who are wearing heavy clothing that is excessively insulating may feel uncomfortable regardless of the temperature of the surrounding environment. In the same way, too little clothing may make the wearer feel cold irrespective of environmental conditions if the relative temperature is low (Metje et al., 2008).

When measuring or accounting for clothing values, 1 Clo = $0.155m^2C/W$ (Metje et al., 2008). In the survey carried out by Metje et al. (2008), participants were asked to select the category that their clothing fitted into and whether they would wear more or less to feel more comfort. The total amount of clothing insulation value was calculated based on their identified clothing types, and the preferred Clo values were also noted. Generally, the Clo value was calculated to be approximately 0.6 in summer, increasing to about 1.0 in winter (Metje et al., 2008).

2.3.3.2 Metabolic rate/ Activity (Met)

Metabolic Rate/Activity describes the "*…heat that is produced inside our body as we carry out physical activities.*" (British Standard, 2004a:1).

The human body generates heat continuously at varying rates dependant on biological processes; understanding metabolic rate therefore appears to be extremely important when evaluating thermal risk. Furthermore, physical activities generally produce much more heat than a body at rest because of the ensuing higher metabolic rates. Some common activities and their Met values are shown in Table 9.

Activity	W/m2	Met
Reclining	46	0.8
Seated relaxed	58	1
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Car driving	80	1.2
Graphic profession - Book Binder	85	1.4
Standing, light activity (shopping, laboratory, light industry)	93	1.5
Teacher	95	1.6
Domestic work - shaving, washing and dressing	100	1.7
Walking on the level, 2km/h	110	1.9
Standing, medium activity (shop assistant, Domestic work)	116	2
Building industry - Brick laying	125	2.2
Washing dishes standing	145	2.5
Walking on the level, 5km/h	200	3.4
Bicycling	290	5

Table 9: Details of different Met value (Shakir, 2010:20)

Two main approaches have been used for the analysis and evaluation of the wind environment around objects: wind tunnel measurements and computational fluid dynamics (CFD) simulation.

2.4 Wind tunnel technique in ventilation studies

The wind tunnel technique is an experimental technology that utilizes (a) scale physical models and (b) air or other gases as flow media to study wind pressure coefficients and ventilation rates (Carey and Etheridge, 1999).

Wind tunnels are frequently used to model urban street canyon turbulence and ventilation dynamics (Cook, 1985, Kastner-Klein and Rotach, 2004 and Inagaki and Kanda, 2010). Simplified wind tunnel models reproduce the main features of most common street configurations in relation to pollutant transport and air quality. However, care must be taken to ensure the boundary layer is scaled correctly. As will be shown in this introductory review, there are a few studies in which the mean and unsteady flow dynamics from a wind tunnel and field study have been quantified and compared in order to justify the validity of the wind tunnel results. Urban areas vary drastically in terms of geographic location, not only with regard to natural landscape but also to the style of architecture and building density. Computational Fluid Dynamics and wind-tunnel measurements are two means of determining pedestrian-level wind (PLW) speed as a part of a wind comfort assessment. The comparatively affordable Reynolds-Averaged Navier-Stokes (RANS) method is typically used to carry out a CFD simulation. Affordable techniques are also utilised for wind-tunnel measurements, including Irwin probes, hot-wire or hot-film anemometers, or sand erosion. Other wind-tunnel measurements for PLW are more costly, such as Particle-Image Velocimetry (PIV) or Laser-Doppler Anemometry (LDA). A third means of determining PLW is infrequently utilised due to high costs and convolutions – Large-Eddy Simulation (LES) (Blocken et al., 2016).

During the process of modelling, heating elements can be inserted to generate a buoyancy effect. In wind tunnel tests, both surface pressure and wind speed regions are unsteady, so time-averaged surface pressures with coefficients have to be taken into account, which has been a major part of recent theoretical design and actual operation (British Standard 5925, 1991).

During the study of natural ventilation in scale models, the buoyancy effect has generally received the most attention (Yang, 2004). However, these test results vary according to the accuracy and surface roughness of the model. Manual processes and interference caused by measurement equipment such as sensors for measuring air speed may also reduce the precision of the results.

Several pieces of research use wind-tunnel measurements to study natural ventilation around buildings, including at pedestrian level, and particularly in terms of the building and urban aspects. For example:

Using parametric wind tunnel studies, Tsang et al. (2012) examined how the pedestrian level wind environment was impacted under both weak and robust wind conditions by building separations and dimensions, a podium or a row of buildings. In doing so, their research considered a 400m area downwind from the examined structures. The study resulted in three major findings. First, the researchers found that taller buildings were able to enhance conditions in the ambient air ventilation, in comparison to an individual, wider structure which negatively impacted pedestrian-level natural air ventilation. Next, the study discovered that building separations ought to be more than half the width of each building, otherwise there is likely to be a negative impact on pedestrian-level natural air ventilation. Finally, the study noted that air movement around structures was negatively affected by the presence of a podium.

The research carried out by Zahid et al. (2016) also looked at pedestrian-level wind environment, this time in the context of grouped high-rise structures. To do so, the team specifically looked at different levels of building separation, building shape (L-, I-, U-shape or square), and building orientation. The researchers found that building separations and wind incident direction significantly impacted wind flow within re-entrant corners. Variation in wind speed was greatest on the downstream side as it was where the greatest difference in blockage, building configuration and flow pattern occurred. Wind speed variation was reduced when measured on the windward side, as the researchers uncovered comparable wind events and movement configurations.

In a related study, the impact on the outdoor wind environment as caused by building density was examined by Kubota et al. (2008). This study compared several large Japanese cities, allowing for a range of climactic contexts when evaluating wind tunnel results. Specifically, the study looked at 22 residential neighbourhoods within these cities. The research found robust correlation between average wind velocity ratio and gross building coverage ratio when looking at both detached houses and apartments. It is no surprise that the two are inversely connected: an increase in gross building ratio results in a decrease in average wind velocity ratio. Therefore, the study found the gross building coverage ratio was a better predictor for mean pedestrian-level wind velocity than the gross floor area ratio.

2.5 CFD application in ventilation studies

CFD, as researched by Gosman (1999), has gained widespread acceptance by taking advantage of the recent rapid progress in computer capabilities and new developments in numerical modelling.

In fact, to evaluate the environmental effects of developing an urban design, modelling is preferred over field measurements, as these can be costly and not suitable for optimisation studies. This dichotomy is discussed in detail by Wang et al. (1996) in the context of their research. There are some limits to the capabilities of experimental modelling. Where a scale model is created and tested in a wind tunnel, the technique is sometimes characterised by high time requirements and high costs, especially if optimisation studies are to be undertaken and detailed measurements are needed. When only minor changes in the physical model's configuration and/or geometry are required for a parametric evaluation, however, data acquisition via wind tunnel testing may prove to be highly expeditious and reliable at only moderate cost (Wang et al., 1996).

Computational modelling requires a powerful computer to display a virtual model of an urban fragment; once created, however, this can be modified relatively easily compared to physically modelling buildings. The whole simulation may take hours, days or weeks depending on the resolution required. After studying simulations in CFD, detailed wind flow descriptions, including wind direction and speed at each point around objects such as buildings can be described directly. Importantly, accurate model validation is required to apply this tool with confidence (Blocken and Carmeliet, 2004).

The earliest systematic study of CFD simulation in wind environments at the pedestrian level was performed by Bottema et al. (1992) who examined the wind conditions around a wide structure as well as a series of wide structures using a wind tunnel and CFD and compared the results. Later, air flow over a semi-circular public space surrounding by buildings was simulated by Gadilhe et al. (1993). In the same year, dangerous wind zones with high speeds around tall buildings were numerically predicted by Takakura et al. (1993), and the simulation results were also compared with wind tunnel measurements. Bottema (1993) simulated the wind environments around single and group buildings at the pedestrian level with many different models and diverse configurations. Flow over a single building, between two parallel buildings, and around a variety of buildings were simulated by Baskaran and Kashef (1996). To ensure test rigour, available wind tunnel results from the research of Ishizaki and Sung (1971) and Stathopoulos and Storms (1986) were applied to validate these projects. With the developments in computing power, Richard et al. (2002) have been able to simulate and analyse the pedestrian environment in downtown Auckland with a highly effective numerical model. The results from this model were also compared with experimental simulation tests, which showed that wind tunnel tests were much more sensitive to gust wind velocities while CFD technology made effective use of mean wind velocities. As shown in other cases, it may because the high mean air speed is applied to indicate the environment around the corners of buildings when the erosion patterns are in accordance with turbines affected by the building edge and downstream air flow in CFD simulations.

Skote et al. (2005) have applied CFD simulation with 3D steady RANS and wind tunnel measurements to analyse the influence of street location in a proposed city model on the outdoor ventilation. The results have proved that the CFD method is a trusted tool for assessing the outdoor wind environments.

Therefore, the air flow in the specific area between parallel buildings has been analysed with 3D steady RANS and the realizable $k-\varepsilon$ model by Blocken et al. (2007). Comparing the results of CFD and wind tunnel measurements, the deviations were under the acceptable range ($< 10\%$), and they have a close agreement.

Tareq et al. (2015) have also applied 3D steady RANS CFD modelling to analyse the natural ventilation in a lightwell connected to outdoor through horizontal voids. Its validation results are also proved that agrees with wind tunnel tests, and wind environment, including velocity, is affected significantly by wind direction.

Ramponi et al. (2015) analysed the influence of different street widths on outdoor wind environment with new CFD simulations of generic configurations. They have proved that the effect is mainly according to the wind direction, and that the main street is conductive to the ventilation of the downstream district.

Some outdoor thermal environment research projects have also integrated CFD simulation (Bruse and Fleer, 1998, Tominaga et al., 2004, Stathopoulos, 2006). The outdoor air flow around apartment blocks was simulated by Chen et al. (2004b), and the influences of different urban morphological designs according to SET* urban criteria were studied. In addition, based on the CFD technique and a genetic algorithm (GA), Ooka et al. (2008) simulated the optimum arrangement of trees to increase the pedestrian thermal comfort level. Chen et al. (2008) found that applying the distribution of SET* accurately related to the arrangement of structures, which indicated that computational modelling was conducive to urban design, and that appropriate design could improve urban outdoor thermal comfort at the pedestrian level.

2.6 Summary

Theories based on research of urban open space planning have been developing for a long time, but urban planners may have paid too little attention to the relationship between urban morphology and micro-climate. Urban planning plays an important role in local climate, especially in terms of air flow and solar radiation, and micro-climate itself is extremely important to residents. Architects also tend to consider indoor thermal comfort, but they may ignore the effect of their buildings on outdoor space, the environment, and pedestrian thermal comfort. The thermal sensation and adaptive capacity of humans' responses to their micro-climate alters based on some of these effects, and when it does, their behaviours and usage of outdoor spaces is changed.

Buildings can be considered as obstructions to air movement, and the changes in air flow are much more complex in high-density, tall building areas. Applying wind tunnel tests and computational simulations for wind environments at urban and street canyon levels can determine the air characteristics around single buildings and group buildings, allowing planners to experiment with various arrangements.

Air ventilation is beneficial to negate pollution emissions. As well as this, more wind is desirable to reduce urban heat islands, increase human heat loses, and decrease heat stress in hot and humid urban conditions. In contrast, buildings and trees can prevent the air that creates low wind-velocity zones in leeward streets, which may be preferable on extremely cold days. Increasing building height to some extent and descending stepped building heights in the direction of the prevailing wind can mend thermal climates in high-density tall buildings zones such as central business districts in mega cities. Indeed, specific urban design should take full account of climatic conditions, such as the prevailing wind direction and people's requirements in summer or winter.

Air ventilation assessment and thermal comfort indices have been developed during the past decades based on modern requirements for safety and comfort. In general, wind speeds should be less than 5m/s to minimise risk, while the assessment of thermal comfort requires micro-climate, residents' Clo factor and Met to be considered. Therefore, considering the air quality, especially the air change rate and pollutant dispersion, the minimum of wind speed in urban areas needs to be carefully considered. Although this aspect has been mentioned, few researchers have researched deeply enough to obtain the criteria or data. It may because the component and concentration of contaminant is very complicated, as well as the terrain and structures standing on the land.

As opposed to indoor comfort research, outdoor thermal comfort is a relatively new field to urban designers. However, the outdoor thermal comfort environment has received increasing attention over the past few decades, which generated a series of thermal comfort criteria, generally extended from the indoor indices. However, due to fact the external environment measurement and management is much more complex than that used in the indoor environment in terms of spatial and temporal micro-climates and the uncontrollability of various climatic conditions, users' outdoor behaviours will vary widely, especially with reference to their physical and socio-cultural adaptations. With micrometeorological measurements and thermal comfort survey results, the local thermal comfort criteria can be obtained, which is suggested in this research to be the first stage of making urban design.

Improved microclimates can help cities, including CBDs, to reduce energy consumption and become more comfortable and healthier, enabling them to attract a huge number of people and businesses. It is clear from this that successful urban outdoor spaces can benefit the sustainable development of any given city.

CHAPTER 3 METHODOLOGIES

3.1 Introduction

To assess the outdoor thermal comfort of different climate zones around the world, many researchers have investigated urban scale climatology over the past decades. Most of these research studies applied field measurements and surveys of outdoor thermal parameters and human behaviours in urban districts (Nikolopoulou and Lykoudis, 2006, Lin, 2009a, Ng and Cheng, 2012). With a detailed analysis of local meteorological data and mobile weather monitoring, the correlation between weather parameters and human thermal comfort can be illustrated. Indeed, the use of wind tunnels to analyse physical scale models and CFD with numerical simulations has been applied to predict the wind environment around the built areas and to evaluate outdoor thermal comfort (Chen et al., 2004a, Ali-Toudert and Mayer, 2006, Berkovic et al., 2012).

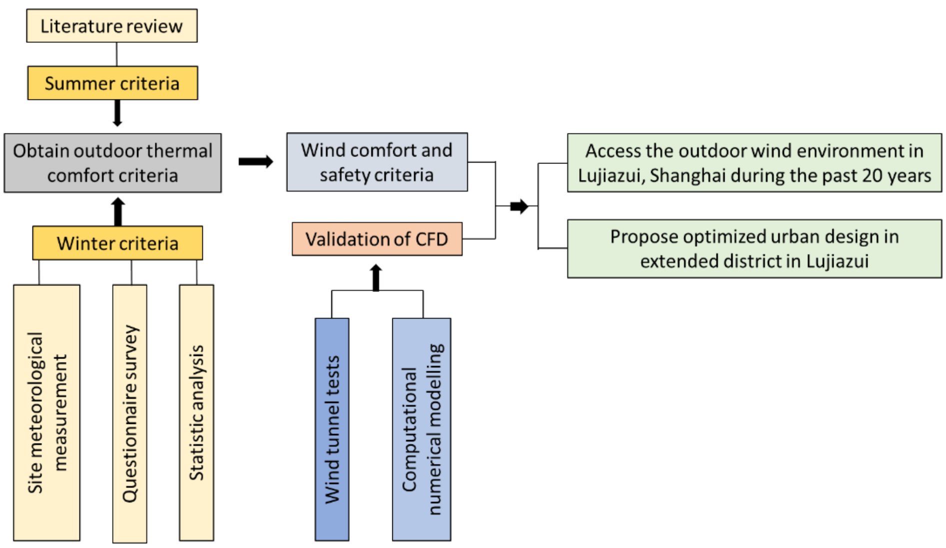


Figure 8: Research method map linked to objectives

Figure 8 has described the research method map linked to the research objectives. This chapter mainly discusses the assessment methods and available modelling techniques for studying outdoor thermal comfort and ventilation at the pedestrian level. The outdoor thermal comfort questionnaire survey, which has been widely utilised, and the application of SPSS for data statistical analysis used as tool to obtain the local outdoor thermal comfort criteria. Time limitation restricted this to a study of the winter conditions. A review of studies made on similar cities/climates was used to estableish comfort criterial for the summer. Then, wind tunnel modelling techniques will also be presented. The applications and procedures of computational fluid dynamic modelling techniques and general turbulence modelling with its principles and formulas will also be explained.

A pilot site in Hong Kong was selected to analyse its outdoor air flow with comparing the results between wind tunnel and CFD, which aims to validate the new software, FlowDesigner. Then, the wind environment will be simulated and assessed by wind comfort criteria in high-density Lujiazui district, Shanghai. It is simulated with two prevailing wind directions in summer and winter respectively with the development of tall buildings in the past 20 years. Finally, some optimized urban design proposals for the extended area will be formulated as well as being simulated and assessed by the wind comfort index.

3.2 Micro-meteorological measurement

In general, measurements of outdoor meteorological data by means of mobile meteorological stations located in survey sites with a reference height of 1.5m have been widely employed in previous studies (Spagnolo and Dear, 2003, Nicol et al., 2006, Ng and Cheng, 2012). With different applications of sensors, the meteorological station can measure air temperature (℃), globe temperature (℃), air velocity (m/s), relative humidity (%), solar radiation (W/m^2) and tec.

All equipment applied in this research study will be discussed in more detail in Chapter 5. In addition, all equipment must be calibrated before taking site micro-meteorological measurements.

3.3 Thermal sensation vote model

With the monitoring of microclimate conditions and the results of the user questionnaire survey on the behaviour and experiences of participants, a thermal sensation vote (TSV) model can be applied to develop an advanced design strategy (Lai et al., 2014b). Multiple linear regressions are employed to identify the link between thermal sensation and data generated by the survey and to evaluate the thermal comfort of the outdoor environment on the basis of widely accessible environmental data (Lai et al., 2014b):

$$\mathrm{TSV} = \mathrm{a} * T_a + \mathrm{b} * G + \mathrm{c} * WV + \mathrm{d} * RH + \mathrm{e} \qquad \text{(Equation 3.1)}$$

TSV: Thermal sensation vote scale from -3 (very cold) to +3 (very hot), TSV = 0 is neutral

T_a: Air temperature at mobile weather station ℃

RH: Relative humidity at mobile weather station %

WV: Wind velocity at mobile weather station m/s

G: Global radiation at mobile weather station W/m^2

and a, b, c, d, and e are regression constants

3.4 User questionnaire survey

There are several different procedures for conducting comfort research which differ in terms of the nature of the information collected, the amount of control exerted by the researcher and the overall cost. Procedures also vary based on the human subjects used in the research project (Stathopoulos, 2006).

One key objective of comfort research is to find out the 'comfort temperature' of any given participant in a given location and season. This determines the range of temperatures in which the largest fraction of users would feel most comfortable. A complementary consequence of such research is the statistical distribution of thermal sensations at that temperature, from 'cold', through 'neutral' to 'hot'. In order to obtain information representative of the population, the size of the sample should be as large as financially possible and each person should be interviewed only once (Francis et al., 2010).

An alternative objective, calling for a different research procedure, might be to determine directly how people respond to changes in climatic conditions such as changes in global radiation, temperature, humidity and wind speed. A complementary objective might be to discover the relative effect of changes in one climatic element (e.g. wind speed) relative to changes in other climatic elements (such as temperature) (Givoni et al., 2003, Nikolopoulou and Lykoudis, 2006).

Moreover, some comfort indexes have been established for assessing the influence of the wind on the human body in the wind engineering community. The criteria in different countries and institutions vary, although wind speed is the most frequently used parameter as a criterion to determine threshold values for acceptable/unacceptable wind environment in the current research study. Indeed, these differences are generally attributable to wind speed averaging period (mean or gust) and its probability of being exceeded (frequency of occurrence) to the evaluation of its magnitude (experimental or computational) (Stathopoulos, 2006).

On the other hand, in many outdoor thermal comfort research projects around the world, the thermal comfort survey is widely applied (Ng and Cheng, 2012). For example, the pedestrians' thermal comfort survey has been incorporated into the EU-funded Project RUROS (Rediscovering the Urban Realm and Open Spaces), which covers seven cities across five countries in Europe, namely Athens, Thessaloniki, Milan, Fribourg, Kassel, Cambridge and Sheffield (Nikolopoulou and Lykoudis, 2006).

Generally speaking, the survey is comprised of two main sections: (1) meteorological condition measurements; and (2) questionnaire survey for participants. When people are filling out the survey, their surrounding temporal micro-climate condition will be measured and recorded by a mobile meteorological station located in the vicinity of the participants. Meanwhile, the questionnaire survey requires participants to express their feelings towards their thermal condition, including various thermal sensations such as global radiation, wind speed, air temperature, overall level of comfort etc. In addition, information on participants' clothing and activity during the survey is collected. Sometimes, demographic background details about gender, age, thermal experience/adaptation is observed and recorded by the interviewer conducting the survey (Ng and Cheng, 2012).

Thermal comfort is estimated from the measured environmental parameters around participants. All basic thermoregulatory processes should be taken into account by the universally applicable models. The user could estimate 'real values' of body thermal conditions, such as skin temperature, core temperature, sweat rate or skin wetness (Niu et al., 2015). Therefore, the Munich energy balance model for individuals (MEMI) is a thermosphysiological heat balance model, which is the foundation for the calculation of the PET.

Ventilation is quite relevant in promoting necessary air movement in urban open spaces with a hot and humid climate. In the Shanghai research site, people may require high air velocity in summer but low velocity in winter. The methodology in this case applied microclimate measurements, which were recorded at the same time that questionnaires on thermal sensations were conducted. The field survey results provide support for the proposal of a scale of wind perception and preference. The results also prompted the suggestion to calibrate the thermal comfort prediction index to the real-life climate of Lujiazui, Shanghai.

3.4.1 Introduction of survey questions

Two versions of the survey were utilised: Chinese and English, and they are presented in Appendix 2 and Appendix 3 respectively. The respondents received the corresponding version based on their nationality. The questionnaire includes two parts: part one is designed to determine the demography of the participants such as gender, age group and provided some options regarding the type of clothes worn by the interviewees and their activities just prior to the interview. Fabbri (2013) has presented that the results of questionnaire about indoor thermal comfort measurement and evaluation is different between children (4 and 5 years old) and adults due to metabolic activity, clothes and Adaptability. Thus, only those people aged 18 or above were invited to participate in this survey. In addition, age and gender composition was considered in order to reduce bias. The clothing insulation values (Clo) checklist is taken from the ISO 7730 standard (2005) (Table 10), and could be calculated to assign a clothing value to each interviewee for further analysis in SPSS.

A. Underwear	Clo	C. Sweaters	Clo	F. Socks	Clo
T-shirt	0.08	Sleeveless, thin-thick	0.13-0.22	Ankles-high Athletic socks	0.02
Full slip	0.16	Long-sleeve, thin-thick	0.25-0.36	Calf-length socks	0.03
Long underwear top	0.2			Panty Hose	0.02
Long underwear bottom	0.15	**D. Coat**	**Clo**		
		Leather jacket	0.46	**G. Shoes**	**Clo**
B. Shirt and Blouses	**Clo**	Cotton-padded clothes	0.6	Sandals	0.02
Sleeveless, scoop-neck blouse	0.12	Down jacket	0.69	Leather shoes	0.08
Short sleeve, dress shirt	0.19			Boots	0.1
Long sleeve, dress shirt	0.25	**E. Trousers and Coveralls**	**Clo**	Sport shoes	0.12
Long sleeve, flannel shirt	0.34	Walking short	0.15	Snow boot	0.2
Long sleeve, sweat shirt	0.34	Trousers and Coveralls	0.24		
		Sweat pants	0.3		

Table 10: Clothing values checklist (adapted from ISO 7730 standard, 2005)

Furthermore, this part addressed the thermal experience of the participants in the instantaneous past and their subjective sensation of the corresponding microclimatic conditions. In addition, most of the questions were adapted from the previous research (ASHRAE, 2004, Cheng and Ng, 2006, Ng and Cheng, 2012). The questions and their purposes in part one are shown below:

1) Have you done this kind of questionnaire before?

Purpose: to determine whether the participant has done this kind of questionnaire and if it would affect the overall thermal sensation.

2) In your opinion, is it important to consider thermal comfort in urban outdoor space?

Purpose: to obtain the people's attitudes towards thermal comfort in outdoor areas.

3) When was your most recent visit to Lujiazui district, Pudong?

Purpose: with the next question to compare the participants' comfort level (could simulate in the CFD over three years to understand the development of this area's pedestrian thermal comfort).

4) With the increasing number of completed tall buildings, do you think the current outdoors environment is more comfortable than last time you came here?

Purpose: to compare the users' feelings and the simulation results.

Which factors affect your comfort level? (Multiple choice)

Purpose: to identify the factors that affect people's comfort.

5) Have you been staying in Shanghai during the past six months?

Purpose: to understand the participant's long-term acclimatisation.

6) In the past 15 minutes, have you been to (or stayed in) indoor spaces with air-conditioning or heating (including bus, taxi, underground, etc.)?

Purpose: to understand the participant's short-term acclimatisation or thermal adaption.

7) What were you doing during the past 15 minutes?

Purpose: to understand the participant's activity just before starting this survey.

8) Why did you use this particular place?

Purpose: to understand the reason for being in the place of the interview.

9) How do you feel in terms of thermal perception about the surrounding environment?

Purpose: to understand the participant's thermal sensation.

10) Are you wearing a hat or other things to prevent the direct sunlight?

Purpose: to know whether the participant is exposed to the sun directly.

11) How do you feel about the exposure to the sun?

Purpose: to understand the participant's perception of the solar condition.

12) How do you feel about the wind?

Purpose: to understand the participant's perception of the wind condition.

13) How do you feel about the air humidity?

Purpose: to understand the participant's perception of the humidity.

14) How is your skin wetness?

Purpose: to understand the participant's skin condition.

15) Overall, what is your feeling about this place?

Purpose: to understand the participant's perception of overall comfort.

Pure observation is employed in part two of this questionnaire, which includes: (a) time of the interview; (b) location of the interview; and (c) temporal weather conditions. Three main activity options (sitting with 1 met, standing with 1.2 met, walking with 2 met and taking exercise with 2.2 met), can be observed and recorded by the interviewers.

3.5 Computational numerical modelling

CFD validation for assessing wind environments has been widely applied across the world, although most studies only simulate and compare the results for validation with one single building or several building blocks. However, the absence of credible experimental data means that validation for different configurations of a set of building structures has not yet been obtained (Blocken and Carmeliet, 2004).

With simulation in CFD, the model applied in the present research study can predict the influence of urban form on the natural environment at a microscale. Therefore, it can be used to analyse the influence of changing urban form and urban designs. Compared to visual observation, CFD can offer an adequate prediction of wind environment, which is also considered to be a valid tool for studying tendencies in airflow characteristics (Blackman et al., 2015). The purpose of the CFD simulation is to generate airflow maps that can detect and depict wind-sheltered areas and intense ventilation zones. Indeed, high wind velocity may occur between buildings or at the corner of a building podium, which may cause people to lose balance. On the other hand, polluted air and dust would move more slowly where the wind speed is much lower, or even absent.

CFD methods can simulate both two- and three- dimensional flow patterns with detailed flow field results. This section introduces basic CFD applications and its procedures as an assessment tool for analysing outdoor wind environments. Some related equations and turbulence models will also be presented.

3.5.1 CFD applications and procedures

CFD solutions are the numerical calculation of fluid flow within space and time. It can deal with many problems of fluid physics and chemistry, such as compressible and incompressible flow, steady and unsteady flow, turbulent and laminar flow with and without heat transfer, and so on.

The application of CFD is often motivated by the limitations of measurement techniques. In many cases, measuring devices interfere with the wind field and produce measurement artefacts (Yang, 2004) or may be limited in spatial coverage. In addition, measurements usually require elaborate equipment, manpower and time, thus incurring high costs. Interpolation techniques are frequently used to overcome this problem and to obtain spatially and temporary coherent information. However, these techniques depend on numerous assumptions and outcomes that may bring some deviation. Thus, CFD models are used to assess different scenarios that cannot be, or are too costly to be, investigated experimentally (Wakes et al., 2010). These models are also shown to be a flexible, efficient and cheaper alternative to experimental setups (Alhajraf, 2004 and Parsons et al., 2004).

On the other hand, there is a strong need for the validation and assessment of the data obtained by simulation. This does not refer merely to the feedback process of formalising knowledge and testing if the theory is in conflict with reliable data, but the manner in which numerical approximations, parametrisation schemes (e.g. turbulence models, discretisation techniques) and the choice of boundary conditions can introduce errors in simulated data sets that should be evaluated against measured data.

In general, once the model is built, a computational domain can be created to display the geometry of the objects (such as buildings). Then, the model and the fluid medium (such as air) contained in the boundary will be divided into a large number of cells (mesh or grid). Within each cell, the fluid properties and specification of appropriate boundary conditions can be defined. For example, the bottom surface that makes direct contact with the building could be earth, while some vertical surfaces of the boundary act as flow inlet and outlet if simulating the outdoor wind environment. When making calculations, in these small volumes, the partial differential equations for describing the fluid flow are replaced by algebraic approximations that relate the pressure, speed, temperature and other elements, which then value the neighbouring cells. After that, these equations are solved numerically yielding one complete profile of the flow to the resolution (Yang, 2004).

3.5.2 Computational modelling

Equations for momentum, turbulence, heat transfer and mass all feed into the flow model. The following governing equation 3.2 for momentum, turbulence, mass continuity and enthalpy makes up the principal equation used for heat and non-reactive fluid (Gan, 2013: 257):

$$\frac{\partial(\rho\varphi)}{\partial t} + \frac{\partial(\rho U_i \varphi)}{\partial x_i} - \frac{\partial}{\partial x_i}\left[\Gamma_\varphi\left(\frac{\partial\varphi}{\partial x_i}\right)\right] = S_\varphi \qquad \text{(Equation 3.2)}$$

Where: ρ is the fluid density (kg/m^3), t is the time (s), φ is the flow variable (mean velocity, for example), U_i (m/s) in x_i (m) direction, pressure, temperature and turbulent parameters, Γ_φ is the diffusion coefficient (N s/m^2) and S_φ is the source term.

The variation of flow variable φ in terms of time is explained through the first term on the left shown. The flow variable in terms of convection is explained through the second term shown. The flow variable in terms of diffusion (with diffusion coefficient Γ_φ) or in terms of conducted heat transfer via solid vector (diffusion coefficient Γ_φ= thermal conductivity) is explained through the third term shown. The right term of formula explains from whence the flow comes or sinks.

Turbulence modelling can be used to simulate fluid flow turbulence. The most frequently employed model for this is the standard k–ε model (Launder and Spalding, 1974). When both turbulent and laminar flows are included in buoyancy-induced natural convection, a modified version (introduced and detailed by Gan, 2013: 257) is best utilised.

CFD simulations usually involve the discretization and solution of the Navier–Stokes-equations (NSE) at finite grid locations (Hensen, 1990). Turbulent-flow simulations involve the computation of a velocity field as one realisation of the turbulent flow.

The three best known turbulent simulations are DNS (direct numerical simulations) and LES (large eddy simulations) and RANS (Reynolds-averaged Navier–Stokes) (Kenny et al., 2009). DNS of the NSE renounce a turbulence model and are very cost- and time-intensive since all significant time- and length-scales are resolved (Shao, 2008). It requires a large number of computational resources, which means the calculating time primarily depends on computer characteristics, power and capacity. Besides, it can only be used in simple geometries and with low Reynolds numbers, and the computational costs increase in line with the cube of the Reynolds number (ASHRAE, 2013). However, LES is appropriate for solving the equations for a specific velocity field for larger-scale turbulence motions and apply turbulence models for non-resolved turbulent motions. Turbulence models imply that the fluid motion is computed based on mean quantities (Pope, 2000).

One of the most applied turbulent model approaches is obtained by applying the Reynolds decomposition, which leads to the Reynolds-averaged Navier–Stokes (RANS) simulation. Using RANS, statistically steady flows are time-averaged while time-dependent flows are ensemble-averaged. The former is the most frequently used RANS procedure and is also the most widely validated in the field of computational wind engineering (CWE). This RANS method has been applied in a number of different contexts, such as the approximation of pressure coefficients, natural ventilation, wind conditions on the pedestrian level and the dispersal of pollutants.

A higher degree of turbulence is resolved using the LES approach and this is also a more time-dependent method. As such, it has the capacity to generate more precise data compared to statistically steady RANS calculations (Tominaga et al., 1997). That being said, LES has much higher CPU and memory requirements and necessitates the input of time- and space-resolved data in the form of boundary conditions in order to effectively mimic the inflow. These limitations indicate that CWE measurements will be made primarily using statistically steady RANS for the foreseeable future, which is also applied in this thesis.

Irrespective of whichever method is applied, the validation of CFD measurements through the comparison of results with data generated by field or wind tunnel tests is imperative as turbulence models operate on the basis of assumptions. As such, there is no existing turbulence model that can be applied to a diverse range of contexts and applications.

3.5.3 Numerical solvers and software

There are some different types of commercial software that can be applied to facilitate thermal comfort analysis. As shown in Table 11, the main function of some of the most popular tools have been listed, and the dark green describes the dominating application while the light green describes the secondary function. Wind environment is the main research field in this thesis, so both Fluent and FlowDesigner software have been applied at the early stage of CFD simulation. Fluent was the initial choice, but using this it was difficult to build models of atypical tall buildings, especially for a huge urban site. Besides, it took considerable time to mesh and calculate after importing the building models from other software. However, compared to Fluent, the latter one has more advantages to deal with the calculation for high-density tall building zone, as it can: (a) create a better virtual wind tunnel for outdoor natural ventilation; (b) visualise effects with better control; (c) requires less time for calculation; and (d) import SketchUp (.skp) and Rhino files. This new CFD software (FlowDesigner) has been introduced in recent years, but not applied broadly, which means it still has to be formally validated. In Chapter 4, actual urban environments in high-dense zones in

Hong Kong will be simulated in both wind tunnel tests and FlowDesigner to demonstrate its reliable and accuracy.

Tools	Author Institutions	Radiation	Wind Speed	Air Temp.
Rayman	Univ. Freiburg (Germany)			
SOLWEIG	Univ. Gothenburg (Sweden)			
DIVA	Harvard GSD (USA)			
FlowDesigner	AKL (Japan)			
Fluent	ANSYS (USA)			
UMI/UWG	MIT (USA)			

Dark green	Fundamental function and employed widely
Light green	includes function but not employed widely
White	No function

Table 11: Tools for thermal comfort simulation

The vision of FlowDesigner 11 is used in this study and the main function of "External analysis" is quite helpful in simulating the outdoor wind environment around buildings (Figure 9). Further details on modelling, mesh and analysis configuration will be introduced in Chapters 4 and 6.

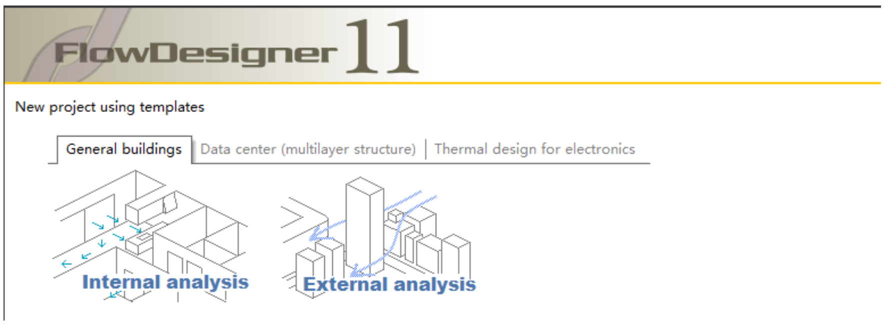


Figure 9: Interface of FlowDesigner 11

3.6 Summary

In this chapter, different methods for studying pedestrian thermal comfort in urban outdoor areas have been introduced. With the utilisation of mobile meteorological stations, micro-climate data, including air temperature, globe temperature, air velocity, relative air humidity and global radiation, can be measured on streets and parks. Integrated with these data, the results of the outdoor thermal comfort questionnaire survey can generate local thermal comfort criteria. This combination has been applied widely in many other research studies to generate local thermal comfort indexes.

Wind environment plays an important role in determining the behaviour of users in outdoor spaces. Thus, wind tunnel tests and computational numerical modelling will be used in this thesis to simulate air flow around buildings in an urban scale. The former is frequently used to model urban street canyon turbulence and ventilation dynamics, while the latter is an adequate estimation of wind environment that can also be utilised for validation purposes. CFD has been developed as a flexible, efficient and cheap alternative to experimental setups in many studies, and as one of the most convenient and efficient types of CFD software for wind flow modelling, FlowDesigner, will be applied for simulation later in this study.

CHAPTER 4 OUTDOOR VENTILATION IN DENSE ZONES IN HONG KONG

4.1 Introduction

Pedestrian level winds play an imperative role ensuring comfort, safety and diffusion of heat in urban areas. Outdoor wind study is especially vital and a prerequisite in high-density cities considering that the immediate pedestrian level wind environment is fundamentally impacted by the presence of a series of high-rise buildings. Roughness elements and variational local flow patterns influence wind characteristics above the actual ground surface. However, one simple mathematical equation does not represent the wind profile, for example, the power law does not describe the wind environment near urban ground levels. Wind profile can be significantly affected by many factors, such as the height, width, distance, arrangement and density of buildings in the vicinity. Therefore, although it may be complex, evaluation of airflow in the urban canopy layer is extremely necessary in order to provide solutions for several environmental problems, such as elevated heat island intensity and critical air pollution levels.

Heat islands are a notable concern in the high tall building density regions of Hong Kong and Singapore, especially on hot days. Consequently, Hong Kong and Singapore have been the focus of a huge number of outdoor thermal environmental studies and most of these received encouragement and funding from the local government. In 2014, I applied to the programme of Universitas 21 (U21) and obtained an excellent opportunity for an exchange period at the University of Hong Kong for six months as a visiting PhD student. Led by Assistant Professor Jianxiang Huang, I was able to study several research projects related to pedestrian comfort in urban areas and have, as a result, further developed my technical knowledge in this area. Therefore, as part of a research team, we performed wind comfort studies in Sai Wan, including site measurements, wind tunnel tests and CFD simulations. This enabled me to pilot the techniques that I intended to apply in my case study under expect guidance. The results on improving wind environment at pedestrian level by advancing building morphology have been approved by Hong Kong Green Building Council (HKGBC). Part of the time spent there was to develop skills in the use of the software tools and the comparison with wind tunnel work allowed me to get a feel for the accuracy of the CFD method.

In this chapter, the research site of Sai Ying Pun in Hong Kong will be analysed first in terms of geography, climate and urban morphology. Following this, the wind tunnel experiment with detailed parameter settings will be described. A Japanese CFD simulation software of FlowDesigner will then be introduced and applied to analyse outdoor natural ventilation at the aforementioned site. Finally, thirteen points at pedestrian-level height (1.5m) will be selected to collect the wind velocity in both wind tunnel tests and CFD simulations, the results of which will be compared to validate the accuracy of the standard k–ϵ model.

4.2 Introduction of site: Sai Ying Pun in Sheung Wan, Hong Kong

As shown in Figure 10a, Sai Ying Pun is situated in the Western District of Hong Kong Island and is a key administrative region for both the Western and Central districts. In the local tongue, Sai (西) means "west" while Ying Pun (营盘) translates as "camp", generally a military camp. The British military were based in this area and the locality was one of the first developmental zones in wider Hong Kong. Although the existing buildings are in poor repair, most of these are residential buildings and a lot of shops, selling sea food products and traditional Chinese medicinal materials, exist on the ground level (Figure 10b). In Sai Ying Pun, there are many small lanes and the majority of these are only open to pedestrians. While these lanes may have been quite significant in the past as they provided access to local residential properties, they now primarily function as back alleys and shortcuts between housing units. Furthermore, the area has a primarily aging population and as many elderly people living in this part of the world prefer to socialise outdoors, the stipulation for a safe, comfortable and healthy outdoor wind environment at the pedestrian level is crucial, not only for the inhabitants, but also for those working here. Additionally, there are many similar narrow streets surrounded by tall buildings in other regions of Hong Kong, which may account for Sai Ying Pun being a popular outdoor thermal comfort research case study for researchers. Although the geometry, urban and building layout in this site are applied as a convenient case study with a high-density tall building district to compare the results between wind tunnel tests and CFD simulation, understanding of some aspects of social environment, neighbourhoods, residents' requirement etc. is conducive to compare thermal comfort criteria in Hong Kong and Shanghai in the next chapter.

(a)

(b)

Figure 10: Introduction of Sai Ying Pun: (a) location in Hong Kong (blue point) and (b) street view (source from google map)

The public climate data, including wind patterns, generally come from airports, however, the wind patterns of sites surrounding airports are frequently quite varied from measurements taken here. Accordingly, to better match the site location and obtain more accurate simulations, understanding basic theories of air movement can benefit regulating the wind data. The local meteorological data is always monitored by the nearest meteorological station, and some are in airports (rural area) while some are located at the top of buildings or mountains (urban area). In terms of the first one, the wind data is always typically measured and collected at 10m (30ft) above ground level, which, as well as the terrain between the airport and site, must be considered when analysing the pedestrian level wind environment. However, the nearest station around Sai Yin Pun belongs to the latter one, and it is located on the roof of one tall building (approximately 60m height) in the University of Hong Kong, and their straight-line distance is about 300m.

The red dashes illustrate the target research site area for wind tunnel testing and CFD simulation (Figure 11a and 11b). Connaught Road West and the ocean are north of this site, whilst the Sai Ying Pun Metro Station is on the south. There are approximately 36 tall buildings and podiums that link a number of these.

(a)

(b)

Figure 11: Target research area in Sai Ying Pun, Hong Kong: (a) 2D version and (b) 3D vision (source from google map)

4.3 Wind tunnel tests

This section details the equipment, experiment set-up, procedure and also results of wind tunnel tests applied in the outdoor wind environment simulation in Sai Ying Pun to modify the parameter settings of CFD simulation. Wind tunnel tests are carried out to evaluate the interference effects attributed to several medium-rise and high-rise buildings.

4.3.1 Test cases and experiment set-up

The experiments were performed in the boundary layer wind tunnel at the Department of Civil Engineering, University of Hong Kong. The working section is 12m long, 3m wide and 1.8m high. To simulate natural wind conditions, 8m long fetch of floor roughness elements have been applied (Figure 12b). The inlet wind for simulation is provided by the fan from behind the wooden rail fence. Opposite the simulation room (Figure 12a), the target building models could be fixed on a rotatable round plate (2.5m diameter). After passing through the building target site, the air will enter another empty room beneath the simulation room, following which it is brought back by the fan into the simulation room creating one closed air flow pipe with the direction of movement depicted by grey arrows.

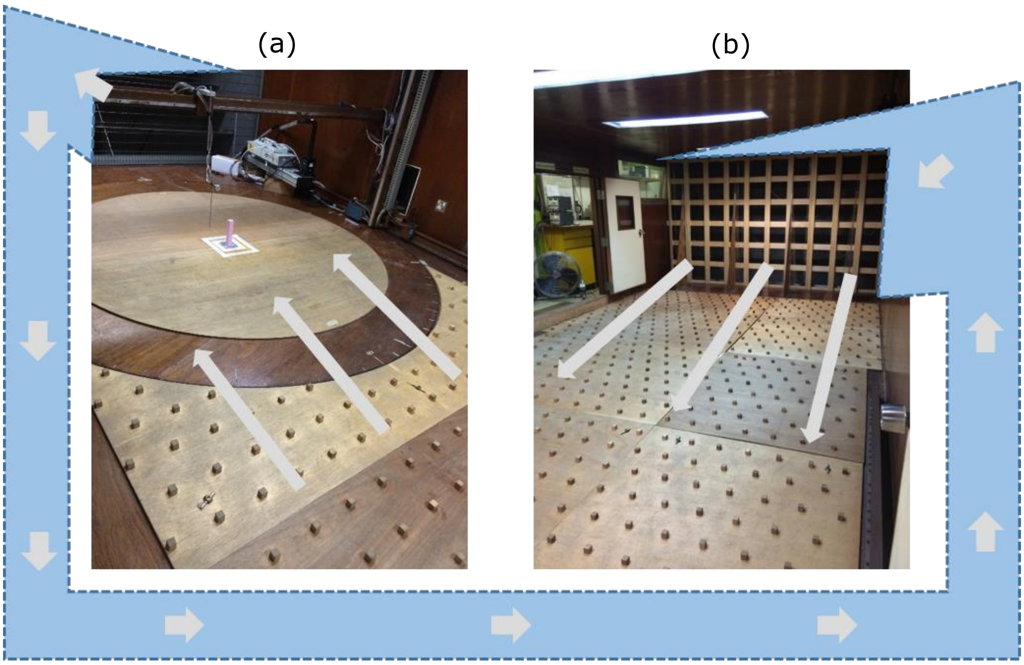


Figure 12 : The boundary layer wind tunnel in HKU: (a) the rotatable round plate for fixing target models and (b) floor roughness elements in wind tunnel

Two pressure sensors connected to a pitot static tube respectively, and they were employed to measure wind factors, such as wind speed, direction and pressure. One sensor and tube unit was installed on the moveable frame above the model, whilst the other one was fixed onto a further frame ahead of the models. This category of sensor and tube unit projects an "L" shape (Figure 13) and it can only move vertically and horizontally when controlled by the external control panel (Figure 14). The sensor does not rotate automatically and, therefore, is manually rotated by the operator when necessary. The wind speed can be monitored from the control panel that is also able to set up inlet wind velocities. In operation, measurements were undertaken without the presence of people in the wind tunnel to exclude any effect they might have on the velocity distribution in the facility and to minimise the chance that they might damage the model. As mentioned above, the unit will move along the horizontal X-axis or Y-axis according to the input distance data from the control panel, which means the path between each selected point should be calculated and designed accurately in advance.

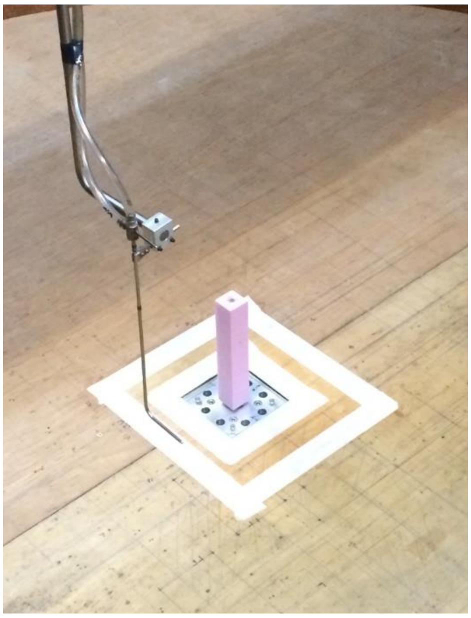


Figure 13 : The unit for reading wind factors in wind tunnel

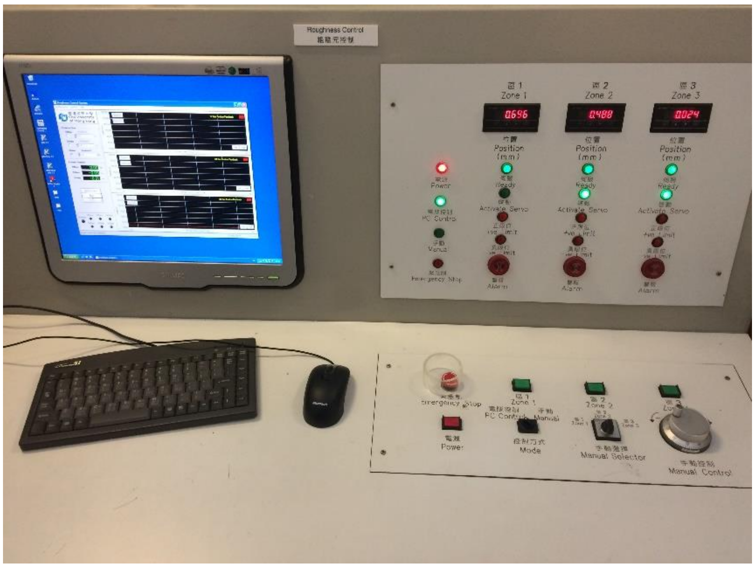


Figure 14 : Wind tunnel control panel

Lam et al. (2013) tested the shielding effects of various configurations of surrounding medium-rise buildings in the same wind tunnel laboratory in HKU. In their research, the vertical profiles of mean wind speeds and turbulence intensities have been measured at the centre of the turntable for the simulated wind, for two terrain types: open land and suburban. According to Equation 2.1, both the terrains have employed the mean wind profile following the power law with power exponent $\alpha=0.13$ and 0.20, respectively. Due to the geographical location (the north of Sheung Wan is sea) and urban morphology (located in high-dense tall building district), the suburban land terrain is chosen to describe Sai Ying Pun and the power exponent 0.20 will also be applied in the latter CFD simulation.

4.3.2 Procedure

The target geometric scale is 1:300; therefore, the tallest building with an approximate height of 150m will be 50cm in model-form. The entire building models were built from a lightweight foam material (Figure 15).

To determine the inlet wind direction and speed, the wind rose diagram for the Sai Ying Pun area (1999-2004) is illustrated in Figure 16. It is important to note that East and North are the two prevailing wind directions with the maximum wind speed exceeding 10m/s. As mentioned above, the only purpose of using a wind tunnel is to compare the results with CFD, so it is feasible to determine the mean inlet wind velocity as 6m/s for both wind tunnel tests and CFD simulations with north and east wind directions.

Figure 15: Test case of high-rise building models in wind tunnel

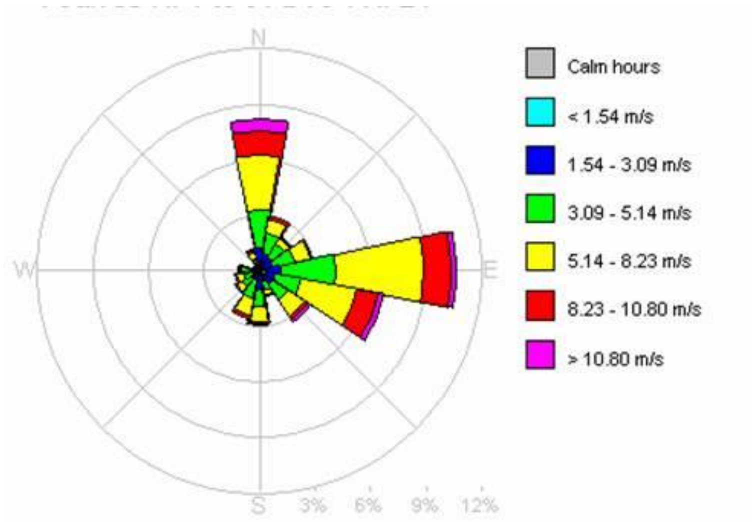


Figure 16 : Wind rose of Sai Ying Pun during 1999-2004 (Source: http://www.weather.gov.hk/)

4.4 CFD simulation

As mentioned above, the CFD simulation software (FlowDesigner) will be applied in this thesis due to its many advantages on model building, time saving, accuracy and convenience for large urban sized model simulation. All structures in Sai Ying Pun have been built in Rhino and then imported into FlowDesigner for simulation. Perhaps the most crucial factor in determining the validity of simulation data is the development of suitable computational modelling methods. In this case, domain size, grid size and grid discrepancy will be discussed. Furthermore, the neutral atmospheric boundary layer profiles of mean wind speed, turbulent kinetic energy and turbulence dissipation rate will be applied.

4.4.1 Set up of the simulation

The target site area is approximately 260 ∗ 450 ∗ 160m (W ∗ L ∗ H), while the whole computational domain size for this validation experiment is 2000 ∗ 2000 ∗ 400m (Figure 17).

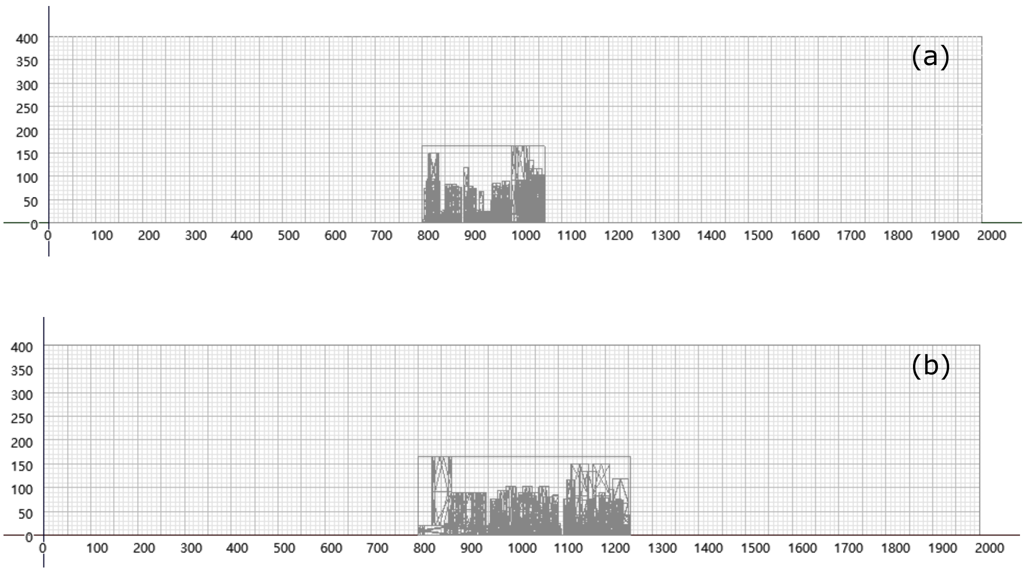


Figure 17: The size of site and boundary: (a) x-z axis and (b) y-z axis

Usually, a smaller size of cells or increased total number of cells in one site will bring much more accreted results. However, it is restricted by the computational technology, which means it requires much time to mesh and calculate. The only way to solve this problem may be under the limitations, increasing the number of cells and decreasing cell size in the interested district, such as UCL. Indeed, the street layer should be obtained much attention when analysing pedestrian wind environment. In this thesis, considering software limitations, an adaptive meshing method has also been employed in view of its ability to obtain increasingly accurate data on wind environment at the pedestrian level, which can, subsequently, utilise the computational resources efficiently too.

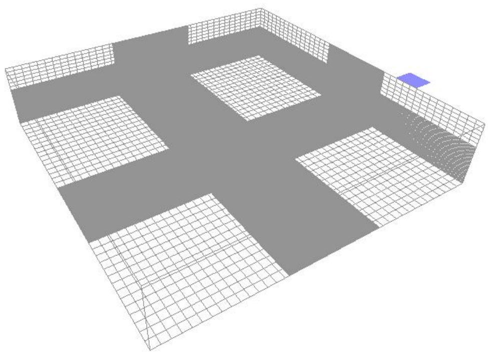
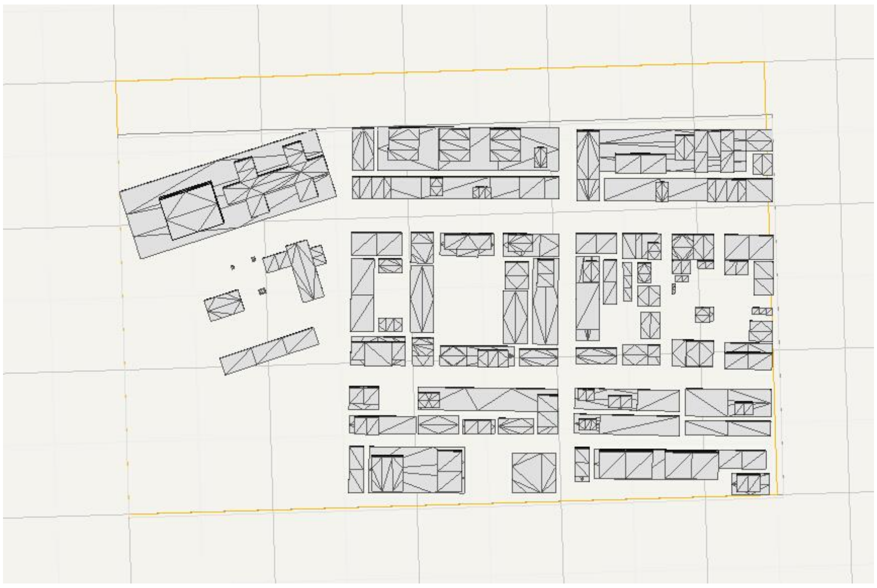


Figure 18: Cross-section of the buildings and grids

Figure 18 depicts the finer scale grids arranged in the areas of interest surrounding the buildings and the ground. In addition, three more layers are arranged below the evaluation height (1.5m above ground level, roughly human head/chest height where the thermal environment is sensed) and the maximum grid size ratio is set to 1.2. There are three levels of cells: In total, the domain is divided into 7,776,000 cells. Furthermore, the grid distribution is established based on the recommendation by the Architectural Institute of Japan (AIJ) (Tominaga et al., 2008), whereby 10 cells correspond to a cube root of building volume, which means the footprint of each building is divided into at least 10 cells to increase the accuracy of results. In this condition, the smallest size of cell in the interested with the most density area is about 1 * 1.2 * 0.5m (W * L * H).

The arrangement and aerial view of a series of tall buildings in Sai Ying Pun are illustrated in Figure 19. The majority of medium to high buildings share an analogous design, whereby approximately two or three floors are dedicated retail spaces, whilst the bulk of the tower buildings are residential. Therefore, inhabitants tend to frequent the surrounding streets as well as the green courtyards connected with the main streets via a 2m-wide alleyway, which contains at least 2 cells in width. Senior citizens typically use this kind of alleyway, but it will be much dangerous for them if the air speed is too high to walk or even stand.



(a)

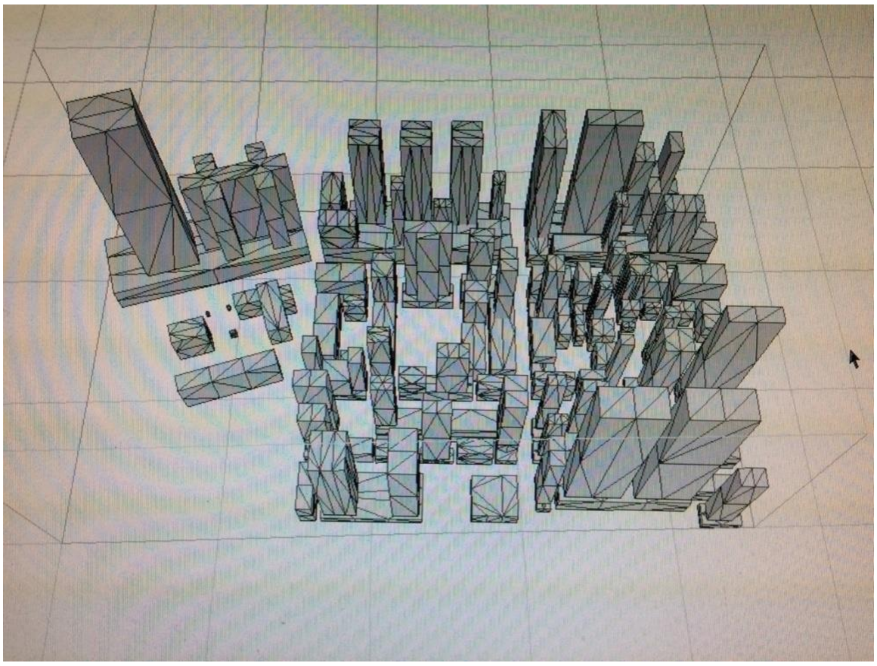

(b)

Figure 19: The model of tall buildings in Sai Ying Pun: (a) 2D plan vision and (b) 3D vision (author, 2016)

4.4.2 Parameter settings

As described by Mochida et al. (2008) and Hong and Lin (2015: 20), the boundary conditions, turbulence model and other boundary parameters are detailed in Table 12. For the purposes of this thesis, the CFD simulations have applied the 3D steady RANS equations and the standard $k-\varepsilon$ turbulence model provides closure. A basic algorithm is used to stabilise pressure velocity-coupling. For the convection and viscous terms of the governing equations, pressure interpolation is the second order utilised. Once the scaled residuals stop dropping in line with continued iterations, convergence has been obtained.

Turbulent model	Standard $k-\varepsilon$ model
Discretization scheme	Second order upwind
Inlet	$U = U_0(Z/Z_0)^{\alpha}$
	$k = 1.5\cdot(I \times U)^2$
	$\varepsilon = C_\mu \cdot k^{3/2}/ll = 4\cdot(C_\mu \cdot k)^{1/2} Z_0 Z^{3/4}/U_0$
Side, sky	Free slip
Wall	Generalized logarithmic law

Table 12 : Boundary conditions and turbulence model

As mentioned in Methodology, (a) U is horizontal wind speed at the height of Z; (b) $\mathrm{U_0}$ is the horizontal wind velocity at the reference height of Z_0; while (c) α is the exponent affected by the roughness of the ground. In this CFD simulation, $\mathrm{U_0}$ = 6m/s, Z = 1.5m, $\mathrm{Z_0}$ = 10m, α = 0.2 taking into consideration the dense building complexes in this urban site location.

4.4.3 Results

The wind flow can be influenced by objects as well as building patterns and orientation. Generation of high-pressure zones by wind deflection on windward facades is a well recognised phenomenon, while low-pressure zones are attributed to wind separation over the leading sharp edge and leeward façade. Indeed, wind environments with high velocity and turbulence may exist in the leeward and particular attention should be paid towards tackling such occurrences.

Simulation results at the pedestrian level (1.5m height) performed using FlowDesigner with two prevailing wind inlet directions are presented in Figure 20. Likewise for both wind directions, the central space is mostly wind-shaded (areas with blue dashes) and may experience low air movement. Surrounding buildings enclose these spaces and the corridors linking to main streets may be too narrow. Consequently, the majority of separate airflow over the wind-ward buildings did not enter these central spaces. On the other hand, the highest wind velocities are present in the outdoor spaces (purple dashes) for both wind directions as these areas face the inlet winds directly allowing the airflow to penetrate these narrow areas liberally. Comparison of the wind environment depicted by the green dashes indicates that the average wind speed and turbulence levels are higher in Figure 20b than Figure 20a due to there being increased airflow at the pedestrian level when the wind is from east, allowing wind to pass through the aisles between buildings. Furthermore, by analysing the distinction in wind pressure for both variables, the longer windward facades by buildings and podiums encourage greater wind deflection.

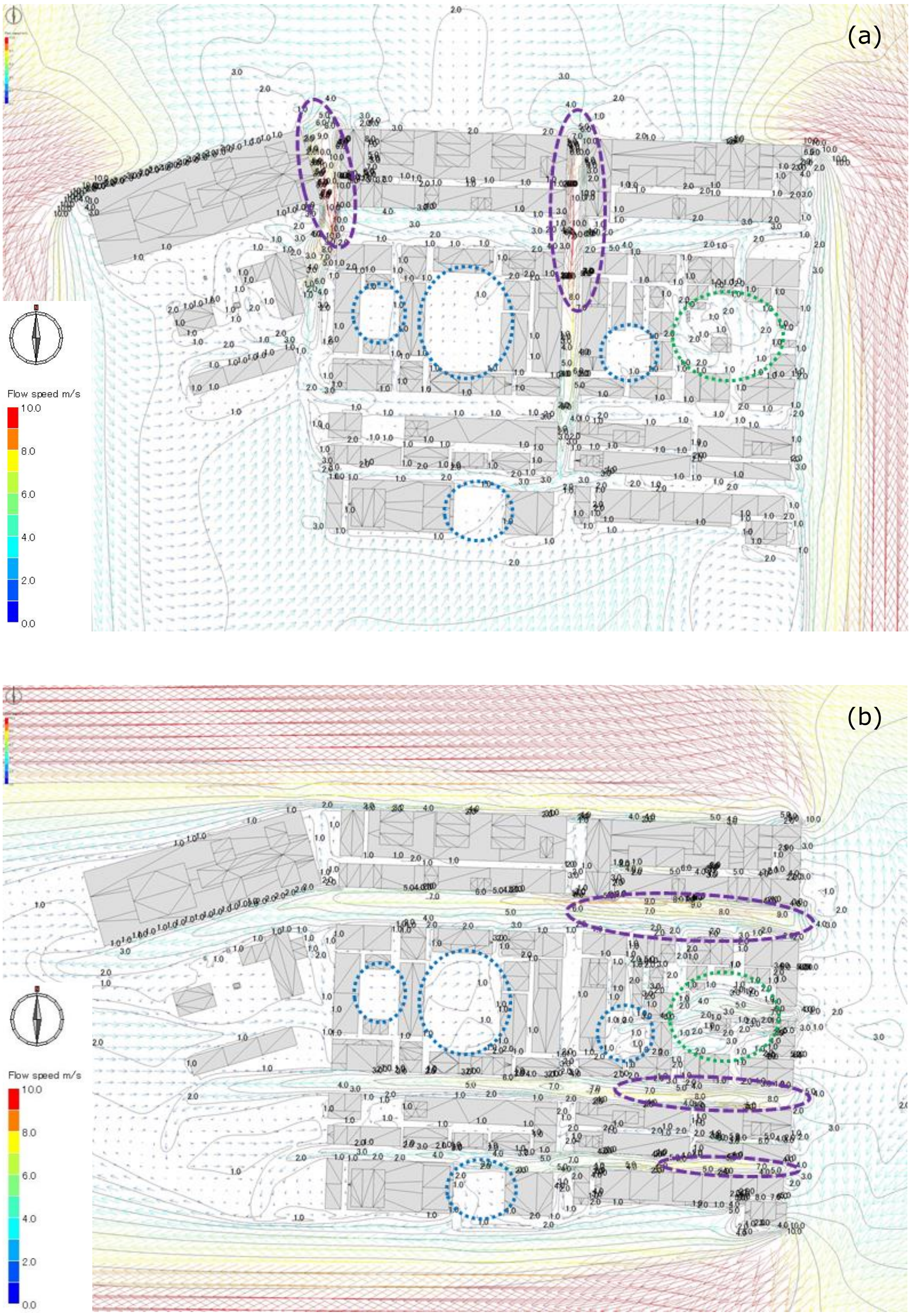


Figure 20: CFD simulation results in Sai Ying Pun: (a) north wind inlet and (b) east wind inlet

4.5 Results comparison and discussion between wind tunnel tests and CFD simulations

For both wind tunnel tests and CFD simulation experiments, the mean wind velocity measurements were analysed at an equivalent full-scale height of 1.5m and a scaled height of 0.5cm in wind tunnel tests. The positions where comparisons of pedestrian level wind speeds were made are detailed in Figure 21. The majority of these locations were selected after careful consideration during the experiment, whereby two positions (locations 4 and 9) encompassed the central aisles and three positions (locations 7, 10 and 11) covered the courtyard region.

There were two monitoring sensors were used during each wind tunnel test; one was always set ahead of the first building facing the incoming wind with a distance of 20cm and a height of 30cm from ground level in scaled, which equals to 60m and 90m respectively. This sensor was applied to ensure the inlet wind speed was keeping at the level of 6m/s. Meanwhile, another remotely operated sensor measured the wind speed of selected points. Once the wind speed at all thirteen positions was recorded with the north wind the building models were rotated 90° anticlockwise for the subsequent simulation.

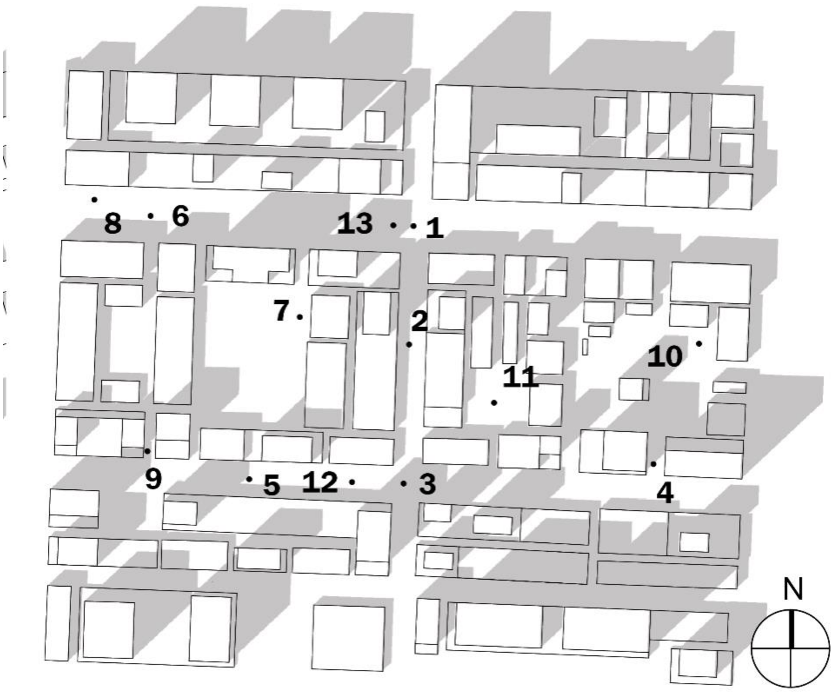


Figure 21: Positions in the site for comparing the results of wind tunnel tests and numerical simulation

The fan was set to deliver a velocity of 6m/s and this was confirmed using the sensor placed at the front of the model to provide a reference velocity. A steady state 6m/s inlet wind velocity was applied for the CFD simulations. Following multiple measurements at all location points, the mean wind speeds were calculated from the nearest cells respective to the wind tunnel measurement locations using the CFD simulations. As there may be a slight divergence between the placement of the wind tunnel and CFD, differences in wind speed may be measured in the neighbouring cells.

Location	North wind speed (m/s)				East wind speed (m/s)		
	Wind tunnel Reference windspeed	Wind tunnel	CFD		Wind tunnel Reference windspeed	Wind tunnel	CFD
1	6.10	7.06	8.16 ± 0.5		6.39	5.72	6.54 ± 0.5
2	6.00	6.01	6.3 ± 0.5		6.44	2.95	1.78 ± 0.5
3	6.08	2.28	2.5 ± 0.5		6.38	4.83	5.76 ± 0.5
4	5.96	3.78	3.61 ± 0.5		7.24	3.35	3.12 ± 0.5
5	5.93	3.62	3.36 ± 0.5		6.61	5.52	6.15 ± 0.5
6	6.12	4.20	3.65 ± 0.5		6.45	6.45	6.28 ± 0.5
7	6.23	3.97	3.14 ± 0.5		6.66	1.75	0.54 ± 0.5
8	6.14	2.75	3.83 ± 0.5		6.42	5.97	5.43 ± 0.5
9	6.01	3.55	3.39 ± 0.5		6.40	3.12	2.76 ± 0.5
10	6.07	2.89	2.7 ± 0.5		6.87	0.76	0.9 ± 0.5
11	6.02	3.32	6.43 ± 0.5		6.69	1.05	2.31 ± 0.5
12	5.87	2.53	2.12 ± 0.5		6.29	4.63	4.97 ± 0.5
13	6.09	2.05	2.24 ± 0.5		6.46	5.81	6.2 ± 0.5

Table 13 : Mean wind speeds with north and east wind in wind tunnel and CFD

As shown in Table 13, discrepancies in the findings with both inlet wind directions show an equivalent order of magnitude. Location 12 shows the maximum inconsistency between each wind direction variable, which is greater than approximately 200%. Conversely, the deviations are within 20% for most of the other locations. The maximum difference tends to occur within the courtyard areas (Locations 7 and 11), while the lowest variation arises nearest to the building corners (Locations 4, 9 and 10). This divergence may be explained by limitations of CFD in modelling complicated air flow patterns, including those in re-circulating regions. Alternatively, it may be caused by errors made when taking measurements on account of interference by sensors during wind tunnel experiments. In addition, the roughness of model surface in the wind tunnel is not as smooth as CFD, and it may reduce the level of details when meshing the model in CFD.

Therefore, from the ratio between the measured wind speed and the reference wind speed at each selected location in wind tunnel tests and CFD simulation shown in Figure 22, the great majority are between 0.8 and 1.3, which is suggesting that application of the standard $k-\epsilon$ model in FlowDesigner can predict accurately the pedestrian-level wind environment.

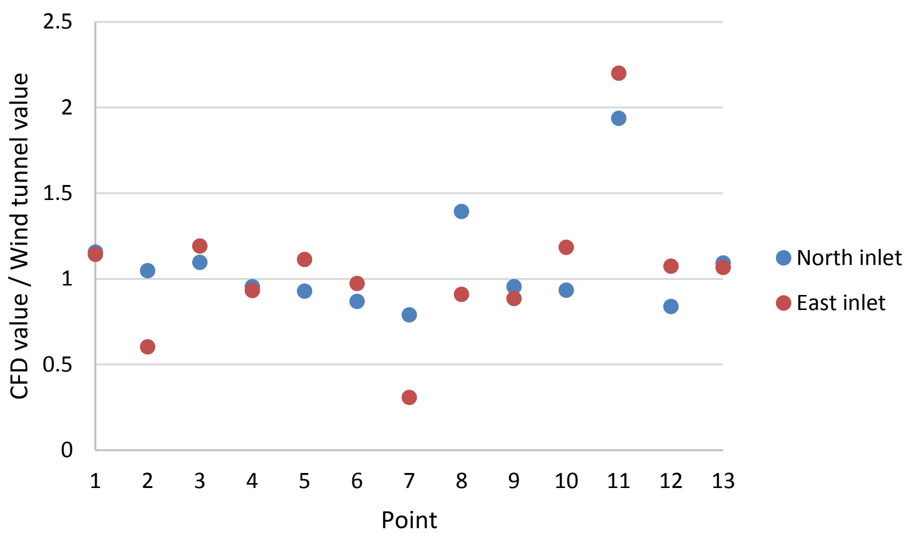


Figure 22: wind speed ratio of CFD simulation and wind tunnel tests

4.6 Summary

The realistic airflow around buildings in complex high-density urban settings is extremely difficult to grasp, and can only be done by using equipment installed to measure the situation. However, wind tunnel tests have the ability to simulate the mean velocity using scaled down replicas in a boundary layer as all buildings in the surrounding environment are included in the wind tunnel model and, therefore, computational numerical modelling has been applied widely in much research for the simulation of the wind environment immediately adjacent to buildings and surrounding landscapes, with relatively accurate results at the pedestrian level.

This chapter has addressed the experimental and computational assessment of pedestrian outdoor wind environments neighbouring a series of tall buildings in Sai Ying Pun, Hong Kong. Local inhabitants' living conditions and natural wind statuses in the urban environment have been introduced. Therefore, the buildings have been used in wind tunnel tests and CFD to analyse the outdoor ventilation. Integrating the results to the realistic state can demonstrate that, the elderly may have to use some narrow streets with high velocity, followed by dangerous, and citizens may also have to apply the courtyards with stagnant wind that is not beneficial to the healthy air change. Furthermore, with both detailed parameter settings, a mean inlet wind velocity of 6m/s from two local prevailing wind directions (north and east) have been applied in wind tunnel experiments and CFD simulations. Subsequently, the mean wind speeds at pedestrian level for thirteen different locations have also been compared. The maximum discrepancy in results transpires at the centre of courtyards, whilst minimal variations are detected at building corners. The data prove that differences between wind tunnel test and numerical simulations are within 20% for the majority of the thirteen locations, which suggests that the standard $k-\epsilon$ model can be applied in FlowDesigner to predict the outdoor pedestrian-level wind environment accurately.

To conclude, FlowDesigner has demonstrated its reasonable accuracy when comparing the simulation results with wind tunnel tests for the determination of mean wind speed values in the vicinity of buildings in urban areas. Moreover, the pilot study in Hong Kong enabled the further development of skills and techniques that were then employed to simulate the outdoor wind environment in the case study, Lujiazui, Shanghai. Furthermore, there are two more advantages of applying CFD that, the complete wind environment profile can be illustrated by means of coloured arrows, inclusive of information on air speed and direction based on the CFD data, which is more convenient to observe than experimental measurements. Therefore, once the process of calculation has been completed, the speed data in any interested location can be exported. For example, the air speed at the layer of the outdoor pedestrian level (1.5m high) can be applied to calculate the area of meeting wind comfort criteria, and the ratio of it to the whole site area. In this thesis, the local wind comfort index will be introduced in next chapter and the ratio will be the main evaluation criterion to assess the outdoor wind environment in the past stages of urban design in Lujiazui (chapter 6) and facilitate plans for various proposed urban designs for the extended area (chapter 7).

CHAPTER 5 OUTDOOR THERMAL COMFORT IN THE LUJIAZUI DISTRICT

5.1 Introduction

As mentioned in the methodology, a user's thermal comfort questionnaire was employed in this research. It is similar to those that have been widely applied in other outdoor thermal comfort research all over the world, for example, the RUROS project (Nikolopoulou and Steemers, 2003, Nikolopoulou and Lykoudis, 2006). Therefore, as one of the major contributors to the adaptive thermal comfort model set out in ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy, Richard de Dear employed this methodology in a study of outdoor thermal comfort in Sydney (Spagnolo and de Dear, 2003). Moreover, thermal comfort questionnaires have been applied in many other comfort studies conducted in different European countries (Ahmed, 2003, Thorsson et al., 2004, Stathopoulos et al., 2004, Nikolopoulou and Lykoudis, 2006) and Asian cities (Ng and Cheng, 2012).

The research presented in this thesis is unique in its kind, both for the characteristic urban design in such high-dense CBD areas and the particular climatic conditions examined. After introducing the geography, climate and urban development in Lujiazui, this chapter presents findings from the field questionnaires in this district. The correlations between microclimate and pedestrian thermal comfort will be followed and analysed using SPSS.

5.2 Introduction of Lujiazui New District, Shanghai

Shanghai is located at 31º14′ N, 121º29′ E, on the eastern coastline of China at the southeast end of the Yangtze River Delta. Shanghai is China's largest economic centre and trading port. It is surrounded by the Jiangsu and Zhejiang Provinces (Figure 23). Shanghai has become a flourishing international port city due to its advantageous geographical location. It is located in the sub-tropical climate zone that has four typical seasons: warm spring, hot moist summer, pleasing cool autumn and cloudy cold winter. Shanghai is near the East China Sea and on the estuary of the Yangtze River, which results in the city having humid air all year.

Figure 23 : Location of Shanghai, China (Source: http://www.skyscrapercity.com)

The weather conditions in Shanghai from 1971 to 2000 are recorded in the ground observation station and described in Table 14. This weather station is located at pedestrian level in an urban area and not far from the site. The mean high and low temperatures in winter were approximately 10℃ and 4℃ respectively, however, they always exceeded 20 ℃ in summer. The coldest months were January and February, while July and August were the hottest. The average relative humidity changed little throughout the year (from 73% to 82%).

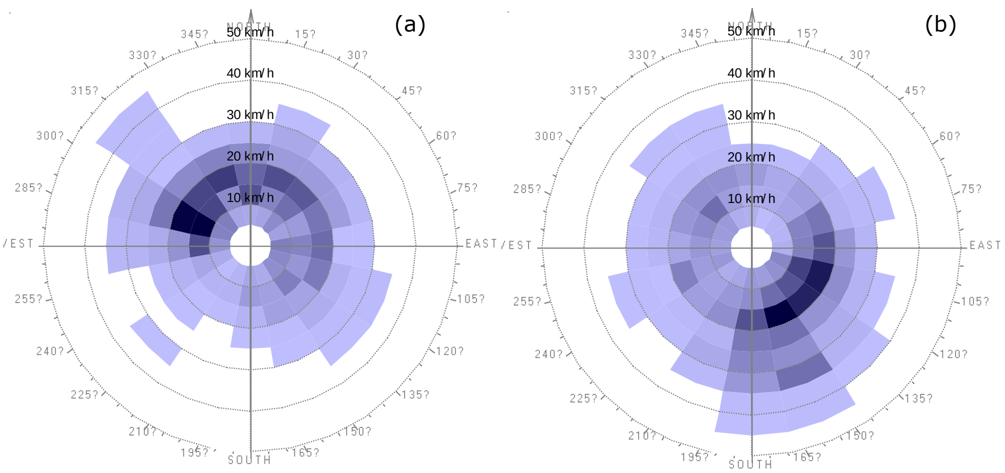
Figure 24 describes the frequency of the prevailing winds (highlight). There are seven annually prevailing wind directions (NNE, E, ESE, SE, SSE, WNW and NW) with a frequency of at least 8%, and the most prevailing winds have a wind velocity between 20km/h (5.6m/s) and 25km/h (6.9m/s). In terms of the prevailing wind in winter, the most frequent wind is from WNW

(292.5°), while the wind from SSE (157.5°) is the prevailing wind with the highest frequency in summer. The simulation of airflow around the buildings in Lujiazui will be based on the prevailing winds, which will be shown in the next chapter. Furthermore, the results of the CFD simulation in winter and summer will be discussed separately due to their different thermal comfort criteria.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high ℃	8.1	9.2	12.8	19.1	24.1	27.6	31.8	31.3	27.2	22.6	17	11.1	20.2
Average low ℃	1.1	2.2	5.6	10.9	16.1	20.8	25	24.9	20.6	15.1	9	3	12.9
Precipitation mm	50.6	56.8	98.8	89.3	102.3	169.6	156.3	157.9	137.3	62.5	46.2	37.1	1164.7
Avg. precipitation days (≥0.1mm)	9.7	10.3	13.9	12.7	12.1	14.4	12	11.3	11	8.1	7	6.5	129
Humidity %	75	74	76	76	76	82	82	81	78	75	74	73	76.8
Mean monthly sunshine hours	123	115.7	126	156.1	173.5	147.6	217.8	220.8	158.9	160.8	146.6	147.7	1894.5
Percent possible sunshine %	39	37	34	40	41	35	50	54	43	45	46	47	42.6

Table 14 : Climate data for Shanghai from 1971 to 2000 (Source: China Meteorological Administration, retrieved 2010-11-10)

In terms of the urban design, as the Pudong Development Office of Shanghai Municipality (1992) noted, Shanghai, a formerly colonised city and now a highly-capitalised metropolitan area, remains a favourite subject of urban studies, and its latest socioeconomic and spatial transformations are reflected in many research projects.



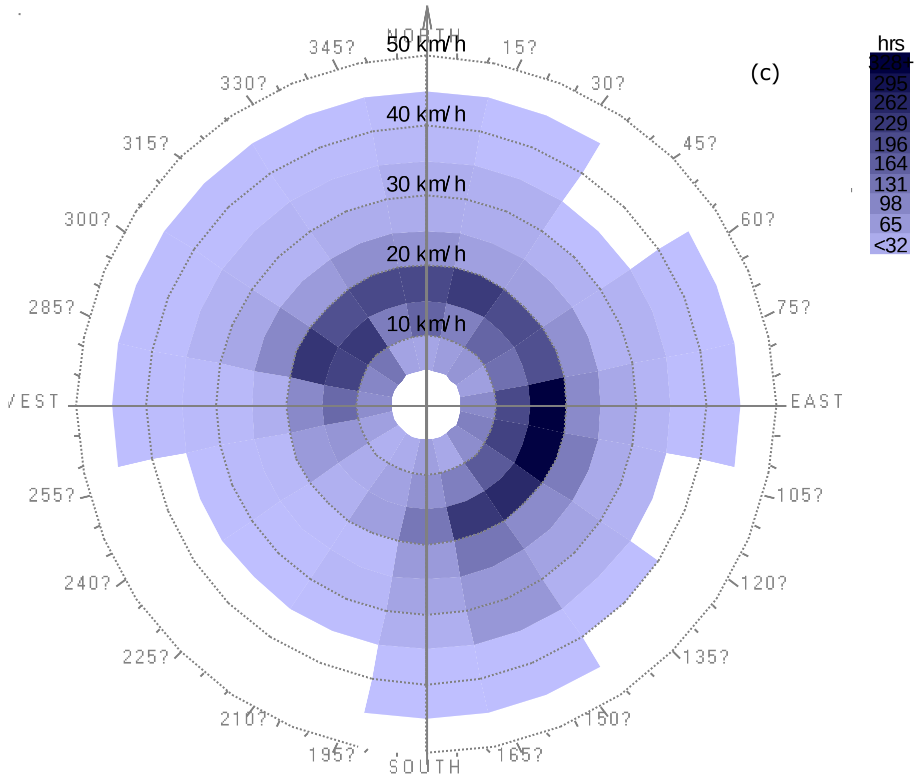


Figure 24: Prevailing winds in Lujiazui, Shanghai (a. winter, b. summer and c. annual) (source from weather tool in Ecotect)

Pudong is frequently presented in urban studies of Shanghai as a phenomenon of Chinese transition (Wang et al., 2013, Wu and Barnes, 2008, Marton and Wu, 2006). Located along the east side of the Huangpu River, Pudong covers a territory of 1210 square kilometres (almost 1/5 of the total municipality area of Shanghai), with a population of 5 million in 2010, and its gross domestic product amounts to an estimated 53.98 billion US dollars, ranking the 72nd in the world if it were regarded as a country (Shanghai Urban Planning and Design Institute, 2007). However, despite extensive planning and promotion by the government, the urban growth of Pudong has resulted in a problematic urban environment in many respects (Rowe and Kuan, 2004).

Pudong's development starts at Lujiazui, which is better known as the Lujiazui Central Business District (CBD). In the context of Pudong's urban development, Lujiazui CBD's destiny is largely determined by the power of globalisation, which links Shanghai to the rest of world (Rowe and Kuan, 2004). Figure 25 illustrates the skyline of the Lujiazui district, including some super tall buildings, such as the Oriental Pearl TV Tower, Jin Mao Tower, Shanghai Financial Centre and the new Shanghai Tower (632m high and 128 storeys).

Figure 25: Lujiazui Financial & Trade District skyline from bund

Due to its international shipping, manufacturing and financial services, the Lujiazui District, the core of Pudong, has become a new hub for globalisation and modern Chinese development (Wang et al., 2013). However, the success of Pudong appears more in its financial statistics than in its conditions for urban living. The experience of living in the natural outdoors environment of this district might not be regarded as fundamental to its design. This absence of aesthetic or qualitative parameters is responsible for the production of unpleasant spaces amongst out-of-context, disproportionate buildings (Wu and Barnes, 2008). Indeed, the lack of aesthetic or experiential considerations has created an environment that cannot meet people's requirements for beautiful urban surroundings.

Therefore, urban design, as a transitional phase which connects the detailed plan and the architectural design, is neglected or appears only as a suggested attachment for the clients and architects (Maruani and Amit-Cohen, 2007). Furthermore, planning in Pudong controls the dimensions but not the volume. The blocks in Pudong are designed to be large (average 500 metres x 800 metres), and one residential block frequently fills one plot, which means that investors need to make a 'private' detailed plan and make decisions for the public interests when these should be a pre-condition of the plan (Wang et al., 2013). Consequently, streets have become the element separating the blocks and have lost their role as the interface between the buildings and public space, because those extremely tall independent building blocks have been erected and undermined the integrity of the urban space, thereby creating a series of problems such as an uncomfortable outdoor environment and urban heat islands.

In conclusion, the previous and current urban plan in the district of Lujiazui might not be an essential, successful urban model for a new urban China because of the lack of consideration for the effect of architecture on outdoor comfort. China continues to experience rapid economic and urban growth with only recent signs of interruption. Thus, the study of outdoor thermal comfort in the Lujiazui district will become a guide for the government to establish a better urban space and hopefully lead to improvements in future Chinese urban developments.

5.3 Outdoor thermal comfort questionnaire survey

To evaluate the outdoor thermal comfort in Lujiazui, micrometeorological measurements, questionnaire design and the interpretation of the results in terms of thermal comfort ranges, thermal neutrality and preferred thermal conditions were implemented as the main research methodologies. There are many international standards, guidelines and handbooks related to this kind of research, however, there is no advice on how to design the field survey in terms of site selection, approximate number of sites, required number of subjects, approximate time of day, description and classification of the characteristics of the sites, etc. The research methodologies in the European Union project RUROS (Nikolopoulou and Lykoudis, 2006) that studied the variation of the thermal comfort and thermal perception in seven European cities during different seasons were adapted in this research. The investigators completed a series of work, including local climatic condition monitoring and an outdoor thermal comfort questionnaire survey. Therefore, at the end of this chapter, the results of the thermal comfort criteria obtained in the Lujiazui district will be compared and analysed with other cities in both oriental and western countries.

5.3.1 Questionnaire location selection

The objective of the site selection process is to contain a wide range of environmental conditions (Cheng, 2008). Therefore, the survey locations should be carefully selected based on the parameters related to the regional climatic conditions, topographic characteristics and urban morphology. Indeed, apart from the microclimatic considerations, the survey locations were selected based on different kinds of land usages and activities. The red dashed lines in Figure 26 show the Pudong new district, which contains a series of tall buildings. The details of these constructions will be introduced in Chapter 6.

There are three survey locations which are described below:

1) Location A is near a metro station, and there is only one tall building (Oriental Pearl TV Tower) to the northwest. The huge flow of people is beneficial to the amount of survey subjects, and they can have different short-term acclimatisation or thermal adaption, because most passing pedestrians are going to the underground station from an outdoors environment or from the underground with its air-conditioning to the outdoors environment;

2) Location B is on a street surrounded by two rows of tall buildings and it may be a canyon wind environment; and

3) Location C is located on the Centre Green Park, and people work in Lujiazui and nearby residents prefer to spend relaxation time here.

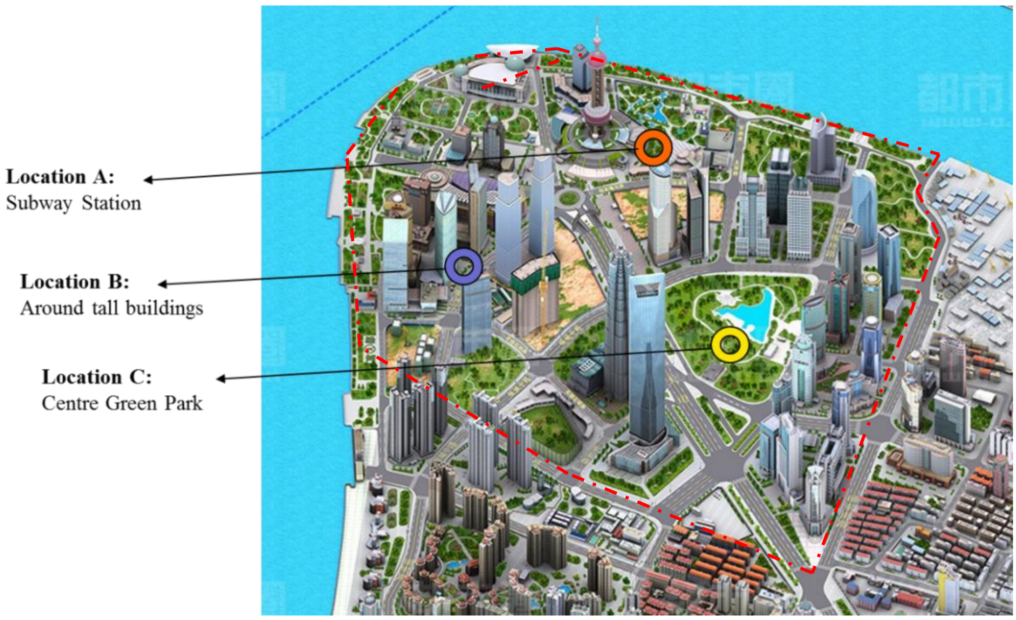


Figure 26: Introduction of the three survey locations (adapted from Google Earth)

5.3.2 Meteorological equipment

Figure 27 describes the two mobile meteorological devices utilised for the outdoor micro-meteorological measurements, and Table 15 shows their specifications. The integrated station was placed in a fixed position and the data collected from the wind sensor, rain sensor and thermo-hydro sensor was automatically sent to a weather station with wireless technology. The real-time data was shown on the panel and recorded. Therefore, the mobile global radiation meter could measure the data from the upper sensor, which was manually operated every five minutes to read and record the data. Here, all equipment are supported by the University of Nottingham, and taken to Lujiazui for site environmental parameters measurement. Unfortunately, thermometer with black globe was not prepared in advance, so the globe temperature could not be measured, and the mean radiant temperature was neither able to be calculated as an indicator for heat stress. However, it is not a problem, because it is winter and people are wearing clothes, MRT will be less important than in summer when they might be wearing less – its influence is determined by area exposed body.

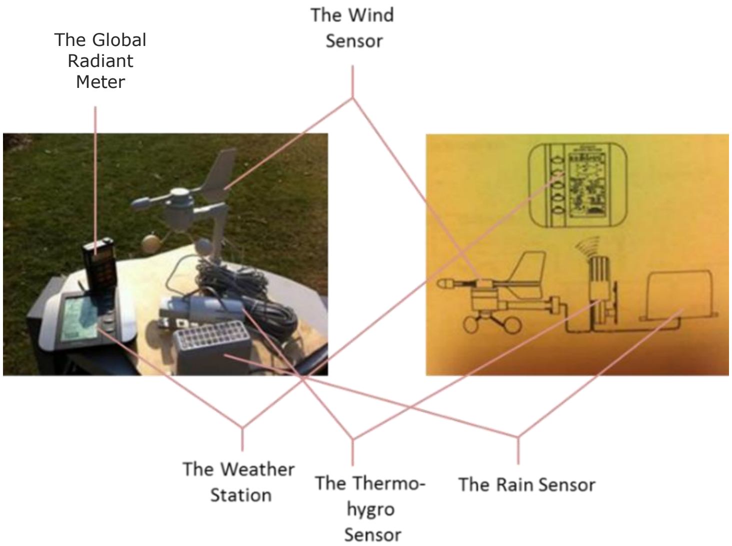


Figure 27: Weather equipment used in this research

Model	Accuracy	Operating range
ISO-TECH ISM 400: Global radiation	± 10 W/m^2	2000 W/m^2 (400-1000 nm)
WMR100 Weather Station: Outdoor temperature	±0.2℃	- 40℃ to 59.9℃
WMR100 Weather Station: Outdoor relative humidity	±2%	1% to 99%
WMR100 Weather Station: Wind speed	±0.1 m/s	0 to 50 m/s

Table 15: Specification of the equipment in use

5.3.3 Procedure

The first questionnaire was done on the 14th December 2013. Because it was a weekend, it was assumed that there would be many participants who could participate in the survey. However, the temperature that day was extremely low and there was a high wind velocity. Therefore, few people chose to go outside to Location B. In addition, there were only two sanitation workers at Location C. In contrast, there were many people at Location A because it was near to the subway station, however, few of them were willing to stop to complete the survey due to the extreme weather conditions. The survey was difficult to complete during such cold days. Fortunately, there were some better-weather weekends which provided an opportunity to complete this survey during the winter over several weeks.

Meteorological data, including global radiation (G), wind velocity (WV), air temperature (T_a) and relative humidity (RH) was collected via the weather station, which was located in the same place for each measurement and was within the vicinity of the interviewee. The integrated equipment was fixed with one wooden board placed in the horizontal plane. The height of the weather station was set to 1.5m above the ground, which is the recommended height of the sensors according to ISO 7726 (1998) for standing subjects since this may represent the centre of gravity for the human body. It should be noted that the weather station was not located under shadow. One research assistant stood beside the equipment to prevent any man-made interference and record the weather data every five minutes. The other assistants invited people in and around the area to participate in the survey. Furthermore, in order to obtain more accurate results, the distance between the survey site and the equipment was within 3m. All of the research assistants/interviewers were fully briefed on the purpose and principles of the survey in advance. Since the research assistants were knowledgeable about the topic, having obtained master's degrees from the University of Nottingham in fields related to architecture or urban design, they easily comprehended the briefing.

Consequently, a number of participants could successfully participate in the survey in one day, however, it did not mean that taking more participants was conducive to this research, because there were some limitations on participant selection. According to the related research in Europe, such as the RUROS project, the background of the participants may affect their thermal comfort, so the ratio of male and female, age group and other background factors were considered to maintain the balance and maximise the validity of the survey results.

5.3.4 Participants

More than 1000 completed questionnaires were obtained through the thermal comfort surveys. In the RUROS project, the each sample for the four cities was approximately 1000 and they were conducted in each season (Nikolopoulou and Lykoudis, 2006). Spagnolo and de Dear (2003) collected 1018 samples in Sydney, of which 585 and 433 were conducted in summer and winter respectively. In Ahmed's (2003) study, the total sample size was approximately 1500 and data was collected in the summer. Thus, the 1000 people target sample size for the thermal comfort survey in this thesis is in line with current international research.

5.4 Results and analysis

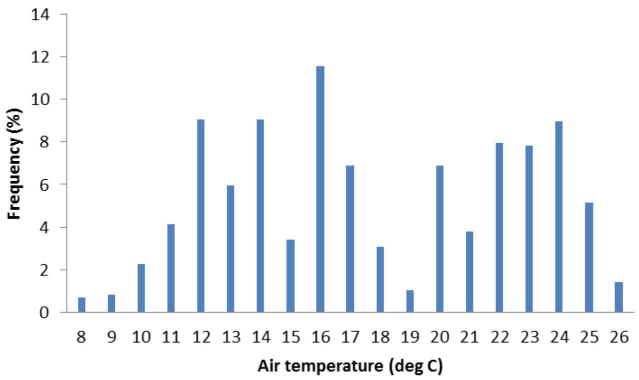
As mentioned above, although there are many people work, visit or live in this financial district, the chosen survey dates were weekends, because the research assistants were available and more people would have time to complete the questionnaire. As shown in Table 16, due to the uncomfortable weather conditions and location, the number of participants on the first three survey days was small. It might due to the high wind speed in the canyon street around tall buildings in Location B, which made people unwilling to stay in location in winter.

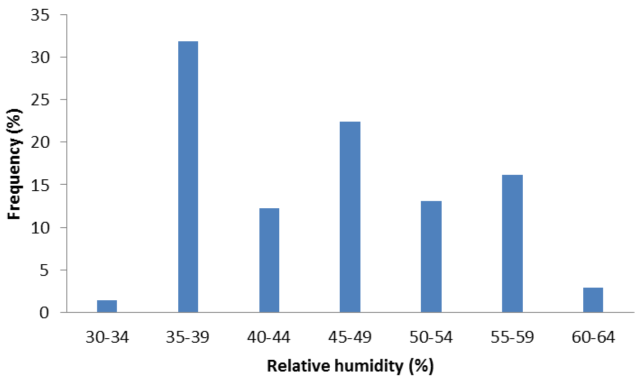
Date	22/12/2013	18/01/2014	19/01/2014	22/02/2014	23/02/2014
Location	B	B	C	C	A
Number of subjects (male/female)	24 (18/6)	24 (12/12)	45 (24/21)	502 (227/275)	419 (204/215)
Total	1014 (485/529)				

Table 16: Details about the site questionnaire

5.4.1 Simultaneous environmental parameters monitored

From the meteorological measurements, the air temperature, relative humidity, wind velocity and global radiation on the survey days were recorded. The variant frequency of the basic meteorological data on the five survey days on these three sites in Lujiazui are shown in Figure 28. The survey started at 10 am and ended at 4 pm. The whole range of air temperature was from 8℃ to 26℃, which may be acceptable and common in winter. The highest air temperature was in noon. It is significant that these figures are higher than those shown in Table 14. As we know, the global temperature is increasing year by year, and the inner city outdoor air temperature is higher than the global temperature because of the urban heat island effect (Jihad & Tahiri, 2016: 25). The Lujiazui district is a high-density area with a large number of tall buildings, therefore, the heat island effect may appear more significant. The highest relative humidity was 60% (morning), the lowest was 30% (noon), and the average was 42%. The maximum outdoor wind velocity was 3.4m/s and the minimum was 0 meaning there was no or stagnant wind when recording. The average air velocity was 0.7m/s, and more than 70% was under 1.5m/s. With regard to global radiation, the lowest was 44 W/m^2, due to the location being shaded by heavy cloud cover and surrounding buildings. The highest was 890 W/m^2, and the average was 547 W/m^2.





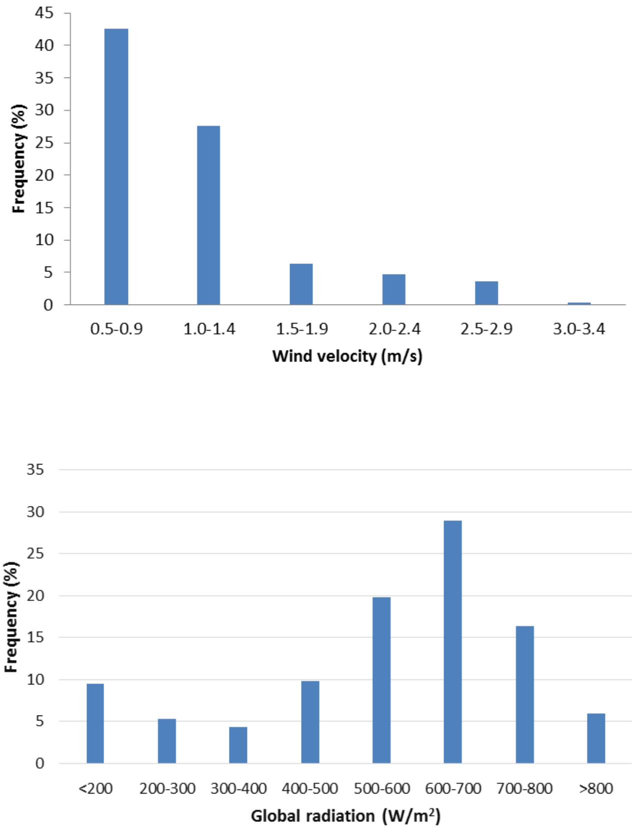


Figure 28: Outdoor weather parameters distribution in Lujiazui during winter (air temperature, relative humidity, wind velocity and global radiation)

5.4.2 Demography

In part one of the questionnaire, the interviewees were asked to provide their backgrounds such as gender, age, nationality and occupation. There were 9% more females than males, which can be considered as an effective element for gender analysis. Therefore, Figure 29 illustrates the distribution of these parameters from age and occupation. It shows that the majority of the participants were young people between the ages of 18-29 (73%), and 22% of the interviewees were mid-aged people (the age range is 30-49). The largest percentage of participants were employees followed by students. These two groups accounted for 92% of the interviewees.

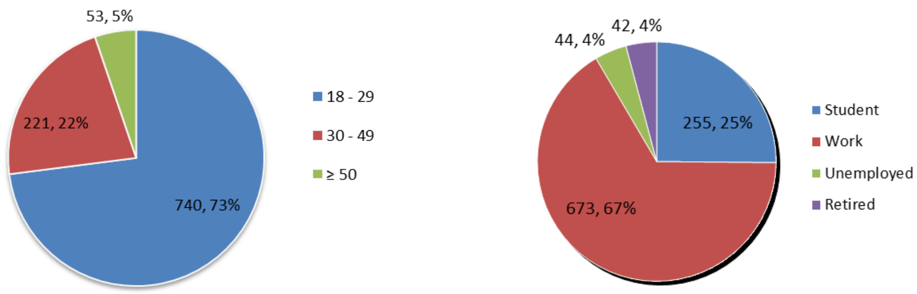


Figure 29: Demography of age (left) and occupation (right)

Furthermore, the majority of the respondents are from China (99%), however, 13 foreigners participated in the survey. One reason is that there were few foreigners walking by the survey sites, and another might be that all of the research assistants were Chinese, and they may have lacked the confidence to approach the foreigners and avoid ask them to complete the questionnaire even though they had an English version in hand.

5.4.3 Clothing values

As mentioned in the literature review, clothing can be classified according to its insulation value. Clothing reduces heat loss, therefore, people may prefer to wear more on cold days or wear less on hot days. The Clo unit is normally applied to measure clothing's insulation, where 1 Clo = 0.155m^2℃/W (Metje et al., 2008). The lowest Clo is zero for the naked body. Participants were asked to select the type of clothes they were wearing (as shown in Table 10), and each anastomotic clothing value was added together to obtain a total clothing value.

In the questionnaire, the lowest, mean and highest Clo value of males and females was described in Table 17. Some females wore clothes with less insulation than males in Pudong in winter, because they wanted to show their 'beauty' without wearing too many clothes. Exothermic clothing was popular with females for keeping their body warm in China, so it might be another reason that they could wear less clothing in winter. In contrast, some males wore clothes with the highest insulation in winter. However, the mean male and female Clo in this survey in winter were both approximately 1.6. Givoni et al. (2003) completed experimental surveys in a park in Yokohama, Japan, and they believed that Clo value in spring and autumn is 1.1, 0.65 in summer and 1.67 in winter. However, Metje et al. (2008) research found that the average Clo in summer in Europe is approximately 0.6, while it is around 1.0 in winter. Therefore, it is obvious that the Clo in summer is similar among Asia and Europe, however, the Clo in winter is significantly different, and it is larger in Asia, which may because people cannot wear less clothing in summer whether in Asia or Europe, however, people in outdoor spaces in Asia have to wear more in winter to resist adverse environmental factors such as lower temperature. Furthermore, physique, long-term thermal adaption and lifestyle may influence their choice of clothing.

	Male	Female
Lowest Clo.	0.72	0.55
Mean Clo.	1.6	1.6
Highest Clo.	2.33	2.05

Table 17: Clothing value of males and females in Lujiazui in winter

5.4.4 Metabolic rate/Activity

In terms of the participants' behaviour, the activity checklist used for statistics in this survey was extracted from the ASHRAE Standard 55-2004 (ASHRAE Standards Committee, 2008) and the ISO Standard 7730 (2005). In general, the metabolic rate for sitting is calculated as 1 met, 1.2 met for standing and 2 met for walking (Givoni, 2010). According to Shakir (2010:20), the Met value of outdoor exercise (such as slow dancing and sweeping) is between 2.2 and 3. Based on the location and weather condition, these exertions were slight, so 2.2 was chosen as the Met value for doing exercise in this research.

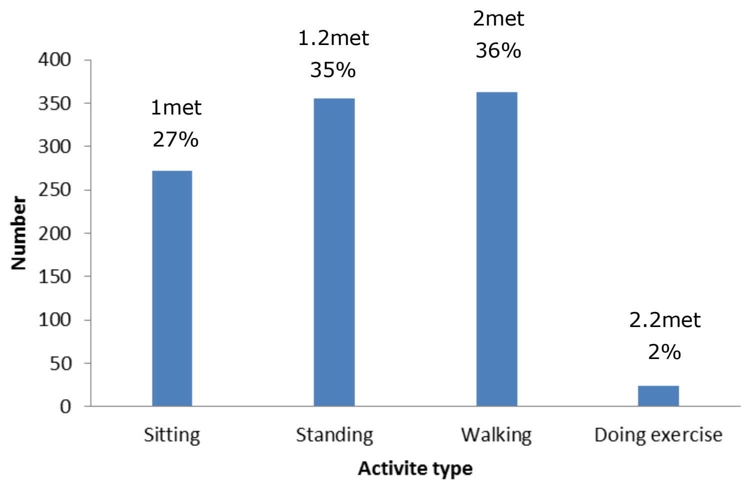


Figure 30: Outdoor activity distribution

Figure 30 describes the subjects' activity distribution during the survey. 355 people (approximately 35% in total) were standing while waiting for friends or public transport, and 363 (about 36%) were walking. Therefore, approximately 280 people were sitting nearby, however, only 24 participants (about 2%) were doing exercise, such as jogging, when passing through. Most of the participants who exercised were male and in Location C.

5.4.5 Attitude, life history and experimental conditions of participants

Approximately 87.9% of participants had not participated in a survey about outdoor thermal comfort before while the rest 12.1% had. In similar research conducted by Cheng (2008) and Ng and Cheng (2012) in Hong

Kong, the survey was terminated if the subject had done the interview before, however, he did not explain why. However, during other thermal comfort questionnaires in other regions, the question of whether the participants had completed similar surveys before was not mentioned.

Furthermore, about 64% and 21% of participants stated that considering outdoor thermal comfort at the pedestrian level is important or quite important in urban design respectively (Figure 31a). Only six participants believed that it was not important and the rest had never considered it before. According to the frequency of those staying in Lujiazui, about 30% of the participants were visiting the area for the first time, while 9% came to the site every day, which may be due to the fact that they worked or lived nearby. Approximately 34%, 19% and 8% of the participants had visited this area during the past month, year or more than one year ago respectively (Figure 31b).

Except the participants who were first-time visitors to Lujiazui, the level of comfort between the past and present was compared by the participants and was followed by factors that could affect their comfort. As shown in Figure 32, with the increasing number of tall buildings, only 11% of the participants believed that the outdoor environment was less comfortable than before, while 28% of them deemed that it was more comfortable. Therefore, approximately 21% of participants did not feel a change in the outdoor comfort. It was interesting that the greatest proportion of participants (30%) did not know whether the comfort level had changed, which might because it was difficult for them to compare it with an old memory about the previous experience. However, there are other variables that may have affected perceived comfort on the day. For example, the weather condition can influence some people’s comfortable feeling and judgment, but have nothing to do with the development or the urban plan.

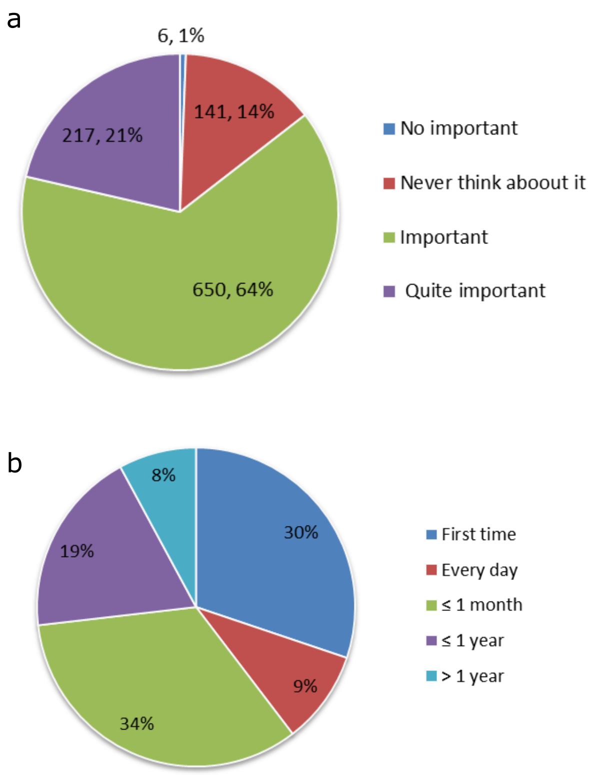


Figure 31: The distribution of (a) participants' attitude and (b) their frequency of visiting Lujiazui

In addition, the statistics on reasons for feeling less or more environmental comfortable are introduced in Figure 32. Approximately 55% of the participants who felt less comfortable deemed that the worse air quality encouraged them to make this decision, while about 26% of participants believed that air quality was an important factor when considering the comfort of the environment. Therefore, the largest proportion of the participants (36%) believed that the development of the landscape played a key role in the level of comfort, however, approximately 18% of participants believed that this was a negative factor. However, more people believed that the air temperature became more suitable, leading them to feel more comfortable

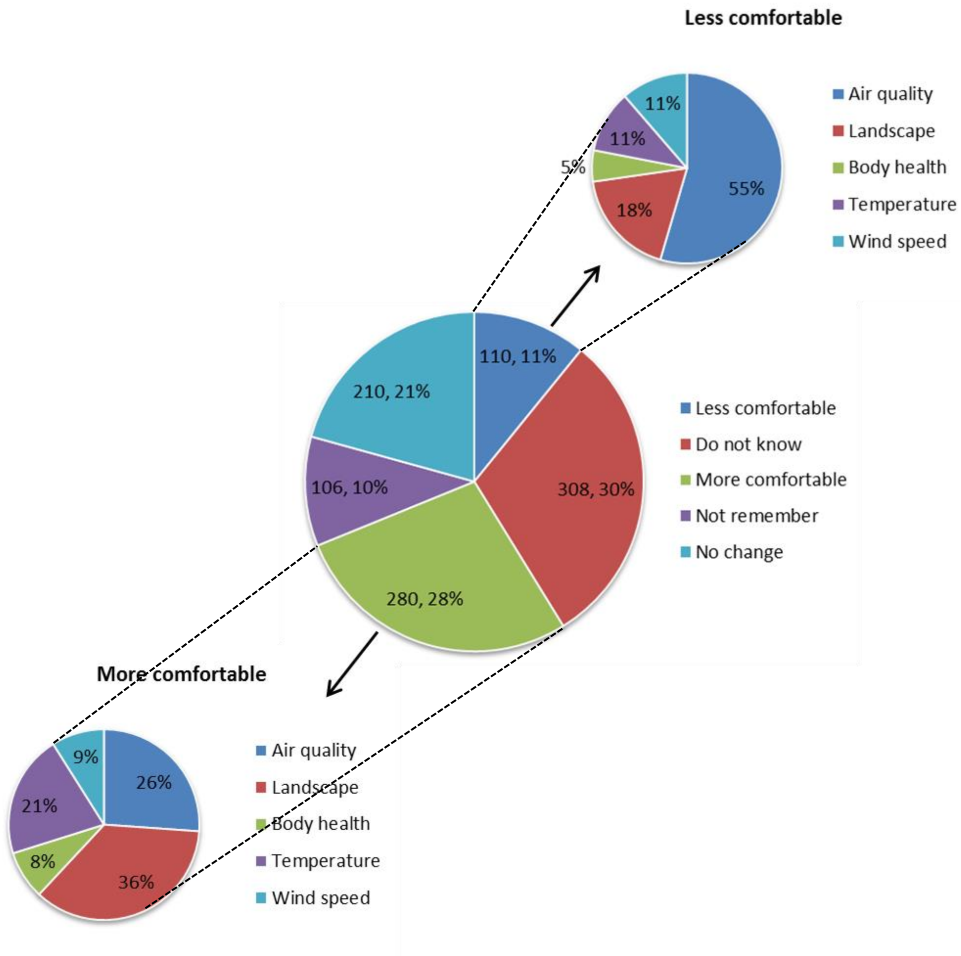


Figure 32: The comparison of outdoor thermal comfortable between temporal and the past

In terms of the long- and short- term thermal acclimatisation, approximately 55% of the participants were residing in Shanghai during the past 6 months (long-term), and 42% of the participants were staying in air-conditioned or heated indoor environments, which included buses, taxis, the underground and so on during the past 15 minutes (short-term) (Figure 33). Therefore, the influence of AC and non-AC space on thermal sensation will be discussed below.

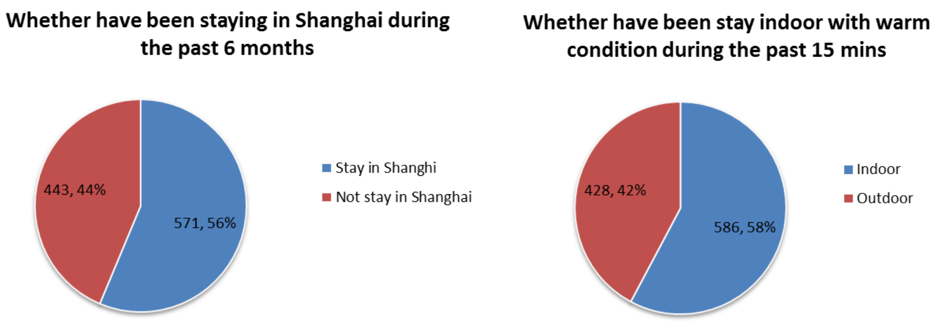


Figure 33: Long- and short-term thermal acclimatization

The survey included a number of behaviour related factors which influence thermal adaptation to determine its effect on the participant's thermal adaptation. These factors included how long they were resident in Shanghai (LEN), access to air conditioning in the last 15 minutes (AC), and why they were at the survey location. The participants Thermal Sensation Votes (TSVs) were compared to these factors following labelling. The Kruskal Wallis H Test was employed to determine if the adaptation factors influenced the TSVs to account for the possibility that the responses would not align with the normal distribution. The Kruskal-Wallis H test can also be called the "one-way ANOVA on ranks", and it can be used to assess whether there are statistically significant differences between two or more independent samples variable on a continuous or ordinal dependent variable. Yang et al. (2013) also employed this method. The null hypothesis' (There are no significant differences in TVS between different groups) p value was derived and the TSVs were categorised. 0.42, 0.27 and 0.33 were the p values for AC (whether stayed in the air-conditioning space), ACT (activity during the past 15 mins), and PV (purpose of visiting here) respectively. These values exceed the 0.05 threshold, suggesting that the TSVs were not influenced by these factors. However, in warmer environments, like Singapore, recent exposure to air-conditioning did influence the TSV (Yang et al., 2013). It has been suggested that people leaving a cool environment for a hot one may be more sensitive to changes in temperature than those leaving a hot environment for a cooler one with sunlight, which may explain this difference (Chen et al., 2015).

The respondents' adaptation to the local meteorological conditions could account for the p value of LEN being below 0.01. It is postulated that extended and repeated exposure might increase a person's tolerance for low temperatures. People who have resided in Shanghai for six months or longer regard the environment as neutral as they have acclimatised to the local conditions, however, newcomers to the city regard it as cold if they come from warmer regions, while they may also feel warm or neutral if they come from cold regions.

5.4.6 Correlations between microclimate and thermal comfort

5.4.6.1 Thermal sensation vote

According to the data analysis, the percentage distribution of the thermal sensation vote is shown in Figure 34. People's thermal sensation was reported on a 7-point scale, "-3" means very cold, "-2" means cold, "-1" means cool, "0" means neutral while "1", "2" and "3" mean warm, hot and very hot respectively. Approximately 93% of participants voted among "-1" to "1", while approximately 53% voted for 'neutral', therefore, the majority of the participants could accept the thermal environment. However, only 7% of the participants thought that the outdoor thermal environment was unacceptable. There was a great variation in the microclimatic conditions in project RUROS, however, their results had a similar distribution with approximately 90% of participants voting in the region between cool and warm (Nikolopoulou and Lykoudis, 2006).

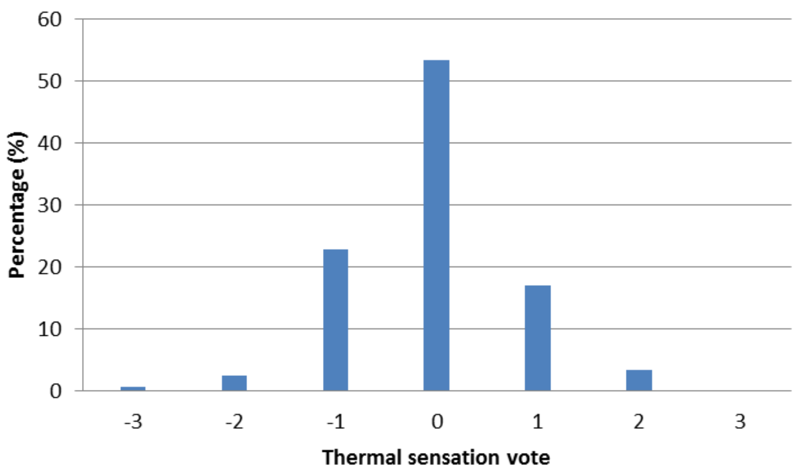


Figure 34: The percentage distribution of thermal sensation vote

In order to compare thermal comfort index between Lujiazui and other regions (RUROS, Hong Kong and tec.), it is necessary to adapt the same linear regression in this thesis. By applying the TSV model with equation 3.1 in the Linear Regression in SPSS, an outdoor thermal comfort formula as a function of air temperature, relative humidity, wind speed and global radiation was developed (equation 5.1):

$$TSV = 0.067T_a + 0.021RH - 0.068WV + 0.008G - 2.276$$

(n=1041, R^2=0.82) (Equation 5.1)

Therefore, to compare the results from other studies on outdoor comfort in different locations:

- In Japan and Israel by Givoni and his colleagues, RH has been shown to have a statistically insignificant effect on comfort perception (Givoni et al., 2003, Givoni and Noguchi, 2004), which is similar to this study;
- Lai et al. (2014b) obtained a similar TSV model (equation 5.2) in Wuhan in winter, central China that is in a typical subtropical zone.

$TSV_{Wuhan} = 0.0643T_a - 0.00376RH - 0.16WV + 0.00076G - 1.382$ (R=0.67)

(Equation 5.2)

It is clear based on the comparison of the Shanghai and TSV_{Wuhan} models that relative humidity is not as significant a meteorological variable as air temperature in affecting outdoor thermal comfort.

Furthermore, Ignatius et al. (2015: 128) suggest that the adapted model can only apply outdoor air temperature and wind speed as the independent variables. Thus, setting T_a and WV as independent variables could generate a correctional regression model:

$TSV = 0.37T_a - 0.081WV - 0.728$ (n=1041, R^2=0.87) (Equation5.3)

T_a and WV are significant in this case (p<0.001) and from the above equation, when wind speed increases by 1m/s, a 0.22℃ increase in air temperature can maintain the proportion of people perceiving neutral conditions.

5.4.6.2 Temperature sensation vote

In terms of utilising temperature to examine thermal sensation, from the previous research of thermal comfort discussed in the literature review, T_a, ET and SET* are the typical evaluation criteria for thermal comfort. However, each of them has benefits and drawbacks. T_a can be measured by the weather station and can be applied to evaluate thermal comfort directly. ET considers the effect of dry bulb temperature, air humidity and wind velocity on human thermal sensation and it is generally applicable to sitting people with standard clothes. According to the human's physiological responses, SET* is obtained from the calculation of human heat transfer and is seldom applied because of the complex calculation process (Lai et al., 2014b). Therefore, the results of ET and SET* may have some deviations, because they both apply mathematical calculations. Thus, T_a was used for the evaluation of temperature sensation in this section. Furthermore, Spagnolo and de Dear (2003) used T_a in their research of outdoor and semi-outdoor thermal comfort in Australia.

To better understand the relationship between two variables, it is only valid if other variables should keep stay at the same level. In this research, after selecting the relative humidity between 35% and 40%, wind velocity between 0.7m/s and 1.1m/s and global radiation 400W/m^2 and 500W/m^2, which takes up the most frequency part respectively, the outdoor air temperature (T_a) was set as the independent variable X, thermal sensation vote as the dependent variable Y, and then a complete the linear regression analysis was performed, with the regression model equation 5.4.

$TSV = 0.34T_a - 0.649$ (n=597, R^2=0.39) $p<0.01$ (Equation 5.4)

Based on the above regression equation, the correlation coefficient between T_a and TSV is only 0.39, which means that they are not highly correlated. This is because even under the same temperature, individual differences leads to variable thermal sensation. Therefore, some researchers have verified that one parameter (air temperature or global radiation) is insufficient for the evaluation of thermal comfort conditions, which means that the relation between TSV and T_a is not obvious (Nikolopoulou and Lykoudis, 2006).

However, due to the defect in the above computing method, a method of temperature-frequency can be applied in this study. It is called the BIN method and is utilized by many researchers to calculate and analyse the correlation between outdoor temperature and human thermal sensation. This method uses instantaneous mean temperature sensation vote calculations at several outdoor air temperature bins, weighted by the number of minutes of temperature occurrence in each bin. The temperature is divided into a series of consecutive parts at an interval of 0.5℃, and the average TSV for each part is calculated. After that, the mean temperature of each part is set as the independent variable X, the mean thermal sensation vote (MTSV) as the dependent variable Y, and a linear regression analysis is performed.

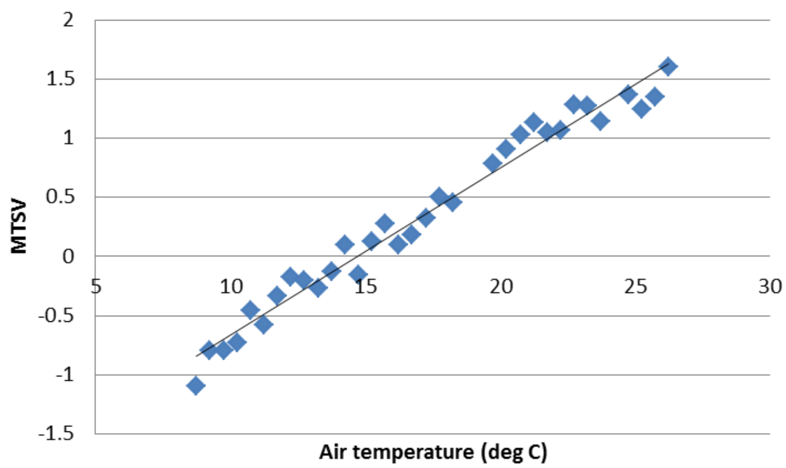


Figure 35: The relation between air temperature and mean thermal sensation vote

$MTSV = 0.1415T_a - 2.0846$ (n=597, R^2=0.86) $p<0.001$ (Equation 5.5)

After applying this method of temperature-frequency, the regression between air temperature and thermal sensation vote is significant (Figure 35), because the R^2 (coefficient of determination) is much higher than previous. In statistics, this coefficient closer to 1, the more it can indicate changes in a variable can have a higher percentage can be explained by another variable. It is easy to calculate according to equation 5.5. The thermal neutral temperature in winter in Lujiazui, Shanghai is 14.7℃ (MTSV = 0). The thermal environment is considered acceptable, when the TSV is between -1 and 1 (Fanger, 1970, Xi et al., 2012), therefore, the accepted air temperature range in Lujiazui is 7.7℃ - 21.8℃ (-1 < MTSV < 1). However, according to Chen et al. (2015), the neutral physiological equivalent temperature in Shanghai in winter is approximately 15-29℃, which is different to the above result. The reasons may be: (a) their survey was only completed in one open area (Shanghai Zhongshan Park) 11km from the Lujiazui district, which may lead to a less complex background of participants in an outdoor environment than this study, and (b) their PET was calculated by considering the mean radiant temperature.

Therefore, based on HKO 1971-2000 monthly T_a data, the mean daily minimum and mean daily maximum T_a data, the neutral PET is 14.6℃ during a Hong Kong winter according to Cheng (2008), which is similar to the thermal neutral temperature in Lujiazui, Shanghai. The latitude in Hong Kong is lower than in Shanghai, therefore the average outdoor air temperature should be higher. However, the two temperature are similar in these two coastal cities, probably because they are both high-density cities. The microclimate is influenced by a number of tall surrounding buildings.

On the other hand, only a few thermal comfort indeces have been established in the world, so taking some typical regions' criteria, such as western countries (Europe), eastern countries (Singapore) and other Chinese cities with different climate zones, is much valuable to explain the differences between Lujiazui and them in terms of living habit, environment and climatic condition. According to Lai et al. (2014a) research in northern China and Nikolopoulou and Steemers (2003) in Europe and Taiwan, 11-24℃, 18-23℃ and 26-30℃ are the neutral physiologically equivalent temperature ranges in Tianjin, Europe and Taiwan respectively in winter. It is obvious that the neutral PET range in Shanghai is much wider than those in the regions mentioned above. This may be attributable to physiological adaption, which refers to physiological response changes on account of long-term exposure to specific stimuli. The repeated exposure eventually lowers the discomfort associated with the stimulus (Nikolopoulou and Steemers, 2003). Since residents in Shanghai expose themselves to a wider and colder climate (monthly mean temperature 1 to 31.8℃) than residents in Tianjin (monthly mean temperature -3 to 26 ℃), Taiwan (monthly mean temperature 16 to 29℃) or Europe (monthly mean temperature 2 to 20℃ in Freiburg) (Lai et al., 2014a), the physiological adaption leads them to have a wider and lower thermal sensation range, because they may live a long time in such outdoor climatic environment, and their bodies become acclimatized. Furthermore, the residents' living habits from generation to generation are quite different, especially in China and western countries. More clothes with a high Clo may be encouraged to avoid illness in winter and seems like folk adage in China. Therefore, the willpower of some people may influence their judgement/vote for thermal comfort, because they can stay longer time in extremely weather than others.

5.4.6.3 Radiation sensation vote

According to Question 11 in the questionnaire, "-1" means the participants would not like to obtain too much global radiation, including solar radiation, "0" means neutral/comfortable, and "1" means they want more radiation. By observation, 664 participants were wearing hats, while the remaining 350 subjects did not wear hats and their forehead was exposure to the sun. As Figure 36 shows, the percentage distribution of radiation sensation vote between wearing a hat and without a hat was similar. Participants felt more comfortable when they were wearing a hat while being exposed to the strong sunlight, but it was not significant.

The difference of percentage distribution of radiation sensation between with and without a hat was negligible, therefore, they could be analysed together, with global radiation, to generate the regression model. However, setting global radiation as X and the response as Y could not obtain a worthy model, suggesting that global radiation and radiation sensation are not significantly correlated.

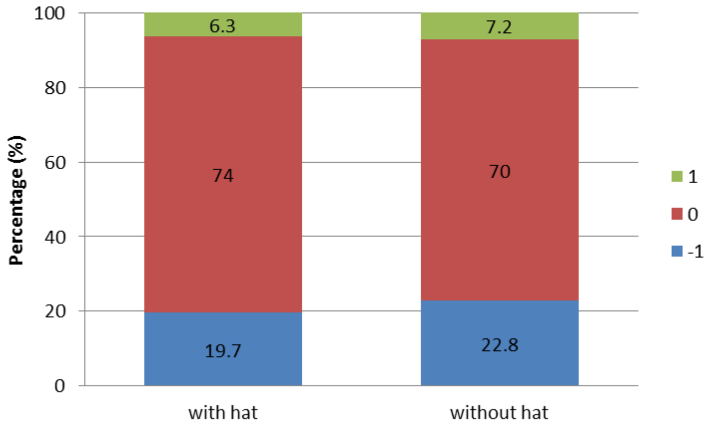


Figure 36: The comparison of percentage distribution of radiation sensation vote with and without a hat

Therefore, the adapted Bin method, was applied to analyse the relationship between global radiation and mean radiation sensation, which uses instantaneous mean radiation sensation vote calculations at several global radiation bins. In this research, the relative humidity between 35% and 40%, wind velocity between 0.7m/s and 1.1m/s and air temperature 14℃ and 18℃ are chosen, which takes up the most frequency part respectively. The average radiation sensation (Y-axis) of each 100W/m^2 of global radiation is calculated, and then the relation equation was obtained with the mean radiation in each part (X-axis) (Figure 37):

$MRSV = 0.0003G - 0.2569$ (n=526, R^2=0.894) (Equation 5.6)

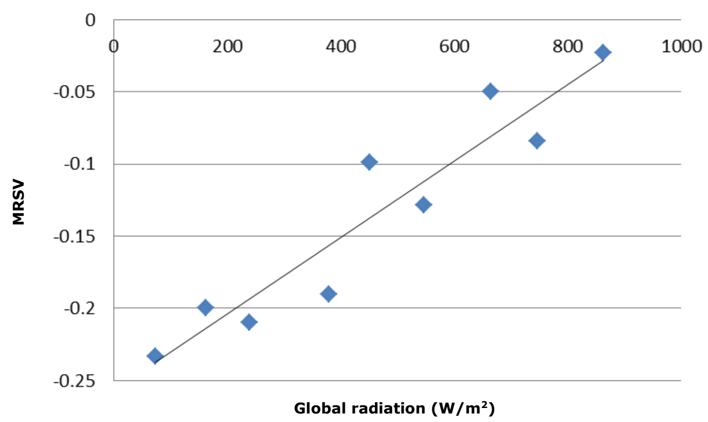


Figure 37: The relation of global radiation (G) and mean radiation sensation vote (MRSV)

From the regression formula (5.6), the correlation coefficient is 0.894, therefore, there is a high correlation between global radiation and radiation sensation. The neutral global radiation could be obtained (856W/m^2) when the MRSV is equal to 0. Therefore, during the research on outdoor thermal comfort in Hong Kong, Cheng (2008) found that outdoor temperature and global radiation have a significant positive correlation with the neutral PET.

5.4.6.4 Wind sensation vote

In this research, according to the wind sensation vote, approximately 23% of participants believed that the wind was neutral, and many of them (about 46%) felt that the wind was slightly still (Figure 38). However, the outdoor wind velocity was actually low, from 0 to approximately 3m/s, and more than 70% was lower than 1.5m/s (Figure 28). Even when the mean and majority wind velocity is low, it could still affect the users' thermal comfort (Stathopoulos, 2006).

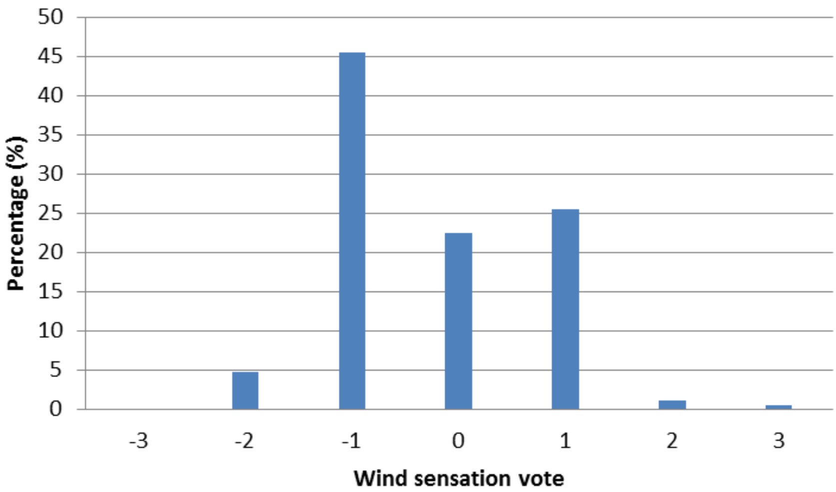


Figure 38: The percentage distribution of wind sensation vote

The relative humidity between 35% and 40%, air temperature from 14℃ to 18℃ and global radiation between 400W/m^2 and 500W/m^2 are chosen, which takes up the most frequency part respectively. Using the Bin method as mentioned before, the wind speed is divided into a series of consecutive parts of 0.2m/s, and then the wind sensation vote (WSV) was averaged for each part. The regression formula was obtained as Figure 39 and equation 5.7. However, the relationship between the wind velocity and MWSV is approaching significance (p=0.064>0.05).

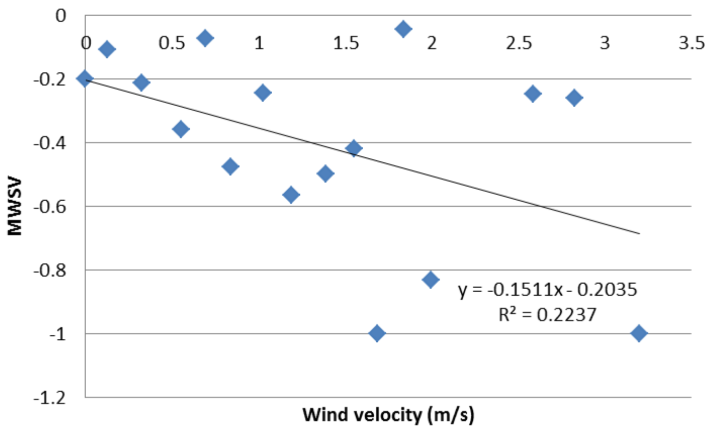


Figure 39: The relation of mean wind velocity (MWV) and mean wind sensation vote (MWSV)

$MWSV = -0.0779WV - 0.2769$ (n=683, R^2=0.2237) $p>0.05$

(Equation 5.7)

The regression formula between wind velocity and TSV could also be calculated (Figure 40 and Equation 5.8). The mean wind velocity is strongly correlated with the TSV (p<0.001). The neutral wind velocity is 0.55m/s, and the acceptable wind range is 0 to 3.2m/s when -1<TSV<1. However, the majority of studies on human thermal comfort conducted in other cities have only obtained the comfortable wind speed range in summer (e.g. 0.53-1.3m/s in Hong Kong (Cheng, 2008), 0.34-1.8m/s in Chongqing (Hu, 2013) and so on). However, these wind environment criteria are much lower. People may not like the wind in outdoor spaces on extremely cold days while they prefer the wind on hot days, therefore, a stagnant wind (0m/s) is acceptable for pedestrians in winter.

$\mathrm{TSV} = -0.3726\mathrm{MWV} + 0.2047$ (n=683, R^2=0.91) $p<0.001$

(Equation 5.8)

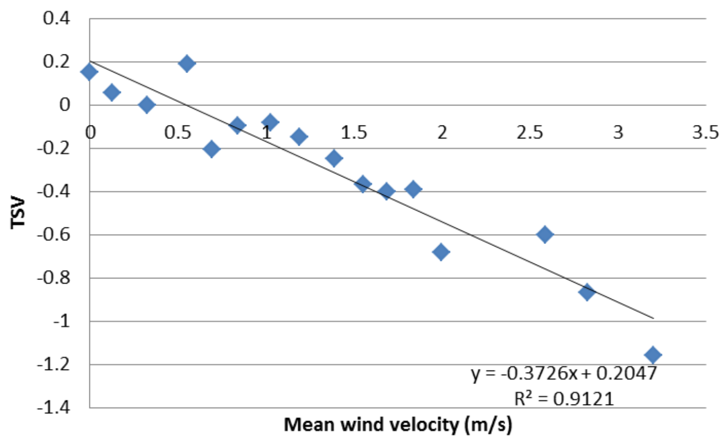


Figure 40: The relation of mean wind velocity (MWV) and mean thermal sensation vote (MTSV)

5.4.6.5 Humidity sensation vote

The earliest research on the influence of air humidity on a human body was conducted in the early 20th century when Houghten and Yaglou (1923) discussed its effect on human thermal comfort. This was followed by a series of related studies and the majority of them have shown that this effect is tiny in a relatively comfortable environment.

During the survey days, the minimum air humidity was 30%, while the maximum was 60%, however, there was no extremely significant distribution (Figure 28). Therefore, according to Figure 41, approximately 80% of the participants voted neutral, while less than 5% of the participants believed that the humidity was too wet.

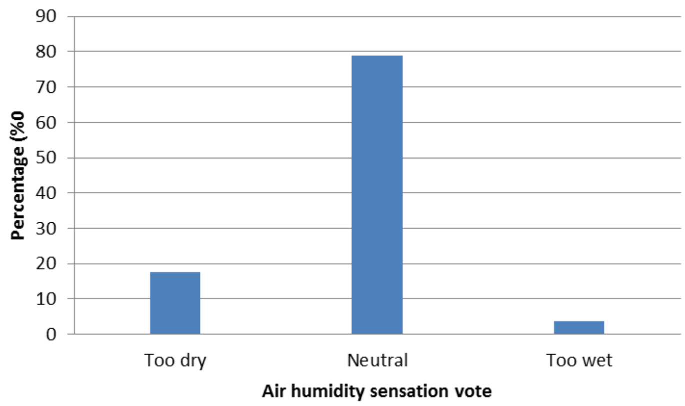


Figure 41: The percentage distribution of air humidity sensation vote

Figure 42 describes the skin condition vote. Approximately 58% of participants selected the neutral air humidity sensation. However, more than 35% of the participants felt that their skin was dry or too dry, while only 18% of participants felt that the air was too dry. The correlation coefficient between air humidity sensation vote and skin condition vote is only 0.115 (p<0.01), which means that skin condition is affected by activity, however, it cannot significantly influence peoples' air humidity sensation. People might sweat excessively during and after exercise, therefore, their skin condition would be wet and this state may cause an inaccurate sensation of air humidity.

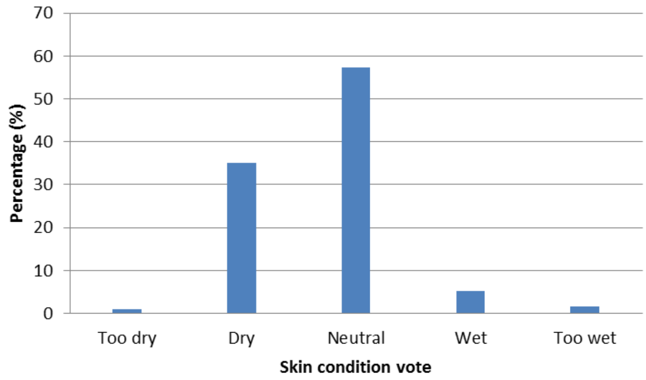


Figure 42: The percentage distribution of skin condition vote

In terms of the relationship between air humidity and its sensation vote, while the wind velocity between 0.7m/s and 1.1m/s, global radiation between 400W/m^2 and 500W/m^2 and air temperature 14℃ and 18℃ are chosen, applying the Bin method mentioned above, the humidity was divided into a series of consecutive parts of 5%, and then the HSV was averaged for each part. The middle temperature of each part was set as the independent variable X, the mean humidity sensation vote (MHSV) as the dependent variable Y, and the linear regression analysis was completed (Figure 43).

The coefficient of determination is 0.89 and the coefficient of association is p<0.001, therefore, this regression line looks like meaningful. By making MHSV equal to 0, the neutral air humidity of 67% is obtained. However, the range of MHSV (-0.14 ~ 0) is too small that voting between 0 and 0.5 means the same thing and all MHSV describe relative humidity is comfortable. Thus, this equation may not describe the relationship between relative humidity and participants' mean humidity sensation vote.

$\mathrm{MHSV} = 0.0037\mathrm{RH} - 0.249$ (n=572, R^2=0.89) (Equation 5.9)

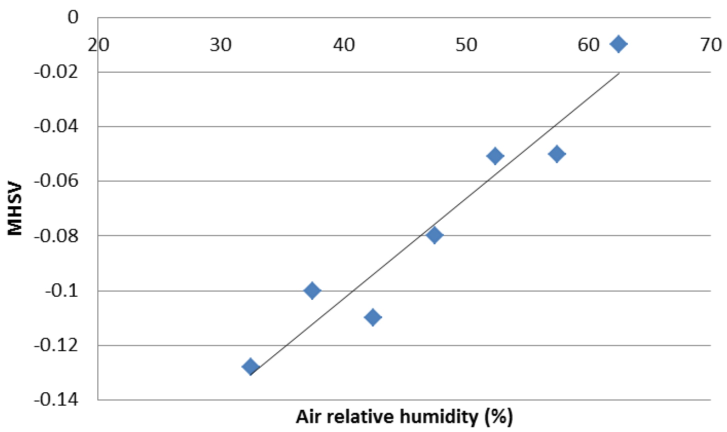


Figure 43: The relation of relative humidity and mean humidity sensation vote

5.4.6.6 Overall comfort vote

In practice, the neutral thermal sensation vote (TSV=0) should align with the thermal comfort level. A 5-point scale is used in this case to measure thermal comfort with -2 indicating very uncomfortable and +2 indicating very comfortable. The results are shown in Figure 44. More than half of the participants felt neutral (OCV = 0), and less than 10% of them indicated that they felt uncomfortable (-1), while approximately 35% and 3% of participants felt comfortable and very comfortable respectively.

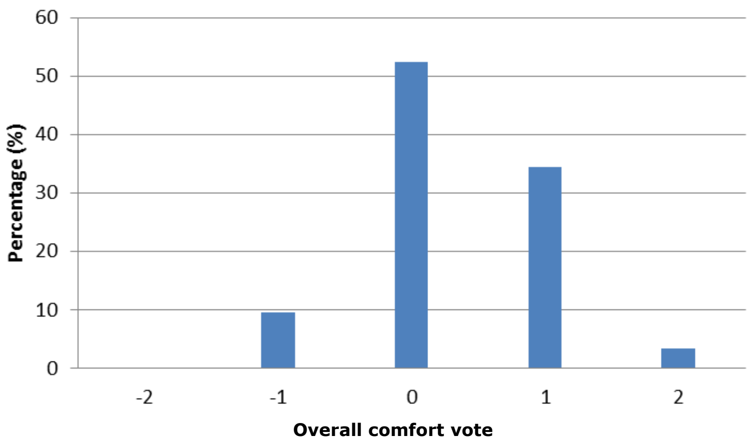


Figure 44: The percentage distribution of overall comfort vote

As Table 18 shows, theoretically, when participants felt between cool to warm ($-1 \leq TSV \leq 1$), they would feel between neutral and very comfortable ($OCV \geq 0$) (Ng and Cheng, 2012). If the TSV is larger than "1" or smaller than "-1", then the corresponding OCV should be smaller than "0," which means uncomfortable or very uncomfortable.

TSV	Thermal sensation
-3	very cold
-2	cold
-1	cool
0	neutral
1	warm
2	hot
3	very hot

OCV	Overall comfort
-2	very uncomfortable
-1	uncomfortable
0	neutral
1	comfortable
2	very comfortable

Table 18: Comparison between TSV and OCV

Furthermore, the scope of the OCV was modified to only comfort (+1) and uncomfortable (-1) in MOCV, while the TSV was modified and divided into three parts: set cold (including "-2" and "-3") as "-1", comfort ("-1", "0" and "1") as "0" and hot ("2" and "3") as "1" in MTSV, and the following regression model was generated:

$$\mathrm{MOCV} = 0.156\mathrm{MTSV} + 0.821 \qquad (n=1014,\ R^2=0.53)$$

(Equation 5.10)

MOCV: modified overall comfort vote

MTSV: modified thermal sensation vote

However, the correlation coefficient is 0.53 that means they are weakly correlated and therefore potentially unreliable. This may be due to the vague definition of the comfort sensation in the lower part of Table 18 where there is potential confusion over the term 'neutral'. The results from this section were not used further in this study.

The overall comfort vote was developed with the investigation and calculated from an hourly TSV and related OCV. The correlation model is shown in Figure 45. The coefficient of determination of 0.7266 is approaching significant meaning that the equation 5.11 can describe the relationship between these two variations. It is suggesting that all TSV is among -1 to 1 while the OCV is above 0. In this outdoor comfort research, the majority of pedestrians felt comfortable when they felt cool or warm, indicating that the current outdoor environment is acceptable in Lujiazui in winter. Equation 5.12 was derived from Lai et al.'s research on outdoor thermal comfort in Northern China using the correlation between the averaged comfort vote and the TSV scale and has further proved that the "hot" sensation (TSV = 2) is much more comfortable than the "cool" sensation (TSV = -1) on cold days, which means people who live in cold regions prefer to stay in a "hot" outdoor environment rather than "cool" because of feeling more comfortable.

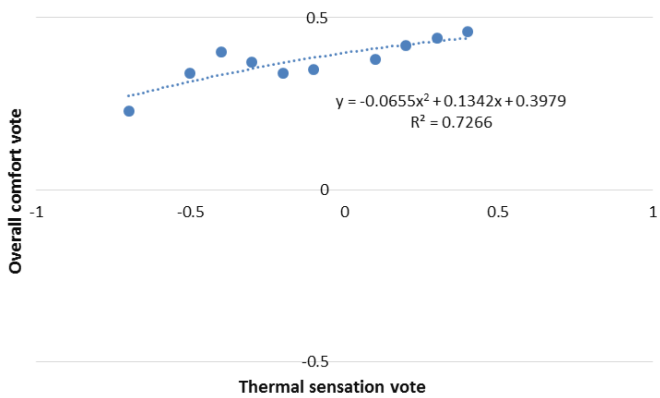


Figure 45: Correlation between TSV and mean OCV

$$\mathrm{OCV} = 0.3979 - 0.065TSV^2 + 0.134TSV \qquad (n=1014, \quad R^2=0.7266)$$

(Equation 5.11)

$$OCT_{Nothern\ China} = 0.421 - 0.072TSV^2 + 0.125TSV \qquad (R^2=0.898)$$

(Equation 5.12)

5.5 Conclusions and Summary

The Lujiazui CBD District, located in the Pudong New District in Shanghai, is becoming a typical international region and has been selected as a primary case study for Chinese city planning. It has been adopted as an urban development criterion by Chinese authorities, because of its socio-economic and spatial transformation. However, as mentioned above, the previous and current urban plan for Lujiazui might not be a successful urban model for new urban developments in China because of its lack of consideration for the effect of its architecture on outdoor comfort.

It is acknowledged that microclimate is a very important parameter for thermal comfort, therefore, combining the physical environment with user requirements and satisfaction could develop open spaces in the urban environment. Sunlight and shade can be provided and wind flow limited or improved between the buildings of inner city spaces though a combination of urban planning and modern architecture. Determining the importance of the various physical conditions on the pedestrian's comfort would enhance our comprehension of the consequences of modifying public spaces. The observations and questionnaire collected data on attitudinal factors, experimental condition and attire which could be applied to the adaptation used to define comfort. T_a, RH, G and WV contributed to the variation presented on the comfort scale.

The results from the survey made a novel contribution to the knowledge of the pedestrians' thermal comfort outdoors in the Lujiazui district in winter by means of the following:

1) Some females wore clothes with less insulation than males in Pudong in winter, and they may wear exothermic clothes to keep warm;
2) Clo in summer is similar in Asia and Europe, however, in winter it differs significantly. It is higher in Asia, which maybe because people cannot wear less clothing in summer regardless of their location, however, they have to wear more in winter to resist adverse environmental factors such as lower temperatures. Furthermore, physique, long-term thermal adaption and lifestyle may influence their choice of clothing;
3) The effect of air temperature on thermal sensation is the most significant, while relative humidity has a statistically negligible influence on people's perception of thermal comfort in winter;
4) In tropical cities, like Singapore, the TSV was influenced by recent exposure to air conditioning which was contrary to the result obtained by this study. It is assumed that this difference is due to people having a greater sensitivity when they enter a cold outdoor environment from an indoor warm condition. In this condition, they may feel more uncomfortable than those staying outside for a long time;
5) A person's tolerance for cold increases if they are frequently exposed to it over an extended period of time as this facilitates their adaptation to the local micro-meteorological conditions. Long term residents of Shanghai typically regarded its conditions as neutral as

they had adapted to the local conditions whereas those who were new to the area found the local conditions to be cold;

6) Approximately 93% of the participants could accept the thermal environment in Lujiazui. After applying the method of temperature-frequency, the regression between the micro-meteorological parameters and thermal sensation vote is significant, and it is established that: 1) the winter mean neutral T_a is 14.7℃ and the accepted temperature range is 7.7℃-21.8℃; 2) neutral global radiation is 856W/m^2; 3) neutral air humidity is 67%, but it might be inaccuracy due to the too small range of MHSV; and 4) neutral wind velocity is 0.55m/s with the accepted wind velocity range of 0-3.2m/s;
7) When the wind speed increases by 1m/s, a 0.22℃ increase in air temperature can maintain the proportion of people perceiving neutral conditions;
8) Residents in Shanghai expose themselves to a wider and colder climate than residents in Taiwan and some European cities, and comparing the thermal comfort criteria in these regions draw a conclusion that people' physiological adaption in Shanghai have a wider and lower thermal sensation range. Furthermore, the residents' living habits differ considerably, especially between China and western countries;
9) Skin condition is affected by activity, however, it cannot significantly influence peoples' air humidity sensation. People might sweat excessively during and after exercise, therefore, their skin condition is wet. However, at this condition, this state of sweatiness may cause an inaccurate sensation of air humidity, because they may feel the air is too humid even though the outdoor actual humidity is lower than they expect; and

10) The majority of participants felt comfortable indicating that the current outdoor environment in Lujiazui is acceptable in winter.

In next chapter, the comfort wind speed range will be applied to assess the historical and current outdoor wind environment in Lujiazui after CFD simulation.

CHAPTER 6 PEDESTRIAN WIND ENVIRONMENT IN THE LUJIAZUI DISTRICT

6.1 Introduction

Since the 1880s, the mean wind velocity has steadily declined in the urban area of Shanghai (Chow, 1992). The urban-rural WV variance has been constantly monitored since the development of the rural wind observatory in the 1950s. A variance in the region of 0.5-1.3 m/s was observed and found to have a negative correlation with the constant growth of residential building coverage as part of the urbanisation process (Chow, 1992). The urban observatory recorded a mean summer WV of 3.4-3.9 m/s (Yan and Xu, 1996, Yang et al., 2013). The wind speed, measured at 10 above the ground, in rural area decreases into approximately 70% at pedestrian level in urban area (Chen, 2004). It is rational to expect even lower WV at the pedestrian level in high density urban regions. Therefore, good urban design should proceed from a prime consideration of enhancing outdoor comfort and facilitating outdoor health and comfort.

The current high speed of urbanisation and economic development in China, and the experiences of other countries and regions (such as Singapore and Hong Kong) can assist the Chinese government and urban designers to understand and meet the requirements of outdoor thermal comfort. It is vital to analyse the past and existing development of wind environment, and made recommendations regarding future urban design in the Lujiazui district. The survey and data analysis were completed in the previous chapter and utilised to develop some local wind comfort criteria. The development of tall buildings and their surrounding outdoor wind environment at the pedestrian level in Lujiazui were simulated. Then, air ventilation assessments are used to describe CFD predictions of wind patterns, which refers to the relationship among built-up area, site area, total building heights and wind comfort area.

6.2 The development of tall buildings in the Lujiazui district

This section introduces the development model of the outdoor wind environment over the past 20 years in Lujiazui district. 41 tall buildings were constructed in this area over the last 20 years and, based on their structure completion time, they are divided into eight groups. The first high building is Shanghai Oriental Pearl TV Tower completed in 1994, while the most recent is the Shanghai Tower which was completed in 2014. Table 19 shows the different stages in three year intervals and Figure 46 describes the development with 3D models. Furthermore, the detailed development plan is included in Appendix 4.

There are eight models representing the development of the initial environment without tall buildings to the current one with high buildings wherein the wind environment will be simulated on the pedestrian level. Following the simulation, the development of the pedestrian wind environment will be analysed via an air ventilation assessment to determine the amount of outdoor space that meets the wind comfort criteria and the level of wind turbulence. According to the previous chapter, under the condition of the highest frequency range of global radiation and air temperature, the outdoor WV_{winter} should be below 3.2m/s to be comfortable and acceptable to pedestrians. The outdoor thermal comfort questionnaire survey was not done in Shanghai in summer, but the wind comfort criteria can reference to other related research that has similar climatic conditions and residents' requirements. Ng (2009) recommended that the pedestrian level wind velocity should be above 1 to 2m/s so as to supply sufficient outdoor ventilation on hot, calm days in Hong Kong. Consequently, the Hong Kong Building Environmental Assessment Method (HK-BEAM) requires that there are no stagnant areas that have a wind speed less than 1.5m/s (Wu and Kriksic, 2012). Both Hong Kong and Shanghai have a high temperature in summer (approximately 30℃ of average temperature) and are typical high density lots of tall building districts, thus the minimum WV is applicable in Shanghai. Therefore, as mentioned in Chapter 3, the Murakami and Soligo research teams specified that the threshold of pedestrian wind comfort is 5m/s of wind speed. To assess the outdoor wind environment in summer, the comfortable and acceptable WV_{summer} range in Shanghai can be set at 2m/s to 5m/s in this study.

NO.	Name	Time of Completion	Location	Building Height (m)	Time Period Number
1	Shanghai Oriental Pearl TV Tower	1994	1 Century Ave, Pudong, Shanghai	468	1994-1996 5
2	Shanghai China Merchants Tower	1995	161 Lujiazui East Rd, Pudong, Shanghai	186	
3	China Minsheng Bank Building	1995	100 Pudong South Rd, Lujiazui, Shanghai	134	
4	Port Building	1995	1 Fenghe Rd, Pudong, Shanghai	102	
5	Shanghai Stock Exchange Bldg	1996	528 Pudong South Rd, Pudong, Shanghai	109	
6	Huaneng Union Tower	1997	958 Lujiazui Ring Rd, Pudong, Shanghai	188	1997-1999 8
7	Customs Bldg	1997	153 Lujiazui West Rd, Shanghai	137	
8	Shanghai International Conference Center	1999	2727 Binjiang Ave, Pudong, Shanghai	51	
9	Jin Mao Tower	1999	88 Century Ave, Pudong, Shanghai	421	
10	People's Bank of China Tower	1999	181 Lujiazui Ring Rd, Pudong, Shanghai	89	
11	Shanghai Sen Mao International Bldg	1999	1000 Lujiazui Ring Rd, Pudong, Shanghai	203	
12	Huaxia Bank Mansion	1999	256 Pudong South Rd, Pudong, Shanghai	85	
13	China Insurance Bldg	1999	166 Lujiazui East Rd, Pudong, Shanghai	196	
14	Bank of China Tower	2000	200 Yincheng Middle Rd, Pudong, Shanghai	258	2000-2002 9
15	Shanghai World Financial Towel	2000	201 Yincheng East Rd, Pudong, Shanghai	168	
16	New Shanghai International Tower	2000	360 Pudong South Rd, Pudong, Shanghai	168	
17	China Development Bank Tower	2000	500 Pudong South Rd, Pudong, Shanghai	170	
18	Shanghai Pu Fa Building	2001	588 Pudong South Rd, Pudong, Shanghai	150	
19	Shanghai Information Tower	2001	211 Century Ave, Pudong, Shanghai	288	
20	Aurola Tower	2001	99 Fucheng Rd, Shanghai	180	
21	Bacom Financial Tower	2002	188 Yincheng Middle Rd, Pudong, Shanghai	230	
22	Super Brand Mall	2002	168 Lujiazui West Rd, Shanghai	50	
23	Azia Center	2005	1233 Lujiazui Ring Rd, Pudong, Shanghai	167	2003-2005 3
24	CitiBank Tower	2005	33 Huayuanshiqiao Rd, Pudong, Shanghai	180	
25	Pudong Shangri-La, East Shanghai	2005	33 Fucheng Rd, Pudong, Shanghai	180	
26	Bank of Shanghai Tower	2007	168 Yincheng Middle Rd, Pudong, Shanghai	230	2006-2008 8
27	Mirae Asset	2007	166 Lujiazui Ring Rd, Shanghai	180	
28	Zhongrong Jasper Tower	2008	10 Yincheng Middle Rd, Pudong, Shanghai	220	
29	Shanghai World Financial Center	2008	100 Century Ave, Pudong, Shanghai	492	
30	Golden Landmark Building	2008	150 Yincheng Middle Rd, Pudong, Shanghai	210	
31	One Lujiazui	2008	68 Yincheng Middle Rd, Pudong, Shanghai	270	
32	China Pingan Financial Tower	2008	1333 Lujiazui Ring Rd, Pudong, Shanghai	170	
33	Standard Chartered Bank Building	2008	201 Century Ave, Pudong, Shanghai	121	
34	Bank of East Asia Fiance Tower	2008	66 Huayuanshiqiao Rd, Pudong, Shanghai	198	
35	Wanxiang Plaza	2009	99 Lujiazui West Rd, Shanghai	79	2009-2011 7
36	21st Century Building	2009	210 Century Ave, Pudong, Shanghai	210	
37	DBS Building (Lujiazui Finance Center)	2009	1318 Lujiazui Ring Rd, Pudong, Shanghai	90	
38	Shanghai International Finance Center	2009	8 Century Ave, Pudong, Shanghai	250	
39	Shanghai Gran Melia Hotel	2010	1288 Lujiazui Ring Rd, Pudong, Shanghai	134	
40	Taiping Financial Tower	2011	488 Yincheng Middle Rd, Pudong, Shanghai	218	
41	China Merchants Bank Mansion	2011	26 Pudong South Rd, Pudong, Shanghai	208	
41	Shanghai Tower	2014	501 Yincheng Middle Rd, Pudong, Shanghai	632	2012-2014 1

Table 19 : The list of tall buildings in Lujiazui, Shanghai (author, 2016)

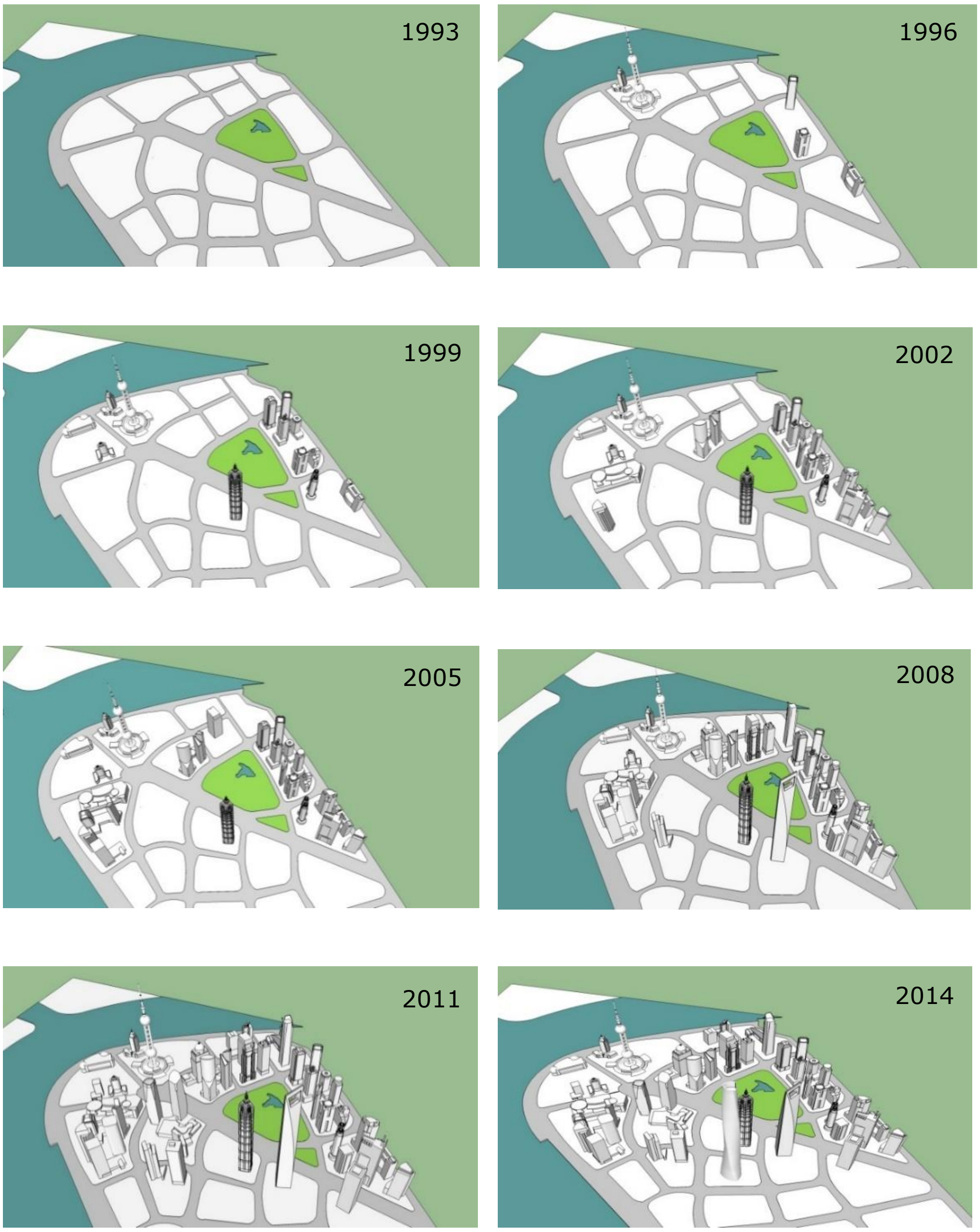


Figure 46: 3D view of the development of tall buildings in Lujiazui, Shanghai

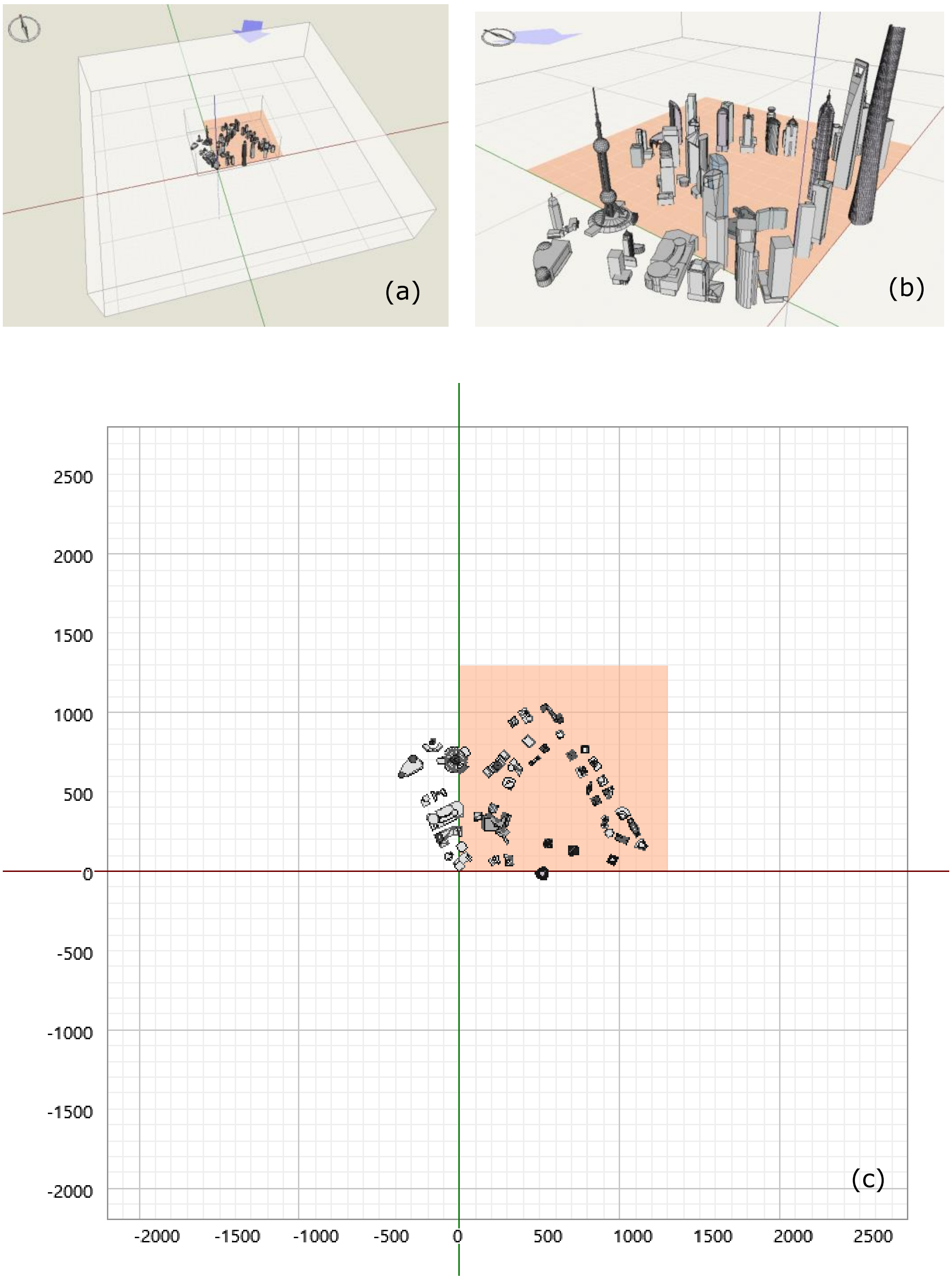
6.3 Computational settings and parameters

The computational numerical simulation software FlowDesigner is used to introduce, employ and compare the wind tunnel test results derived in the previous chapters. The Lujiazui district and Sai Ying Pun have similar landscapes, including proximity to a large body of water (Huangpu River and sea respectively) and high-density tall buildings, the boundary conditions, turbulence model and other boundary parameters of Sai Ying Pun were used (see Table 12).

6.3.1 Computational geometry and domain

A CFD simulation of the wind environment around tall buildings in 2014, which includes the geometry and domain settings, in FlowDesigner can be applied to different stages of development to plan future urban design. Figure 47 shows the tall buildings which receive specific attention in this thesis. Figure 47a shows the computational domain with an aerial photo of the explicitly modelled buildings, while Figure 47b describes the magnifying one. The area of the tall buildings is approximate 1400m * 1100m, while their average height is approximately 260m and the highest building is 632m. From the suggestion of many related pieces of researchers and previous experience obtained in Hong Kong, the boundary should be far enough from any buildings that is at least two times of the specific site width at each side on the plan, and three times of building height, to enable accurate prediction of the air flow at the boundary. Under the limitation of the software and capacity of the computer, a larger boundary size always brings more grids if the same cell size or larger cell size is kept at the same total number. Anyway, any one of them requires a longer time to mesh and for calculation. In this study, the dimension of the whole computational boundary is set as L * W * H = 4700 * 5000 * 900 m, which is significantly larger than other models applied in most research also focusing on outdoor wind environments.

There are some unusual tall buildings in Lujiazui that are difficult to model in ANSYS Fluent, FlowDesigner and other software. Therefore, the models for this thesis were constructed in SketchUp and uploaded to the CFD software. Fluent was the first software to be applied for the simulation, however, its interface and operation are not user friendly and the process of mesh and calculation were time consuming. These details will be discussed in detail and compared to FlowDesigner later.



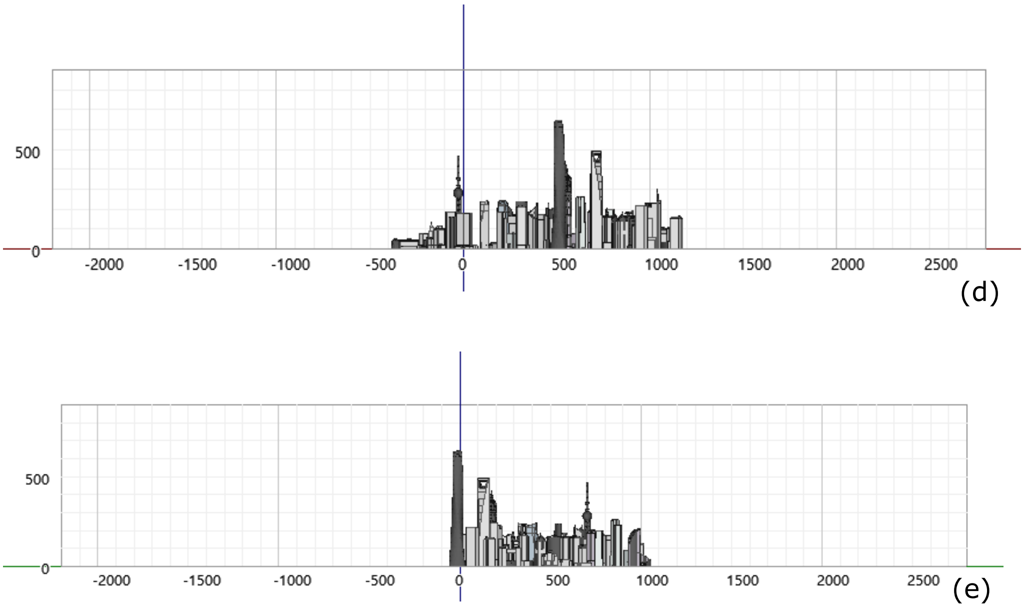


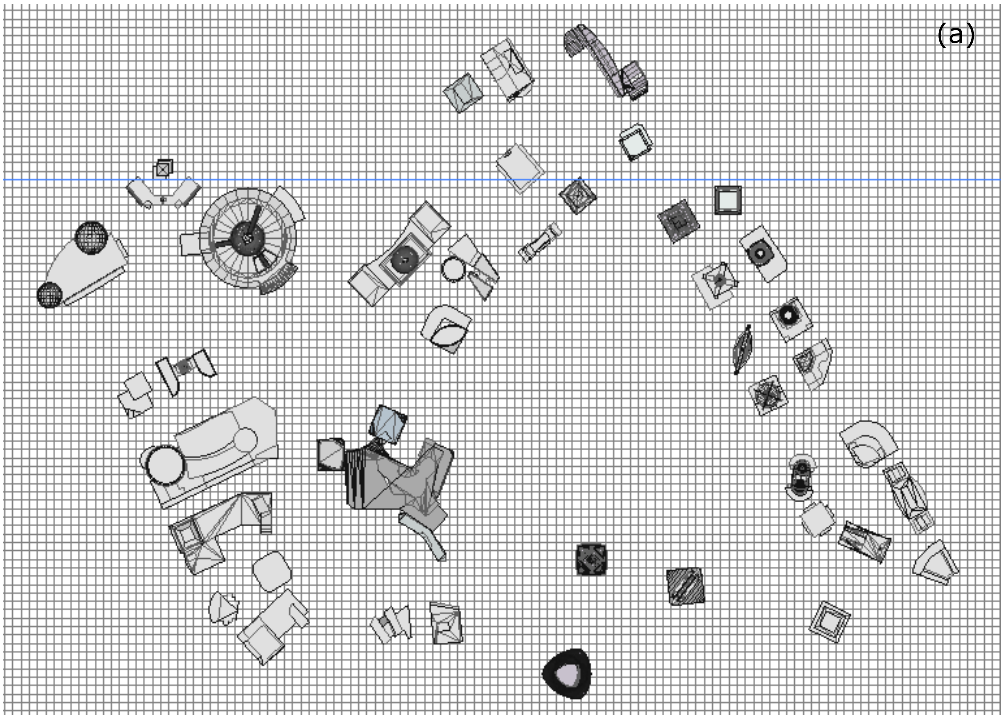
Figure 47: Geometry and domain settings: (a) computational domain with aerial photo of the explicitly modelled buildings; (b) magnifying aerial photo; (c) horizontal domain; (d) vertical domain; and (e) transverse domain

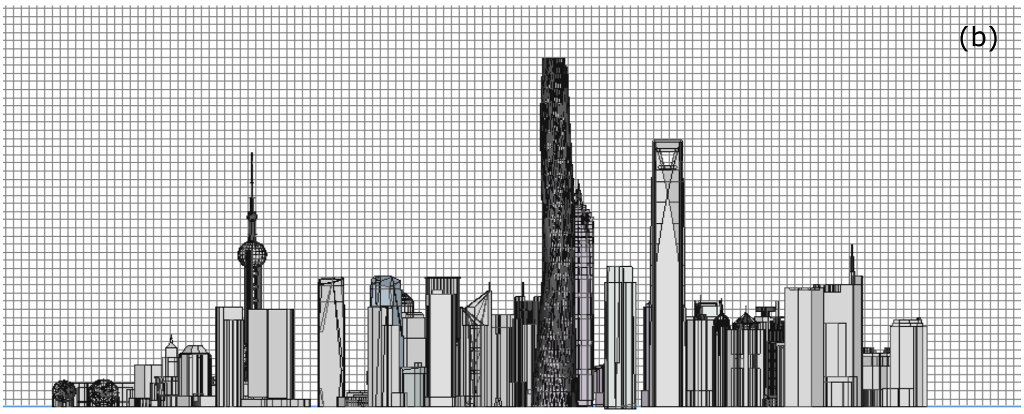
6.3.2 Computational grid

During mesh, there are limitations on the number of computational grids in each CFD tool. Special care was given to identifying a high-quality and high-resolution grid that only consists hexahedral cells. Although Fluent can use hexahedral, prismatic, tetrahedral and pyramidal cells, it requires considerably more time to mesh and calculate. In this study, hexahedral cells were applied to ensure that all cells were at the same position at any mesh and calculation, especially at pedestrian level, because from the calculation results, the air speed in each cell would be recalculated for the total area of wind comfort. Therefore, the process of recalculation is: (1) counting the total number of grids that air speed is during the wind comfort range and (2) calculating the RCS (ratio of comfort size and total site size): $\mathrm{RCS} = \frac{total\ cell\ number\ of\ wind\ comfort}{total\ cell\ number\ in\ site}$.

To obtain a better and more accurate wind environment at pedestrian level, and, considering the maximum limit of the cells when they mesh, the horizontal planes were divided into a 360 * 360 grid, while the vertical zone was divided into 60 parts. Consequently, each cell had dimensions of 13 * 13 * 15m. However, accordance with the AIJ guidelines (Tominaga et al, 2008) and same setup in Hong Kong, three vertical cell layers with a height below 1.5m were added because the pedestrian level is the main research target area. The mean wind velocity of each cell could be obtained from the centre of the cell, therefore, a 3m high cell is conducive to gathering the more accurate results from the calculations. Furthermore, the horizontal plane is divided into two parts: the central part of interested site (high-dense grids) and the boundary (low-dense grids), while the vertical is divided into three parts: the pedestrian level (highest-dense grids); the buildings level from 3m to 200m (secondary-dense grids) and the boundary level above 200m (low-dense grids). The computational grid used for this research consists of (a) 8,164,800 cells (360 * 360 * 63) for the domain. Some other kinds of computational grid were tested, which are: (b) 450 * 450 * 45 (9,112,500 cells) and (c) 300 * 300 * 60 (5,400,000 cells). According to the calculation procedure, a smaller cell size brings more accurate algebraic approximations to value the neighbouring cells, which increases the precision of the final results. However, smaller cells are accompanied by increased total number of grids that means high-resolution requires much more time for mesh and calculation, while fewer cells cannot describe the results accurately through it requires less computing time. Furthermore, the results of (a) and (b) do not have any obvious differences regarding the predicted wind environment at pedestrian level. It may imply mesh at this level in not fine enough, but due to the limitation of total number of cells (less than 10,000,000) in the software, the first kind of grid is applied here.

Figure 48a, b and c presents images of the grid site. According to Janssen et al. (2013), issues can arise when creating a grid containing hexahedral cells alone as this can contradict convergence problems encountered in making calculations that are generally linked with tetrahedral cells in hybrid grids. This is particularly true in cases where second-order discretisation schemes are implemented.





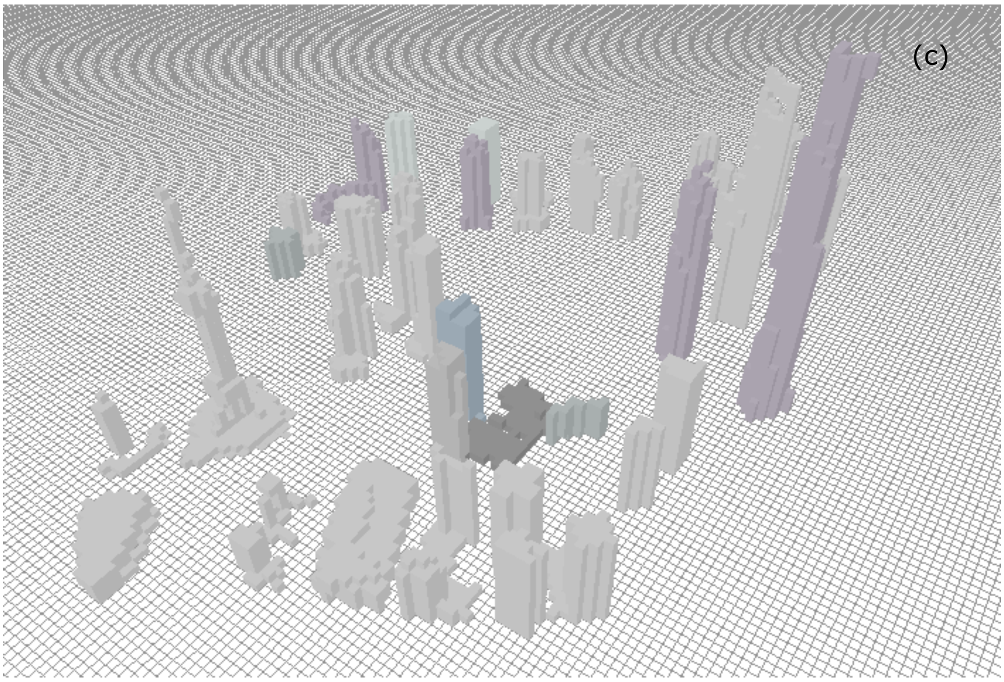


Figure 48: Corresponding computational grid on the building surface: (a) horizontal view; (b) vertical view; and (c) aerial view

6.3.3 Prevailing wind directions and velocities

Figure 24 shows that there are seven prevailing winds (annual occurrence frequency is above 8%), measured from the meteorological station in the Pudong International Airport, during the year in Lujiazui, Shanghai. According to Equation 2.1, the empirical power law representation of the mean velocity profile in the outer layer can be applied to calculate the inlet mean wind speed in the interested site in the CFD simulation (Table 20). Two main wind directions and their velocities will be discussed in this study: WNW, 5m/s in winter and SSE, 5.3m/s in summer. The results of these simulations will be the focus on the analysis and discussion. The simulation results of the remaining five prevailing winds are shown in Appendix 5.

Prevailing wind directions	Average wind speed, m/s	Annual occurrence, %
2*,NNE	5.1	8.4
5, E	5	12
6, SEE	5.3	12
7, SE	5.7	9.3
8, SSE	5.3	8.4
14, WNW	5	8.7
15, NW	3.5	8.4

Table 20：Mean inlet wind speed applied in CFD simulation

(*Note: wind is divided into 16 directions on the compass, and 360^{o} divided by 16 equals 22.5^{o} with cardinal direction) (adapted from weather tool in Ecotect)

6.4 CFD simulation of outdoor wind environment with prevailing wind directions in different years

The influence of developing urban morphology on the outdoor wind environment at the pedestrian level varies based on the buildings' size, location, orientation, distance, arrangement, height difference etc. With the time sequence and development of tall buildings, a pairwise comparison of outdoor air flow between two time periods in Lujiazui will be described and evaluated. Furthermore, the following independent variables are included in the multiple regression models based on: (a) the ratio of built-up area to site area ($\mathrm{RBS} = \frac{Built\text{−}up\ area}{Site\ area}$); (b) total new building heights (TNBH); (C) total building heights (TBH); (d) average building heights (ABH); and (e) the ratio of wind comfort area to site area ($\mathrm{RCS} = \frac{Built\text{−}up\ area}{Site\ area}$).

6.4.1 Outdoor wind flow in summer with prevailing wind direction of SSE (157.5^{o})

There were only five tall buildings in Lujiazui in 1996, and their various building morphologies prevented air flow. When the wind travels over objects, its speed and direction may change, which is described by coloured arrows in the CFD results, and turbulence zones may occur in the wake stream at the rear of the objects. The length of the wake stream primarily depends on the facing-wind-width of the building, especially the building podium.

All the air flow slices are taken at the height of 1.5m for accessing the wind environment at pedestrian level. Therefore, the maximum speed in the speed label (up left corner) is capped by 5m/s with red colour, because it is also the wind safety threshold. Areas with speed higher than that presented by red means they are not comfort or safe, which makes the figures easier to apply for assessment.

Wind speed is reduced in the area of a wake stream, however, it accelerates in the narrow space between two parallel buildings (Figure 49 1996_a).

More tall buildings were completed in a period of three years and the air flow became more complex. More low air speed zones (under 5m/s) occurred because the location of some buildings prevented the wind flow from the SSE (1999_a and 1999_b).

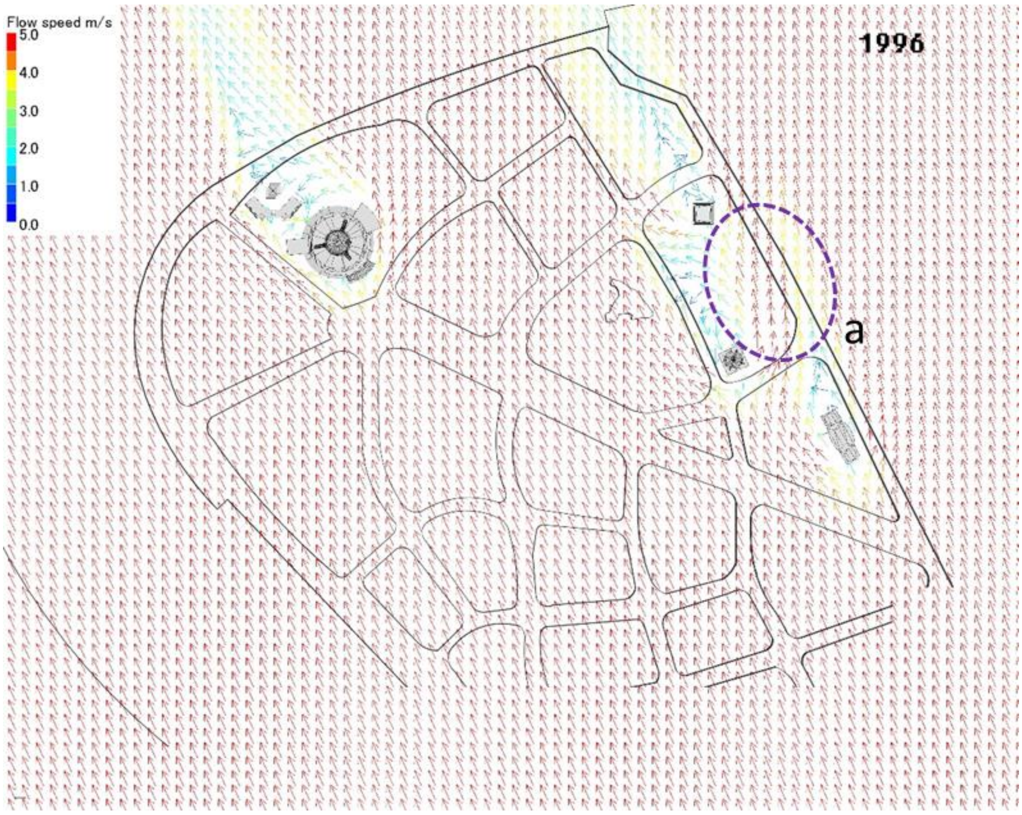
In 2002, a building with a wide podium against the wind direction was built around location 2002_a, which generated a low wind speed space. However, the windward zone of the new building and the leeside of the existing tall building (1999_a) generated at location 2002_b changed the air flow directions. In addition, more buildings were established around area 2002_c, which appeared to be an enclosed space with a low wind speed.

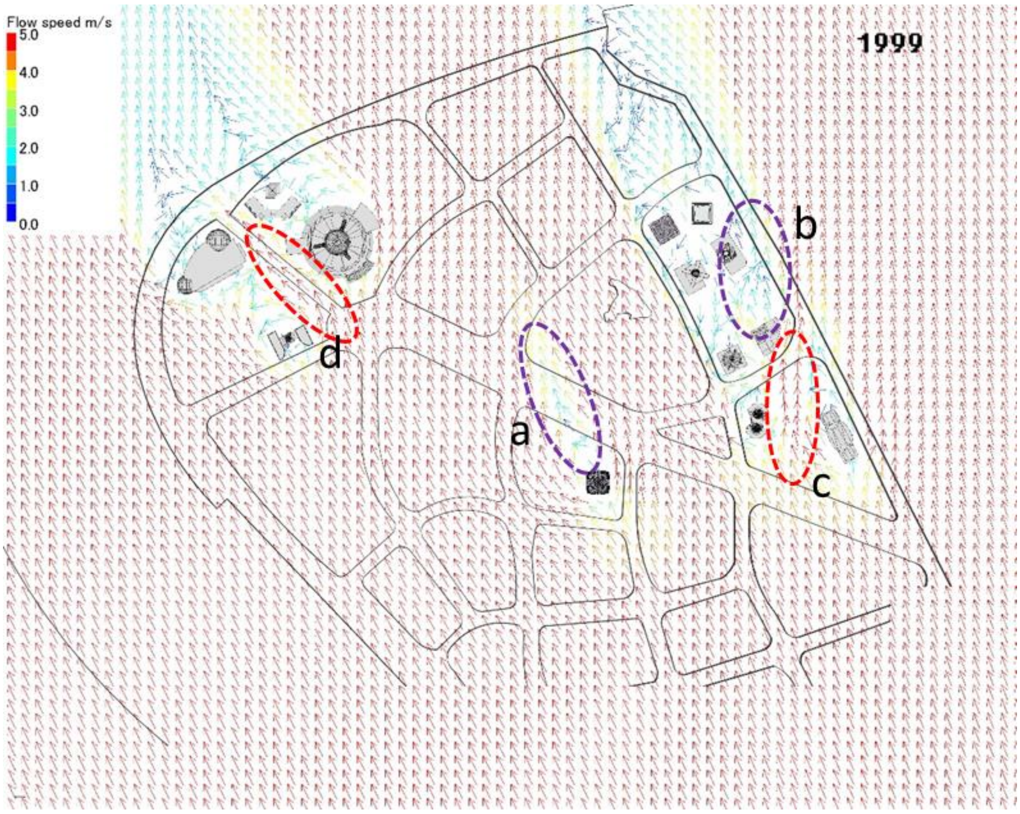
The same situation occurred at space 2005_a in 2005, which created another area with low wind speed in Lujiazui. The air flow direction changed in location 2005_b, because there was a new tall building opposite that influenced the air in the gap.

After another super tall building was constructed in 2008 and the wind was significantly decelerated in its windward area (2008_a). The wind speed in the windward spaces of 2008_b and 2008_c was reduced due to the obstruction caused by the new structure.

In 2011, three tall buildings linked by the same podium were built in 2011_a, and the surrounding wind environment was heavily influenced. An accelerated wind speed was found in street canyons on the west. The construction of two more tall buildings in 2011_b had little influence on the air flow in the leeward area, except the direction. However, with the new tall building, a higher wind speed occurred on the northwest side (2011_c).

The last tall building was built in 2014 and influenced the surrounding wind environment. The wind in the nearby space decreased, however, accelerated winds appeared on its northern and western streets (2014_a).




Flow speed m/s
5.0
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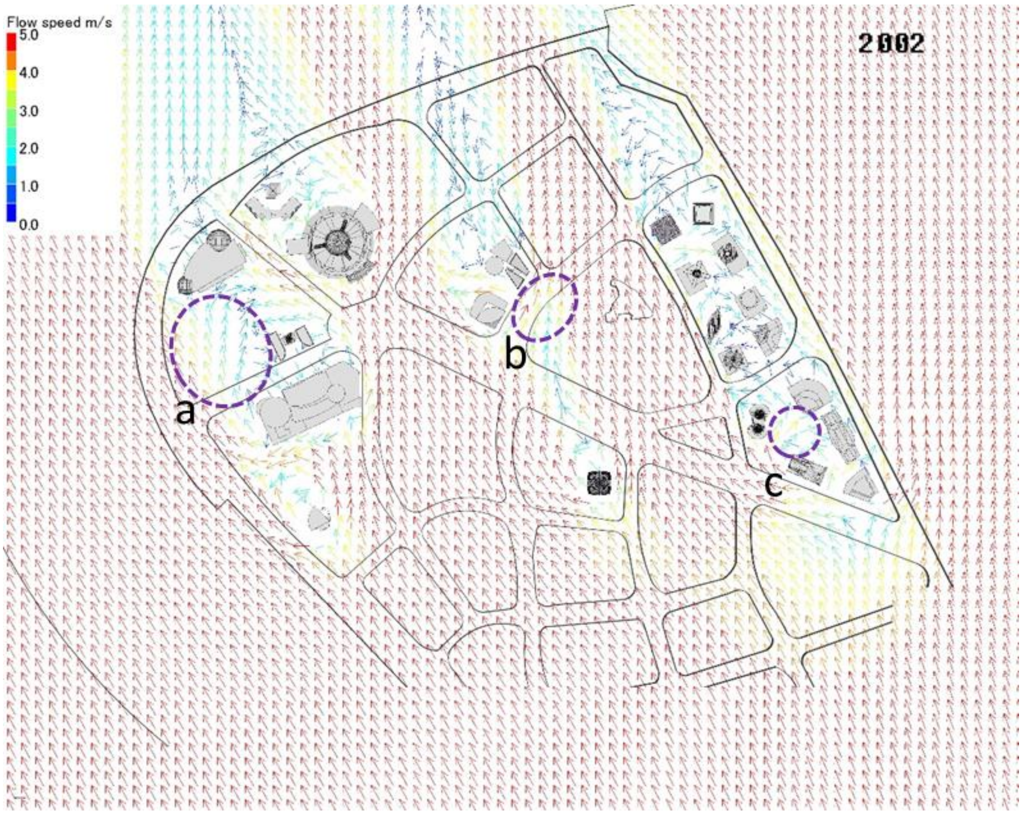
0.0
1999
a
b
c
d


Flow speed m/s
5.0
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2002
a
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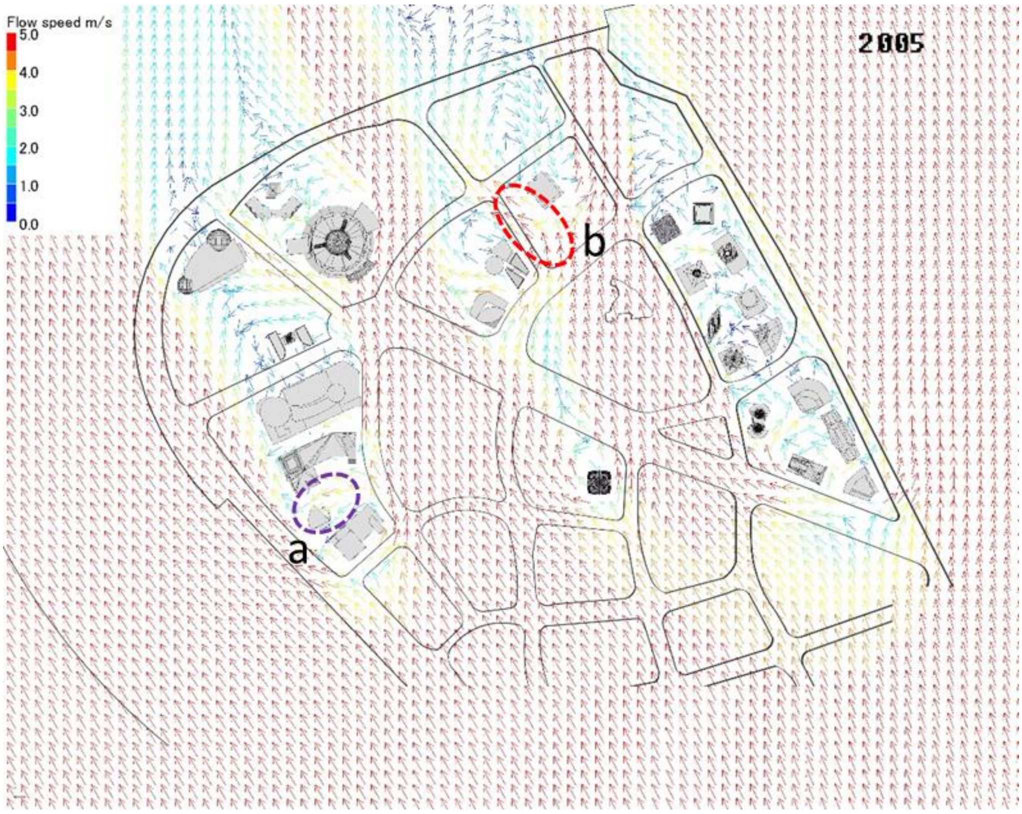
Flow speed m/s
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2005
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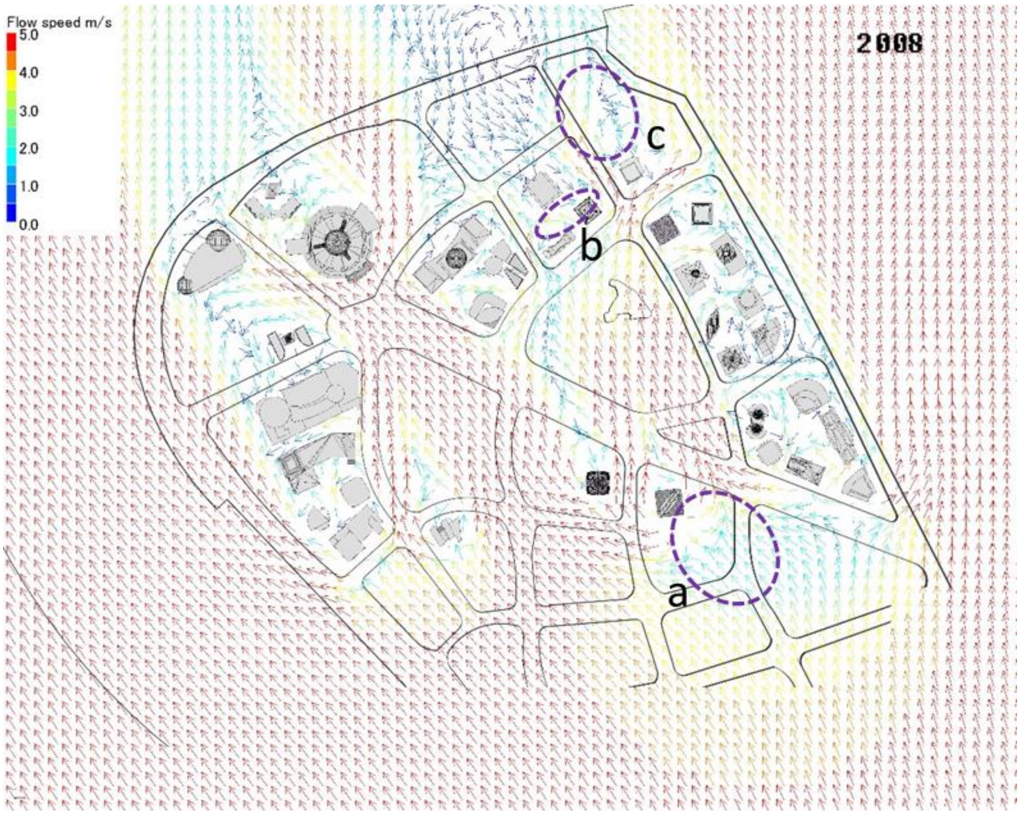
a


Flow speed m/s
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2008
c
b
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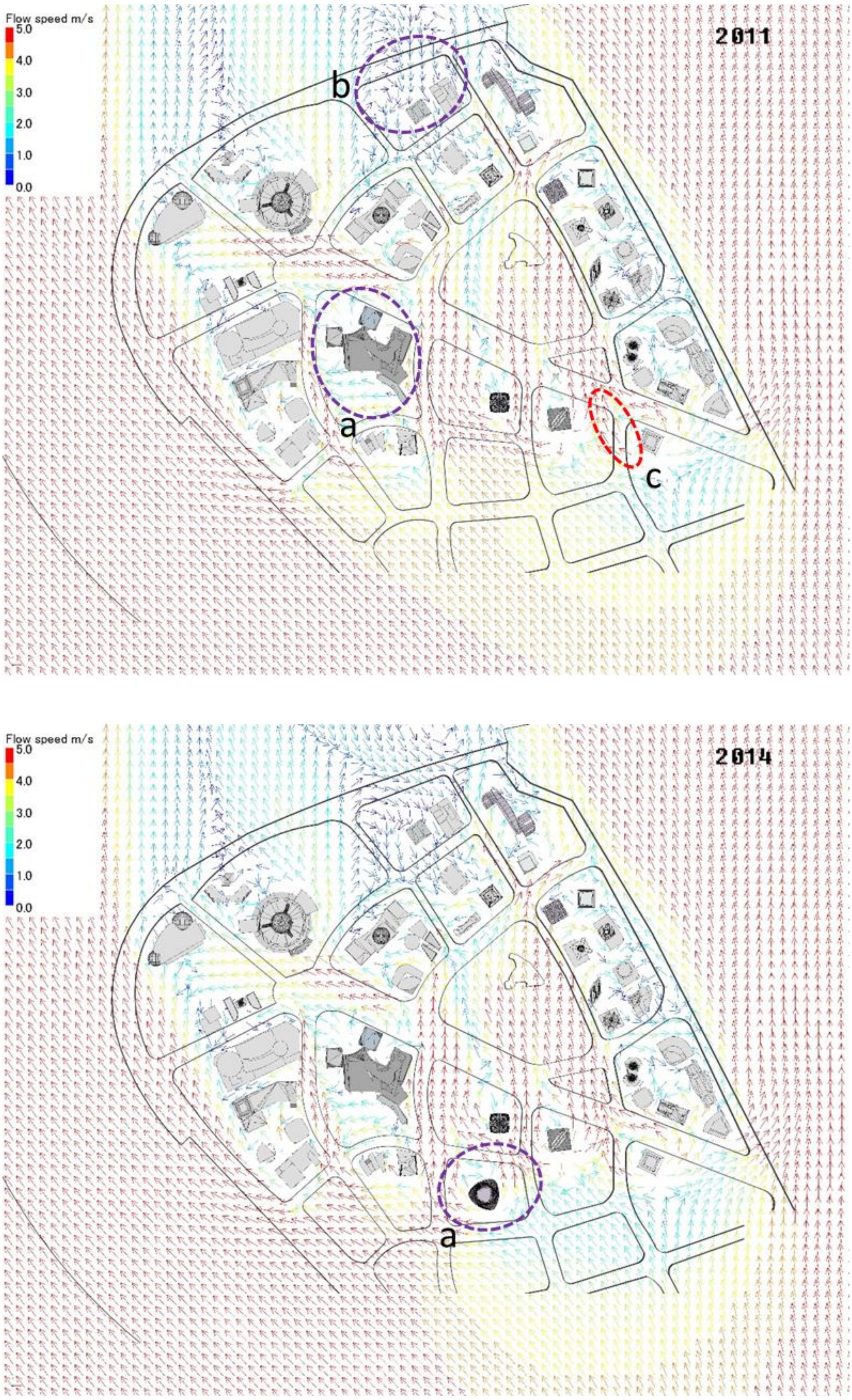


Figure 49: Outdoor wind environment at pedestrian level with wind direction of SSE in Lujiazui (1996 – 2014)

6.4.2 Outdoor wind flow in winter with prevailing wind direction of WNW (292.5°)

The winter winds come from the NWW with a velocity of 5m/s. Therefore, according to the wind comfort criteria in the previous chapter, the neutral wind velocity is 0.55m/s with an accepted wind velocity range of 0-3.2m/s in the Lujiazui district. The yellow and red arrow indicate an uncomfortable or unacceptable wind speed at pedestrian level, because these two colours represent that the air speed exceeds the threshold.

When comparing the leeward side of Figures 50 1996_a and 1996_b, it is obvious that the former is much longer and wider than the latter, because of the larger width of the lower portions of the building (including the podium) facing the inlet wind, the greater its influence on the air flow at pedestrian level.

In 1999, when passing through the gap between two buildings, the accelerated wind dispersed on further streets (1999_a). The distance between two parallel buildings was too large to decrease the wind speed and only changed the air direction (1999_b).

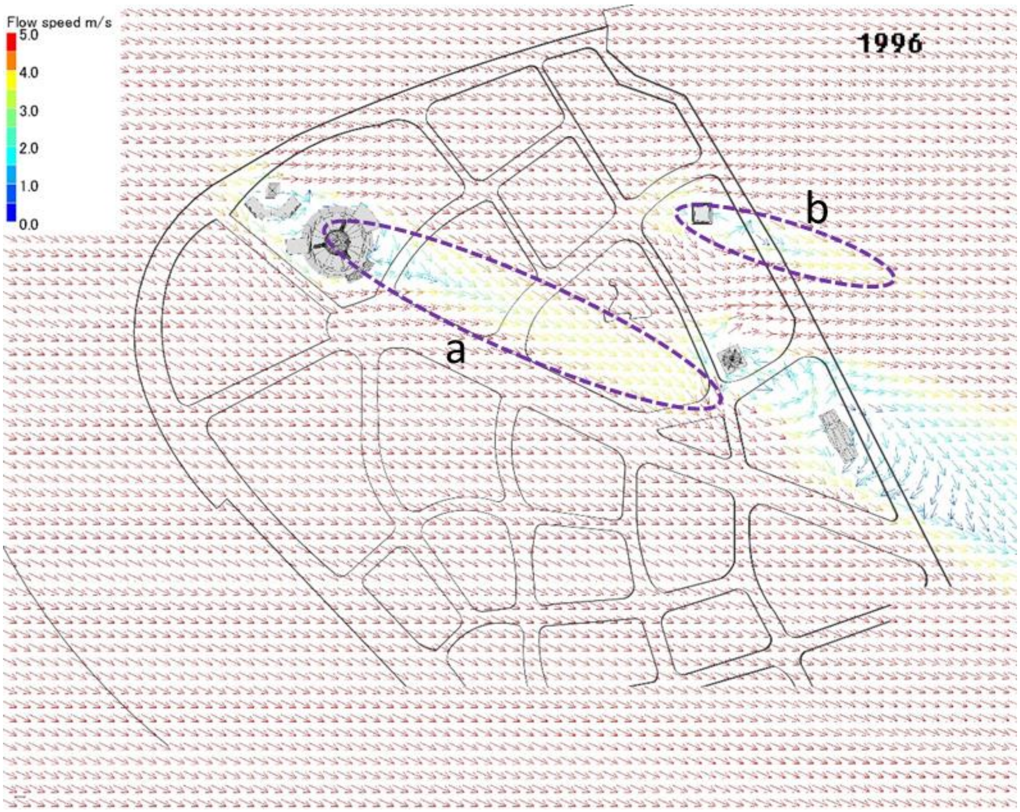
There were more zones with an accepted wind environment around (especially the leeward) the new tall buildings between 1999 and 2002. However, the wind speed could increase to uncomfortable levels as the buildings could prevent and guide air flow (2002_a). When the wind direction and the windward side of a building generate a new windward side, their speed may be superimposed with the new direction.

In 2005, two new buildings had been built in the area of 2005_a in a linear arrangement that prevented air flow directly entering the gaps between them. However, 2005_b had much larger area with high-speed wind than 2002_a. An additional new building on the north of location c prevents some wind and reduces its speed when crossing the central green park, which could encourage residents to enjoy the park in winter.

The wind environment in the park became more acceptable in 2008, because more buildings had been established in the northwest. Therefore, 2008_a and 2008_b could appears to be a semi-enclosed space. The wind was slow in both, however, the mean wind speed was a little higher in 2008_b, because the front opening faced the wind, while the calm zone was in the centre of 2008_a. Furthermore, a faster wind (approximately 5.5m/s) made the two intersections in 2008_c and 2008_d more dangerous and uncomfortable for pedestrians crossing the road.

The wind environment in the important transport node (2011_a) and the south of the site (2011_b) improved due to the construction of a wide podium, eliminating any unacceptable winds. However, once the podium enclosed the area, more air was forced to enter the street canyon and the mean speed reached 6m/s (2011_c). The space of 2011_d was another high speed air path due to the lack of buildings.

The last building was established in 2014, however, it only had a significant influence on the southeast area. While it was the highest building on the site, its position (on the leeward of most buildings in the northwest) determined its influence on the surrounding wind environment. However, there was approximately 600m^2 of space with wind speeds in excess of 4.5m/s, which exceeded the acceptable threshold in 2014_a and decreased the quality of the wind environment in winter in 2011.


Flow speed m/s
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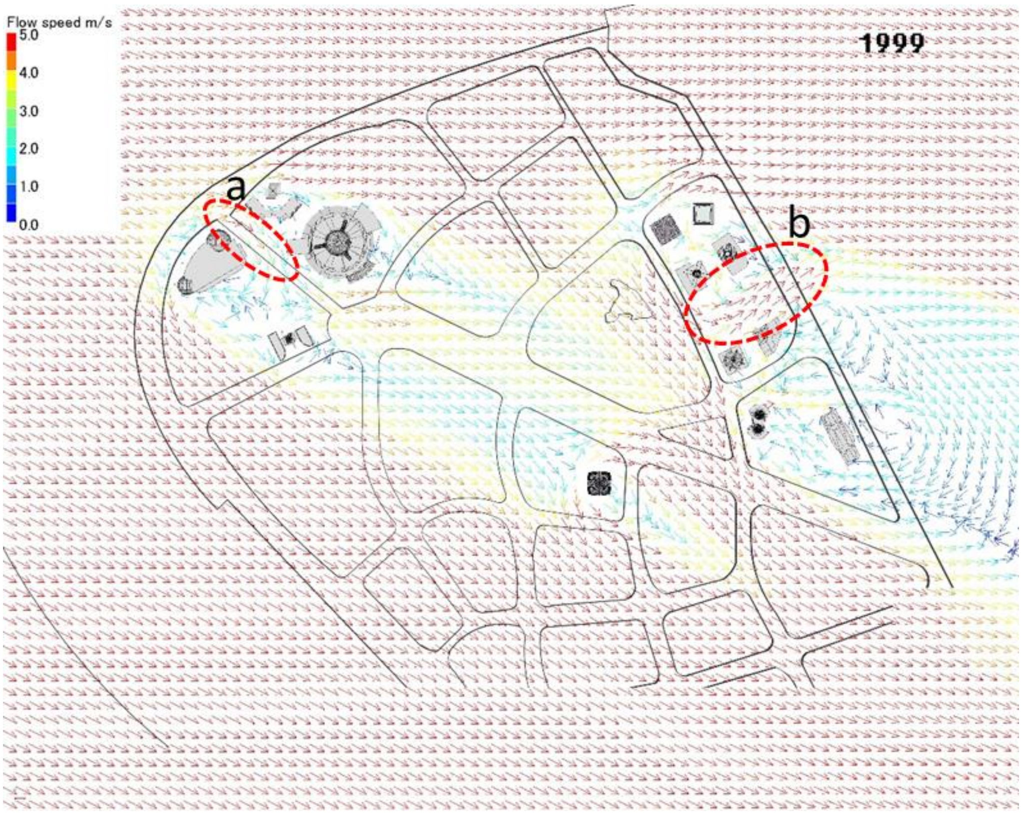
a
b


Flow speed m/s
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1999
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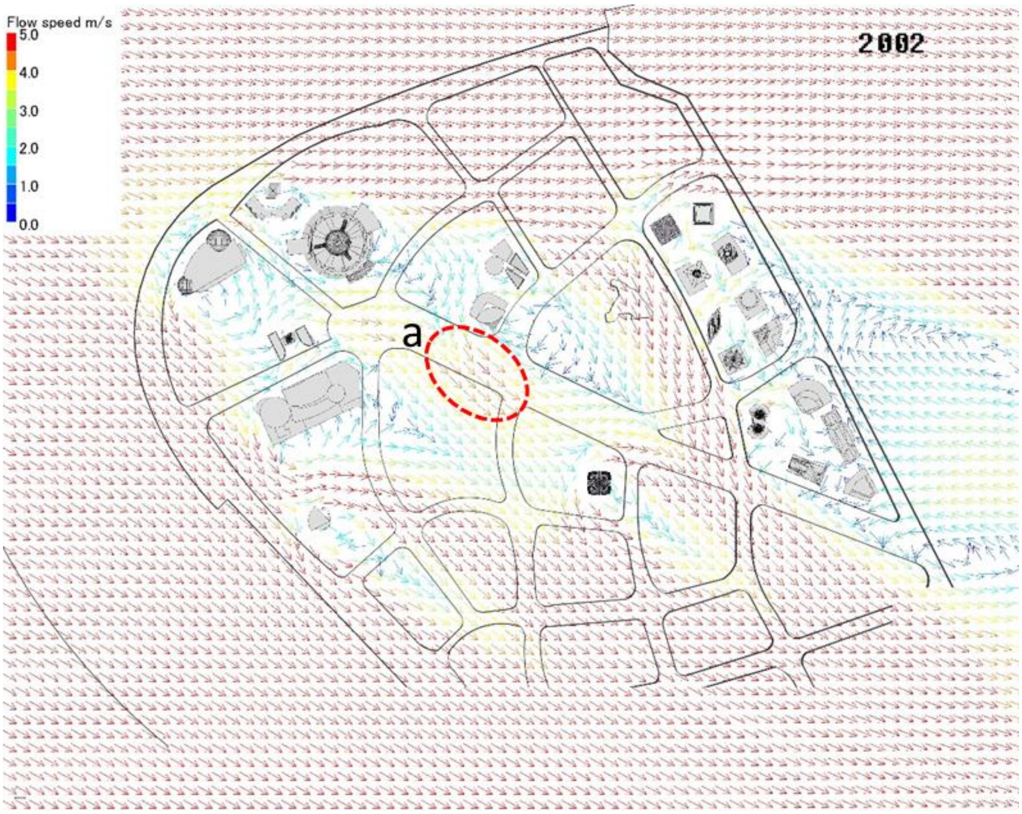
Flow speed m/s
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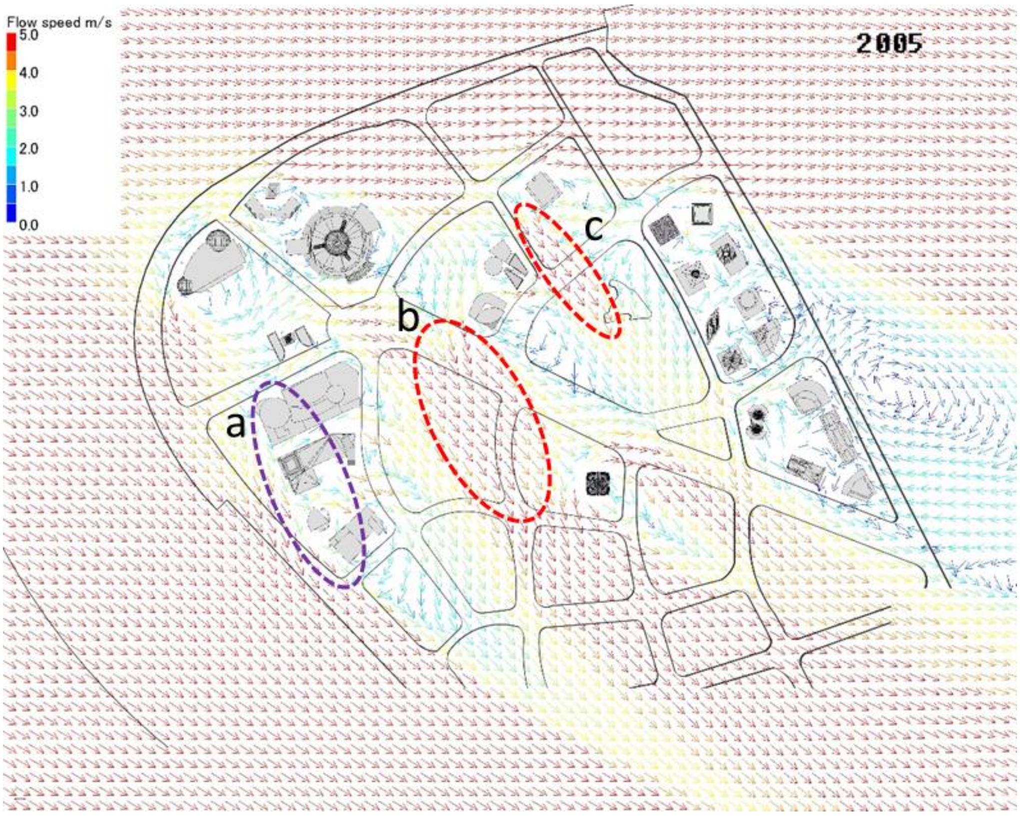
2002
a


Flow speed m/s
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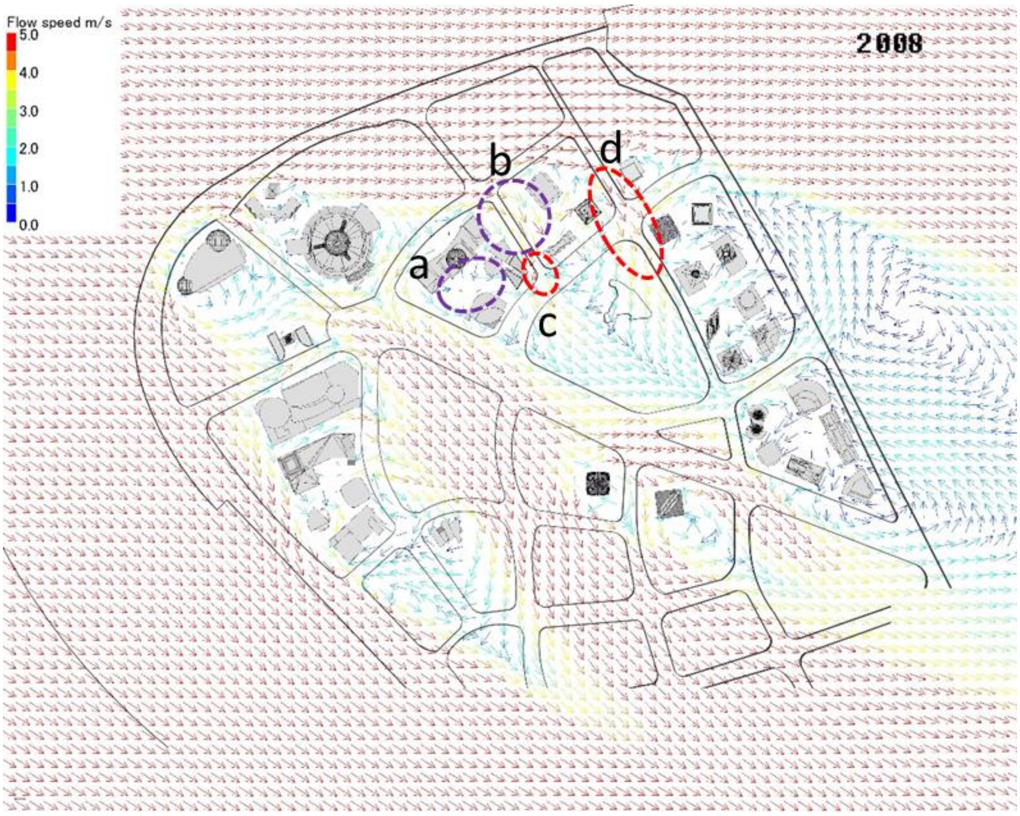
Flow speed m/s
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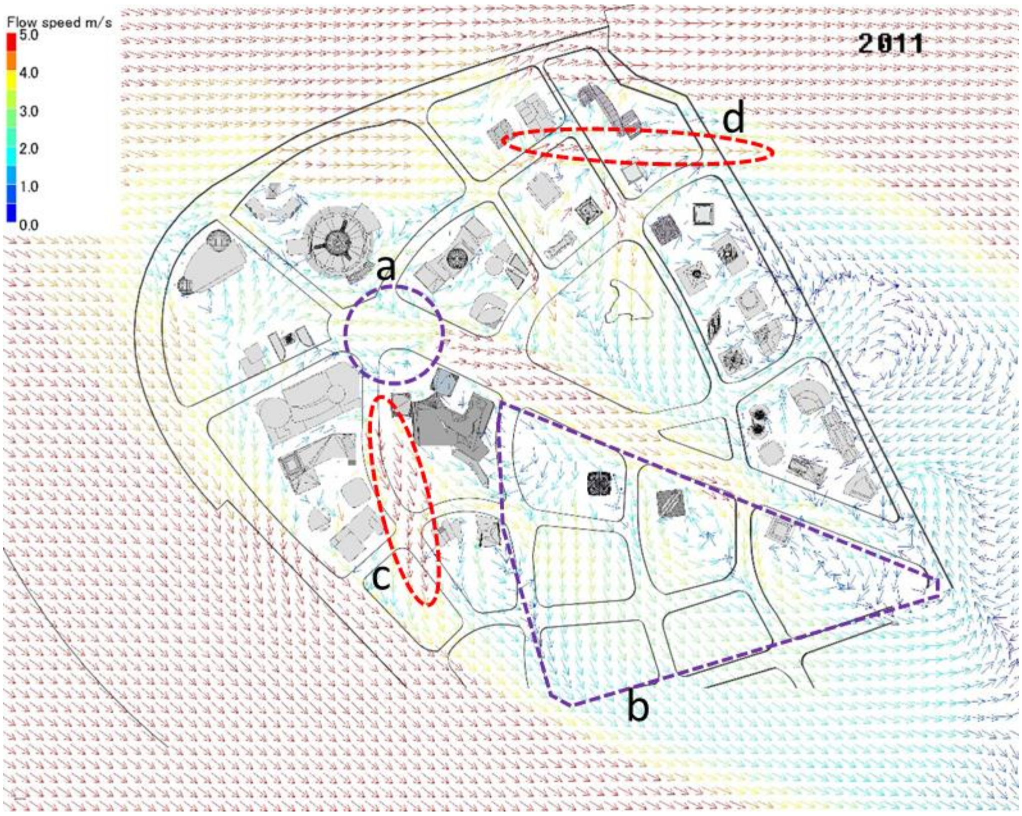
Flow speed m/s
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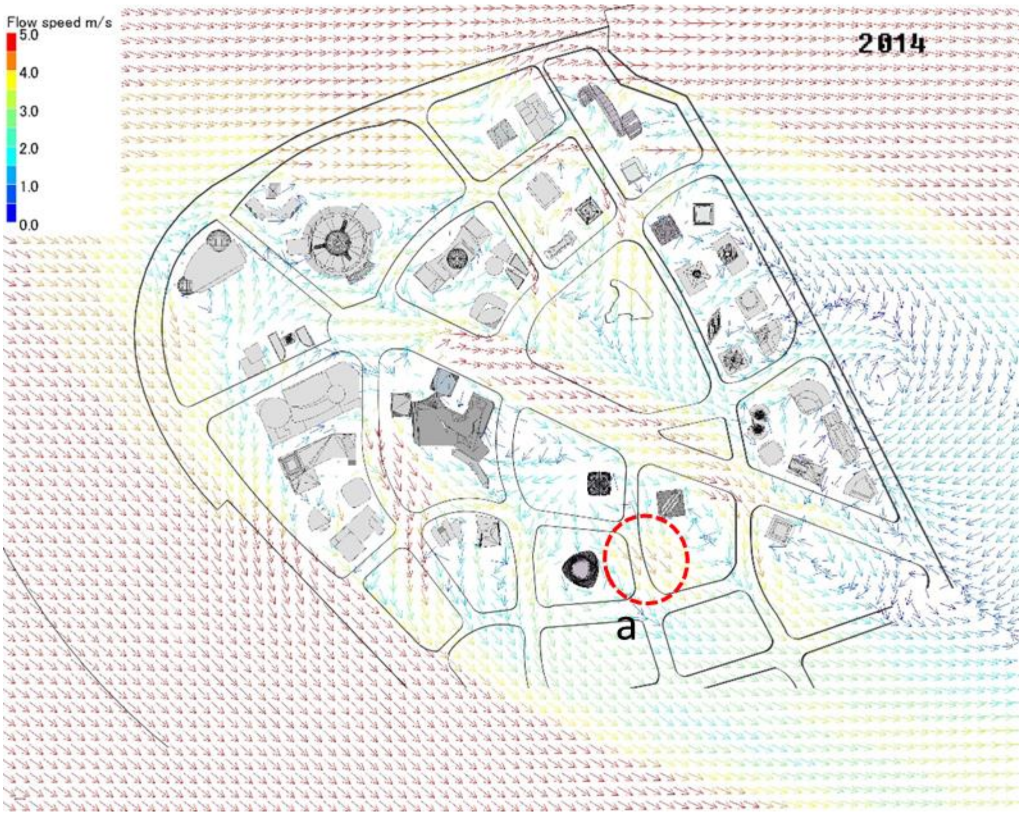


Figure 50: Outdoor wind environment at pedestrian level with wind direction of WNW in Lujiazui (1996 – 2014)

6.4.3 Results comparison with air ventilation assessment

Based on the construction of tall buildings in the Lujiazui district between 1996 and 2014 and corresponding simulated outdoor wind environment at pedestrian level, a series of parameters regarding urban terrain, building morphology and wind comfort were selected to identify the internal relationship (Table 21). Indeed, the RCS_winter is referring to the wind comfort speed range of 0-3.2m/s in winter, while RCS_summer is applying the range of 2-5m/s in summer. Therefore, Equation 6.1 and 6.2 describes the linear relation between RCS and other variables in both winter and summer.

Year	RBS, %	TNBH, m	TBH, m	ABH, m	RCS_winter, %	RCS_summer, %
1996	3.5	999	999	199.8	7.7	3.4
1999	6.8	1370	2369	182.2	20.3	10.3

2002	9.5	1662	4031	183.2	26.8	16.7
2005	14.1	527	4558	182.3	28.3	18.6
2008	17.8	2091	6649	201.5	30.5	20.4
2011	19.4	1449	8098	202.5	43.1	20.8
2014	19.5	632	8730	212.9	43.3	21.3

Table 21：Development of tall buildings and wind environment in Lujiazui

$$RCS_{Winter} = 59.908 - 2.631RBS - 0.255ABH + 0.012TBH - 0.004TNBH$$

(Equation 6.1)

$$RCS_{Summer} = 46.492 + 0.471RBS - 0.235ABH + 0.002TBH$$

(Equation 6.2)

However, the wind comfort at pedestrian level is related to the total building heights in the site, which is described in Figure 51. It is predicted that, with more and higher tall buildings in the district, the surrounding wind environment will be improved at street level, and more spaces with comfortable winds emerge in winter and summer. It is similar to the results of Anisha et al. (2010) who show that increasing building height can improve the urban outdoor thermal comfort. In addition, there are several points that are worthy of note: (a) with the growth of TBH, both RCS_winter and RCS_summer show an increasing trend; (b) the influence of higher total building heights appears more significant in winter; (c) from 2002 to 2005, significant increasing of TBH does not bring high growth of RCS, because these new established buildings have a small footprint that cannot influence air flow too much at the pedestrian level; and (d) in 2014, RCS_winter is much higher than RCS_summer, which is not because of its increase since 2011, but the final result of the cumulative difference.

$$RCS_{Winter} = 2 * 10^{-10}TBH^3 - 3 * 10^{-6}TBH^2 + 0.0175TBH - 6.6861$$

(Equation 6.3)

$$RCS_{Summer} = 3 * 10^{-11}TBH^3 - 9 * 10^{-7}TBH^2 + 0.0083TBH - 4.3567$$

(Equation 6.4)

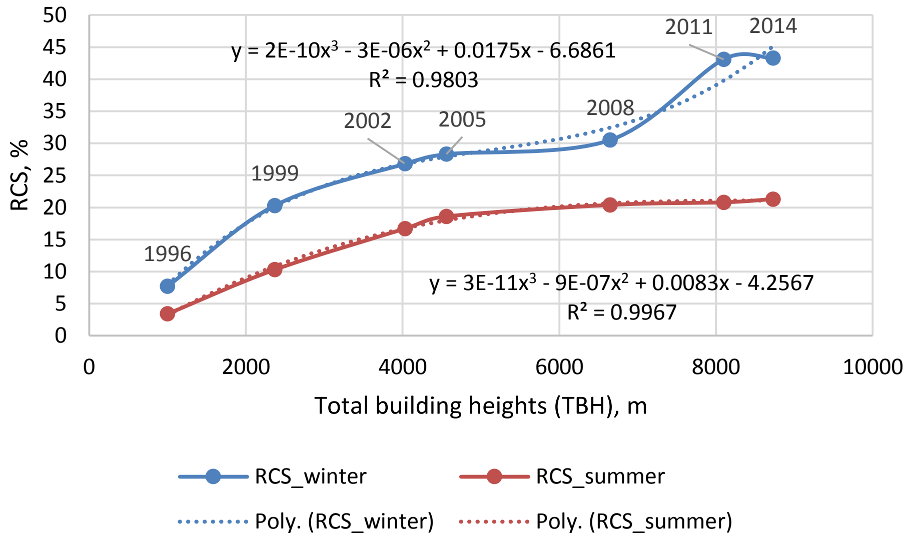


Figure 51: Relationship between TBH and RCS

As an important parameter in urban design, RBS plays a significant role in improving the RCS (Figure 52). More buildings means less outdoor spaces for pedestrian applications, particularly as wide podiums cover a considerable area and have a significant effect on the air flow. It is interesting that the RCS in winter is always higher than summer, and both develop gradually from approximately 9% to 17% of the RBS, which means the outdoor wind comfort changed slightly between 2002 and 2008. However, when the Shanghai Tower was completed in 2014, the RCS in winter increased dramatically.

$$RCS_{Winter} = 0.035RBS^3 - 1.2293RBS^2 + 14.349RBS - 29.592 \qquad \text{(Equation 6.5)}$$

$$RCS_{Summer} = 0.0051RBS^3 - 0.2614RBS^2 + 4.764RBS - 10.558 \qquad \text{(Equation 6.6)}$$

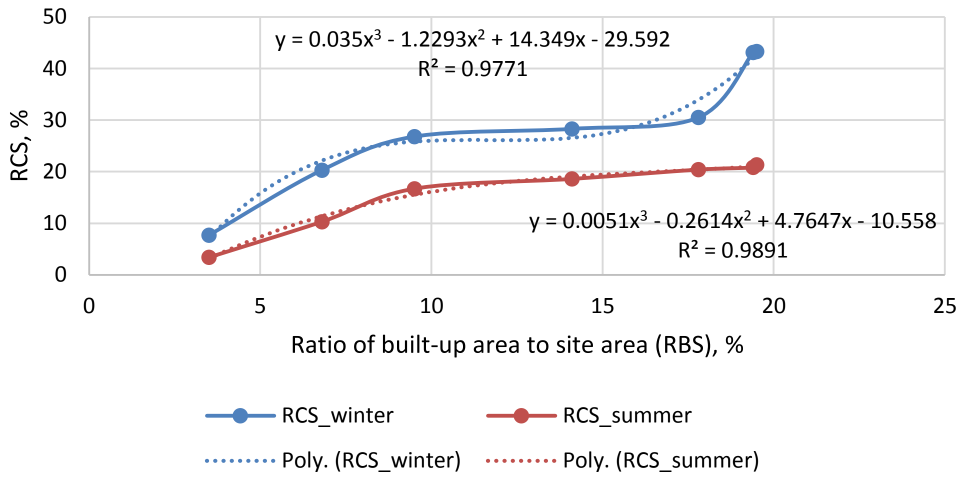


Figure 52: Relationship between RBS and RCS

With the more buildings established in the site, its open space area decreases and the density of RBS increases. To modify the RCS in this condition, it can be calculated as $\mathrm{RCS}_{\mathrm{modified}} = \frac{wind\ comfort\ area}{Site\ area - built{-}up\ area} = \frac{RCS}{1-RBS}$. It describes the ratio of wind comfort area and total open space area. The relationship between modified RCS and RBS both in winter and summer is described in Figure 53. The development of RCS and modified RCS are similar.

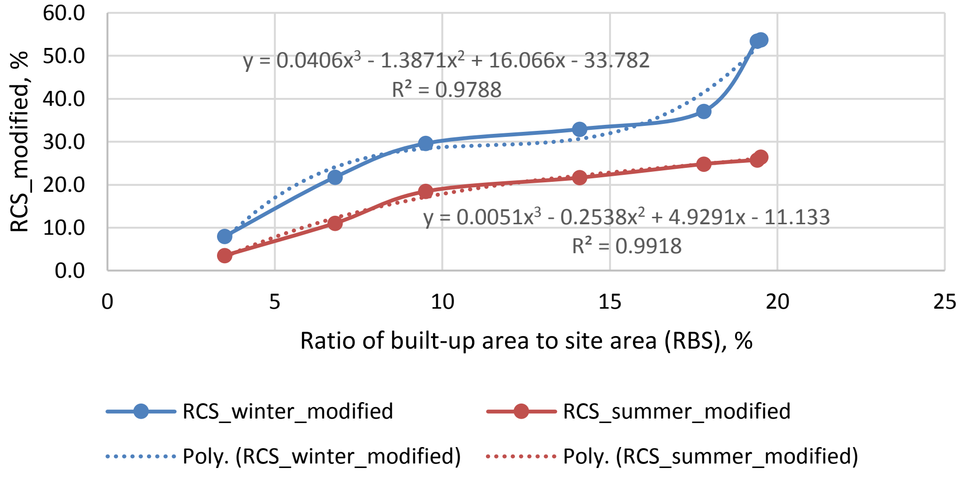


Figure 53: Relationship between RBS and modified RCS

6.5 Summary and Conclusion

With the leap in the economic development of the Lujiazui CBD in Shanghai, a series of problems related to urbanisation, the environment and transportation emerged. Rapid urbanisation increased the population and number of sky scrapers considerably, however it also increased energy consumption, pollution and traffic congestion. A better outdoor environment is believed to be one solution. Improving urban outdoor ventilation is important and necessary for human thermal comfort, saving energy, and air pollutant dispersion. However, air movement over urban morphology is much more complex in high density districts with many tall buildings, because the roughness of the surface may impose a frictional drag. Understanding the past and present outdoor ventilation environment is conducive to analysing the air flow in deep street canyons and generating a more pedestrian-friendly wind environment in the future.

The tall buildings have been listed with their heights and grouped by their completion time. The computational parametric approach was applied to evaluate the influence of various urban morphologies, with a time period of every three years, on the outdoor natural wind environment at the pedestrian level through a CFD simulation. The discussion focussed on the prevailing summer and winter winds. The simulated wind environment is analysed and integrated with the corresponding wind comfort criteria (WV_{winter} < 3.2m/s and 2m/s < WV_{summer} < 5m/s).

The air flow around tall buildings in urban developments during summer and winter can be summarised as below:

- Street orientation is key important to natural wind environment, but it is also affected by surrounding building heights. Generally speaking, the placement of main streets adjacent to the prevailing wind direction can induce greater wind speeds;

- Some turbulence zones may occur in the wake stream in the rear of objects, and the width and length of the wake stream depends on the width of the building footprint, especially the podium. Therefore, the building height also influences it;
- The wind speed is reduced in the area of the wake stream until it receives the effect from other objects, however, it accelerates in the narrow space between two buildings, where air speed may beyond the safety threshold;
- A wide building podium against the wind direction can dramatically affect the inlet wind direction and speed, however, its leeside always has stagnant wind. In other words, the wider the base of the building to the inlet wind, the greater influence on the air flow at the pedestrian level;
- Buildings constructed in the leeward side can influence the existing wind environment on the windward side at street level and also affect the nearby areas;
- Air speed increases when passing through a narrow gap between two buildings, and will disperse on the leeward side. However, if the distance between the two buildings is large enough there will be little effect on the air; and
- Wind direction is affected by buildings in open spaces, so they can be systematically organised to offer plenty of choices in response to various users and activities, both spatially and temporally. For example, under the condition of a healthy environment, air speed in some areas established for the senior citizens and children can be controlled at a low level for safety reasons.

Therefore, considering the building development in the Lujiazui district and its effect on the wind environment for local pedestrians, the following conclusions can be drawn regarding the future urban design:

- Total new building heights do not have strong correlation with the outdoor comfortable and acceptable wind area at pedestrian level.
- The wind comfort at pedestrian level is related to the total building heights on the site, and it appears to be more significant in winter.
- RBS also plays significant role in improving the RCS, and the size of the podium can have a massive effect.
- The outdoor wind comfort improved slightly between 2002 and 2008 in winter and summer.

CHAPTER 7 NATURAL VENTILATION AROUND PROPOSED TALL BUILDINGS IN EXTENDED LUJIAZUI

7.1 Introduction

Relief from the demands of stagnant and exchangeable heat in intensely urbanised regions is fundamental for the establishment of an acceptable and liveable environment, especially considering the steep inclination towards overpopulation. This thesis researches the impact of urban development on wind intensity and, therefore, climatic comfort, in an otherwise geographically affable and aerated locale, such as Lujiazui district. The analysis of architectural construction and organisation of urban networks is imperative due to the direct effects of such developments on local wind environments in an urban setting, therefore, this will remain the focus of this study.

Furthermore, urbanisation simultaneously gears towards the creation of necessary open urban zones for neighbouring inhabitants and visitors to frequent. The nature of such spaces permits both communal and ecological experiences, focusing on the preservation of mental and physical well-being. From the stance of an environmentalist, utilisation of such urban zones reduces the degree of energy consumed indoors as well.

A series of tall buildings are expected to be designed and developed in the next few decades to actively respond to the government's mandate for facilitating the increasing economy and population in Lujiazui, Pudong. Accordingly, in addition to the importance of analysing the development of urban morphology considering the influence of the wind environment, it is also necessary to contribute to proposals on future urban design for the extension of Lujiazui district. The primary location for building further high-rise developments would be southeast to the existing financial centre. Based on the literature review and two studies in Hong Kong and Lujiazui, the presence of buildings significantly impacts the surrounding environment at the street level when they directly face the wind rather than exist in leeward urban zones. Therefore, as mentioned in the literature review, the strategy of stepped building heights along the prevailing wind direction is capable of bringing more air into street openings, with potential for improving natural ventilation and wind comfort for pedestrians.

Thus, the method by which more tall buildings can be developed in Lujiazui CBD may be resolved by considering varying building heights prior to the establishment of calculated building arrangement plans. Therefore, organizing the potential construction completion time may also improve outdoor pedestrian thermal comfort on the extended site, whilst reducing some adverse effects of new buildings to the existing site. This chapter is going to enumerate some different basic urban morphology design situations in terms of different building heights and arrangements of proposed tall buildings in the potential extended site. With outdoor air flow simulation in CFD, the RCS will be the main criteria to assess wind environment in both the initial and extended site in winter and summer. After that, the optimized urban design methods will be obtained, referring to building height and location arrangements. Based on these and according to the construction completion time, three urban design methods for the extended area are proposed, and the outdoor wind environment will also be assessed to obtain the best solution, which may attract the government's attention to improve the urban environment besides economic aspects.

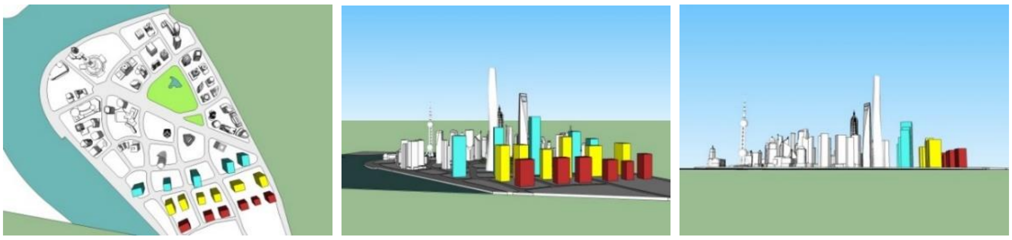
7.2 Different building heights and arrangements

A number of low residential buildings (average 6 floors) and old factories exist southeast of the existing Lujiazui CBD, which may be regenerated according to future extension plans. Four site layout types for building arrangement and height levels in the land for extension will be illustrated and discussed (Table 22). Therefore, the heights of all buildings in the existing area is divided into three levels, and they are applied as reference by the proposed tall buildings as (a) blue is the highest level (average height is 400m); (b) red is the lowest (average height is 260m); and (c) yellow corresponds to a medium height (average height is 120m). Moreover, two general types of building arrangements extracted from the existing site, linear and enclosed, are also applied to the extended area.

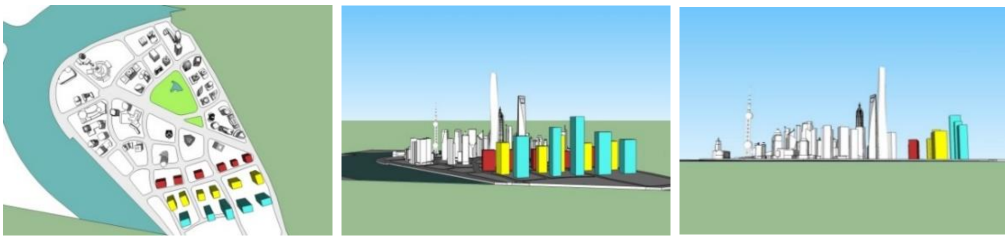
	Building heights	Arrangement
Type A	Follow prevailing wind direction	Linear
Type B	Opposite to prevailing wind direction	Linear
Type C	Follow prevailing wind direction	Enclosed
Type D	Mixed arrangement	Linear

Table 22 : Potential site layouts for future development

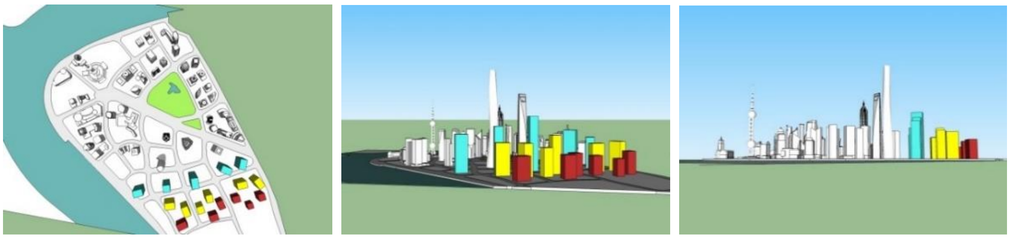
1) Type A



2) Type B



3) Type C



4) Type D

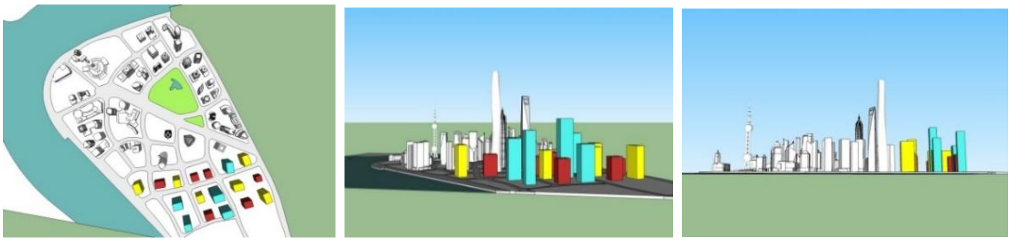


Figure 54: 3D view of different site layouts

Figure 54 depicts 3D versions of all four types of building arrangements and these proposed urban designs are to be simulated in CFD. Furthermore, external air flow surrounding all the buildings, inclusive of the existing and future development, will be analysed with two local prevailing wind directions: SSE in summer and WNW in winter. The results produced for wind environment and air ventilation assessments will be discussed at the end of this section.

7.2.1 Type A: Parallel arrangement facing the prevailing wind directions

The type of linear tall buildings proposed are currently located southeast of the Lujiazui CBD and the building heights are stepped to the summer prevailing wind direction. Figure 55 shows the predicted air flow surrounding these buildings in both summer and winter. Comparing Figure 49_2014 and Figure 54_summer, there are significant changes in wind conditions for areas a and b in summer. The presence of buildings on the windward area results in the impediment and mean velocity reduction of wind in Central Park and neighbouring streets in the summer time. However, the air flow in areas proposed for extension becomes more complex, such as more wind turbulence. Conversely, introduction of wind from the WNW direction in winter results in wind acceleration in two wide streets (areas a and b, winter) and both of these present a 45° angle to the inlet direction. However, there is a decrease in wind entering the initial leeward zone for areas c and d at winter, therefore, inlet air is dispersed with additional directions due to more outlet channels created by the proposed buildings.

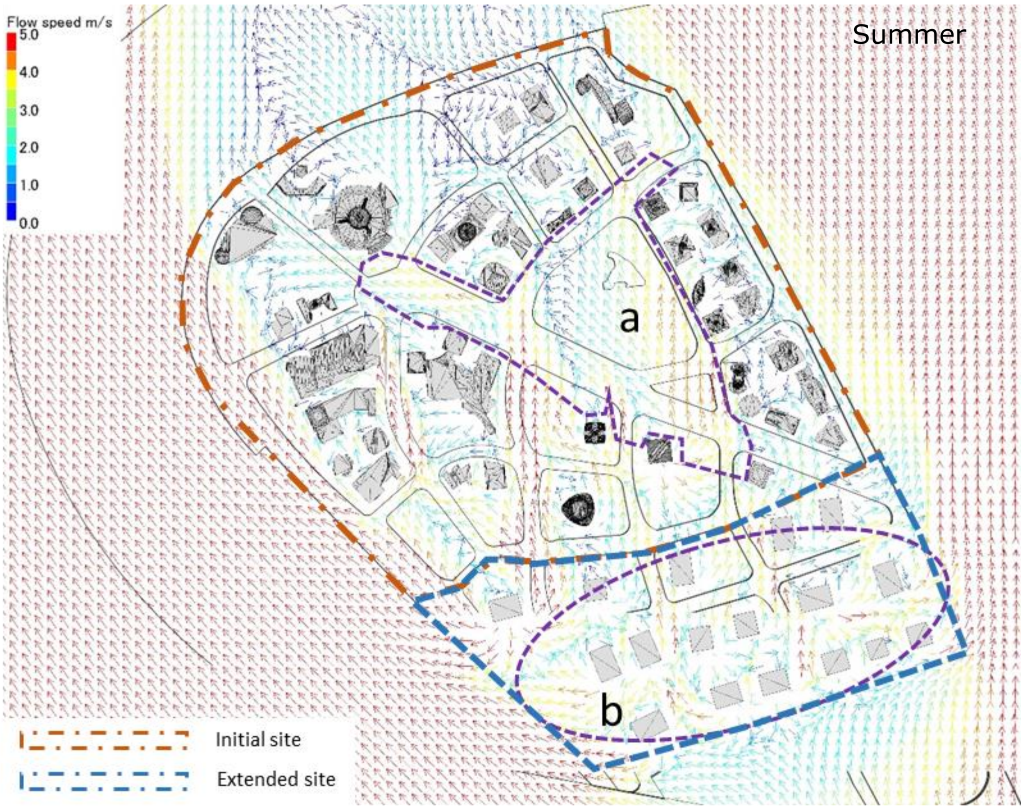
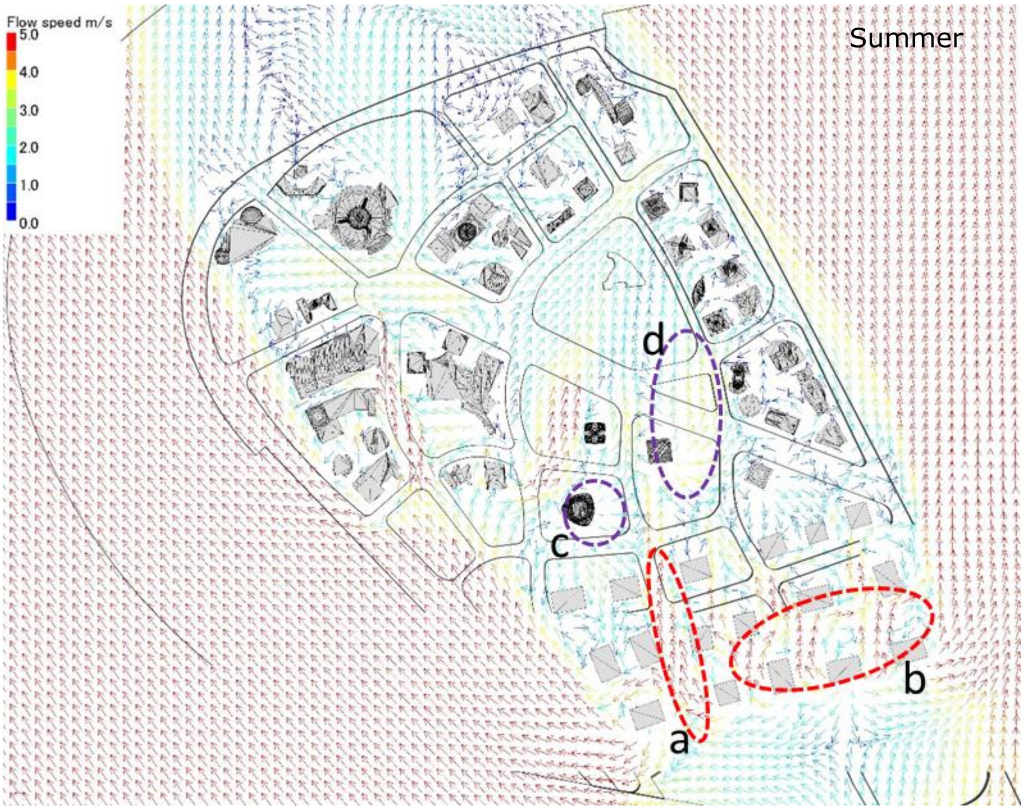


Figure 55: Outdoor pedestrian-level wind environment (Type A)

7.2.2 Type B: Parallel arrangement opposite to the prevailing wind directions

Figure 56 clearly demonstrates that more space will exceed the wind comfort threshold (⩾5m/s) generated around the proposed structures, especially in the case of areas a and b in summer. The primary explanation for this phenomenon is the height of the new buildings, which are opposite to the inlet direction. The first linear buildings are the tallest, therefore, hindering the depth of air flow. Under these conditions, wind velocity reduces to nearly stagnant in areas c and d at summer and, in contrast, introduction of air from the WNW direction in winter causes a modest alteration in wind conditions in the initial district, but only the leeward zones (area a, winter) and the final street that is perpendicular to the inlet direction (area b, winter) in the extended district, which verifies that the building arrangement and street orientation do affect the surrounding wind environment.



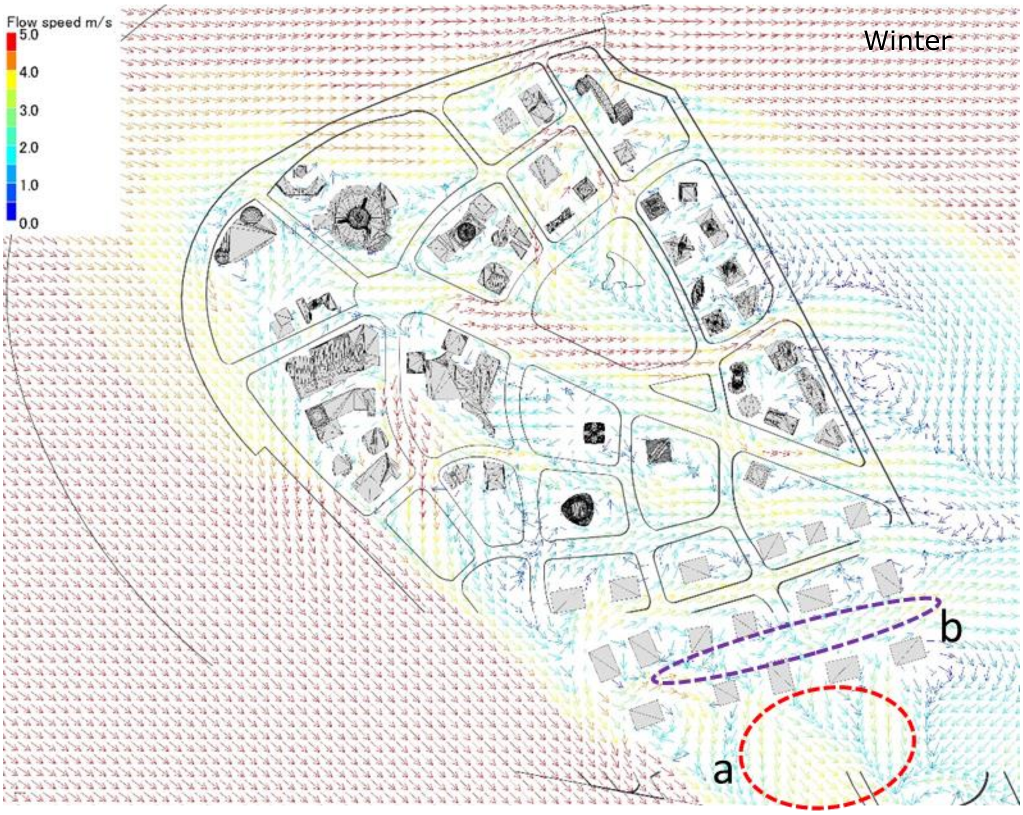


Figure 56: Outdoor pedestrian-level wind environment (Type B)

7.2.3 Type C: Enclosed arrangement facing the prevailing wind directions

Type C uses the same buildings as type A, nut arranges them differently. The location and orientation of the buildings is changed to create an enclosed arrangement (Figure 57). There are two enclosed units and one semi-enclosed unit for the purposes of this study (a and b) and wind decreases to low the centre of enclosed zones. Therefore, wind environment remains similar in winter but it changes a lot in summer, because the proposed buildings are facing the inlet wind in summer, but are in the leeward side in winter.

Figure 57: Outdoor pedestrian-level wind environment (Type C)

7.2.4 Type D: Parallel arrangement with mixed building heights

The type D proposal pertains to an irregular arrangement with mixed building heights, and it represents a more realistic urban design method in China. At present, the local government is not concerned with the effects of building height and arrangement on the surrounding wind environment. Figure 58 describes one simply designed possibility, but no matter what the inlet direction is the outdoor wind environment remains complex, unpredictable and erratic in both existing districts and those proposed for extension, especially in the highlighted zones. Drastic changes in wind direction and the appearance of stagnant wind flow around particular buildings is representative of the typical characteristics attributed to this form of urban design.

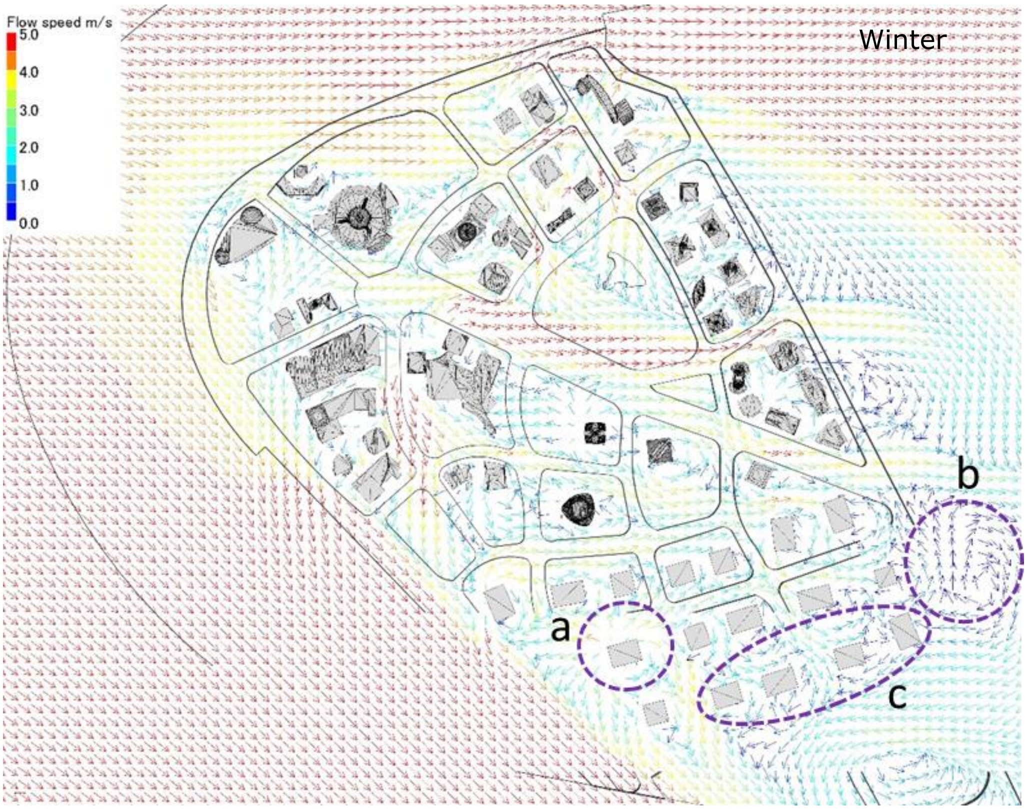


Figure 58: Outdoor pedestrian-level wind environment (Type D)

7.2.5 Wind comfort comparison among four types of urban design

The initial site reflects the existing urban development, whilst the extended site refers to the proposal for tall buildings in the southeast region. Different types of building arrangements and height permutations are capable of generating various outdoor wind conditions in both these sites. Subsequent to a brief description of each air flow, the measurement of RCS (a ratio of comfort area and site area) is used as a standard of comparison to assess which type of building arrangement can provide an optimized urban design for maintenance of outdoor pedestrian wind comfort at the extended site in summer and winter months.

Judging from the results graphed in Figure 59, all four types of urban design generally improve outdoor wind comfort in summer for both initial and extended sites and, furthermore, this is attributed to the proposed buildings being located in the face of the inlet prevailing wind direction. Wind is hindered and, therefore, becomes weak in the leeward zones and additional areas especially in the initial site. This permits pedestrians to experience more comfort in open spaces due to the slower air velocity (<5m/s). In contrast, the wind environment remains unchanged in the initial site in winter, while it improves a minor quantity in the proposed site. Furthermore, outdoor wind environment at pedestrian level is optimal with the type A arrangement, followed closely by the type C building arrangement. Interestingly, type B is minimally conducive to holistic wind comfort, which is inferior to that acquired with type D. Thus, in comparison to the presently applied irregular urban design methods (type D), building arrangements illustrated by type A and C are recommended to be employed for future proposals at this site, however, type B should be rejected.

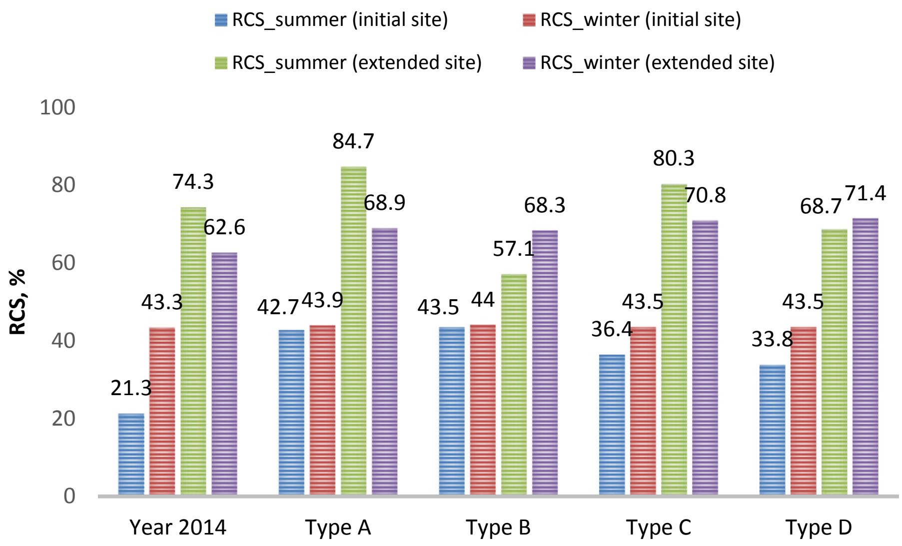


Figure 59: The comparison of RCS with initial and other four types of proposed urban design

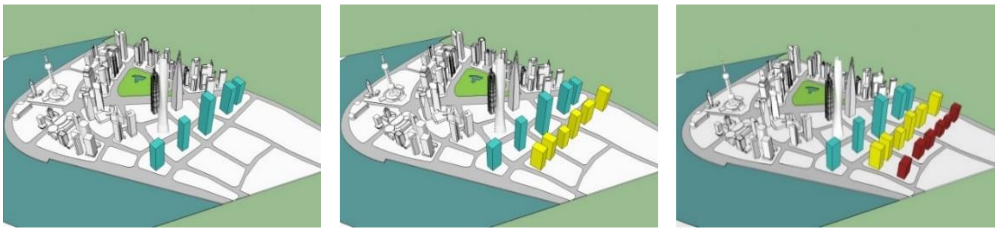
Furthermore, by comparing the results in extended site between type A and B, the RCS_summer is significantly improved in former that inlet wind is facing the stepped building heights. These results further validate Ng's view, suggesting that tall buildings with stepped heights can optimise natural ventilation at the pedestrian level in an urban design.

7.3 Different construction completion time

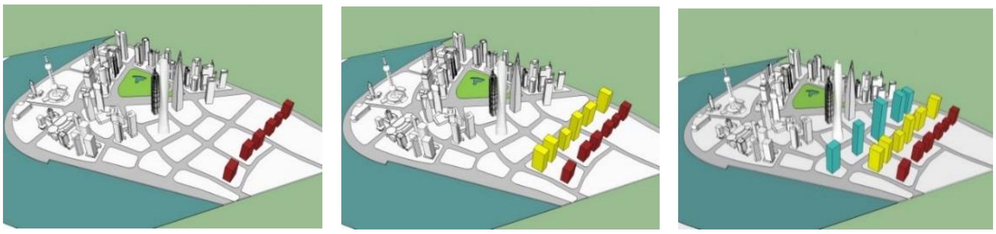
In China and some other countries, once the landlord has acquired the land from the government, they have much authority to decide the morphology, layout and other elements in the procedure of building design. However, few of them and the government are in consideration of the influence of different construction completion time on the surrounding environment. Apart from taking aspects of economy, transportation and function into account, organizing the build in order toy improve to surrounding wind environment is invariably ignored. After obtaining pre-planning, the local urban planning department auctions the land publicly. The property developers agree on a construction completion time and supplementary building plans following purchase of the land. However, the government and developers may disregard the capacity of diverse completion times to stimulate various influences on nearby buildings and open public spaces.

In the extended site, there are three different urban design methods according to construction completion time have been proposed as below (Figure 60):

1) Order A: from inside to outside



2) Order B: from outside to inside



3) Order C: mixed arrangement

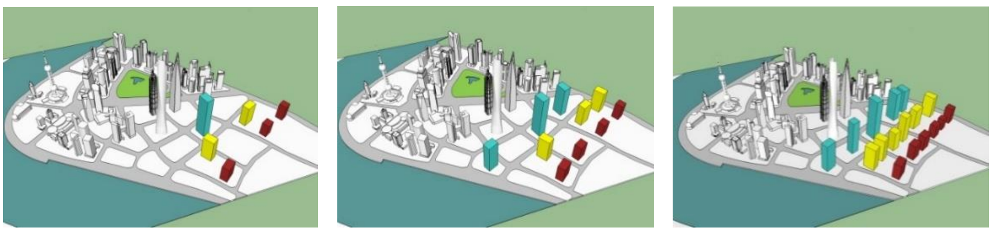
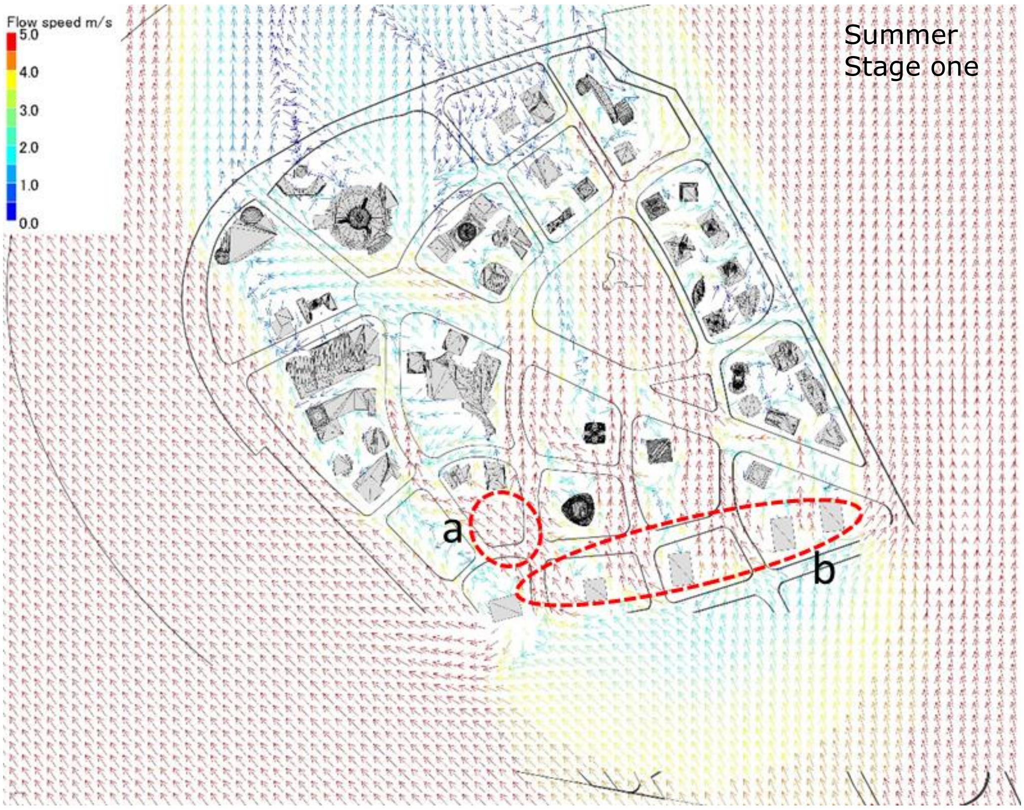
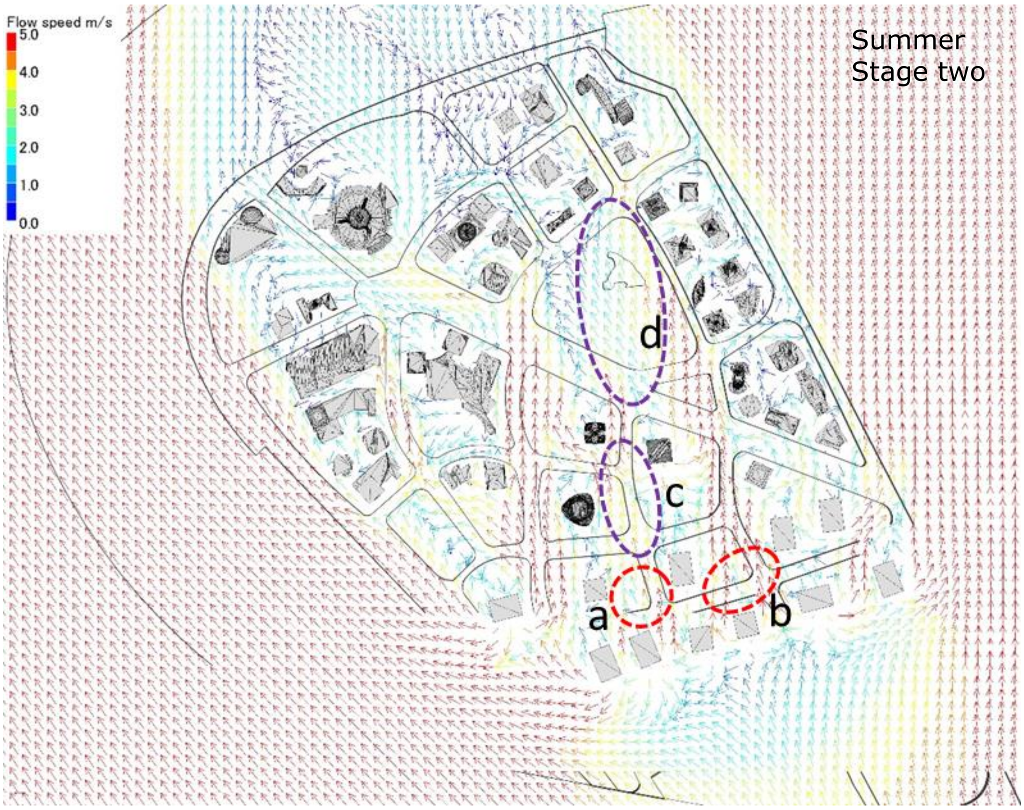


Figure 60: 3D view of the different site layout with various completion time

7.3.1 Order A: From inside to outside

All proposed buildings are divided into three rows and, using time flow, a first row of tall buildings will be established in stage one nearest to the existing buildings and, subsequently, the second row will be completed in stage two. Ultimately, following construction of the last row of structures, the outdoor wind environment will be similar to that illustrated in Figure 55 (Type A). Here, the outdoor air flow at pedestrian level will be simulated by CFD at the first and second stages for both summer and winter conditions (Figure 61). In comparison to the air flow results in Figure 49_2014, the influence of the new row of buildings is significant in area a and b at stage one in summer. Wind accelerates within the gaps between buildings and the newly generated ventilation openings increasingly direct wind to the nearby streets. Subsequently, in stage two, the velocity of air reduces in leeward zones, especially in the Central Park (zone d), which positively impacts acceptable wind comfort area in summer. Conversely, the introduction of wind from the WNW direction influenced the wind conditions in the surrounding new buildings due to the positioning of these proposed buildings on the leeward zone, despite having insignificant impact on the wind conditions in the existing district.


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Summer
Stage one
a
b


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Summer
Stage two
d
c
a
b

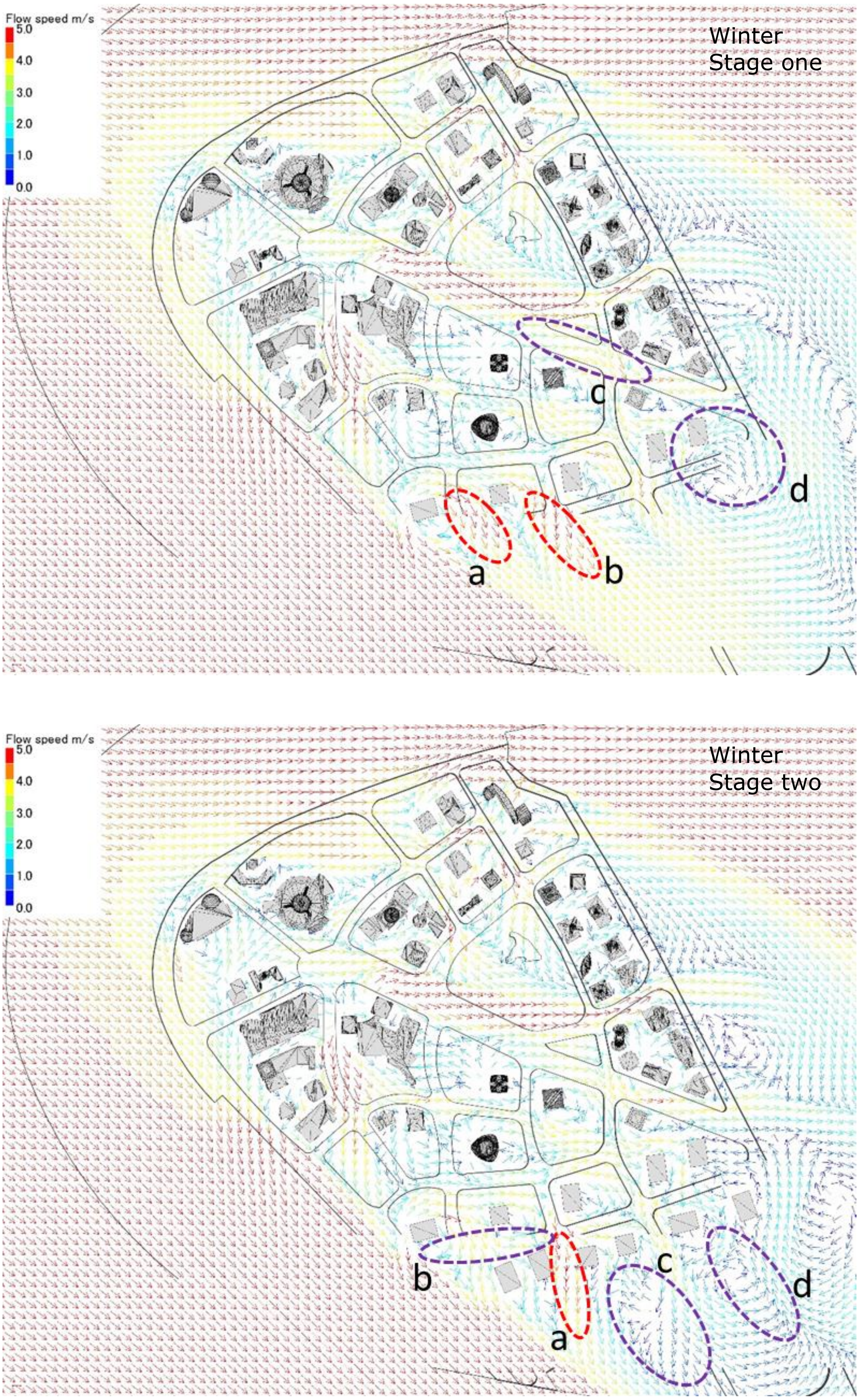
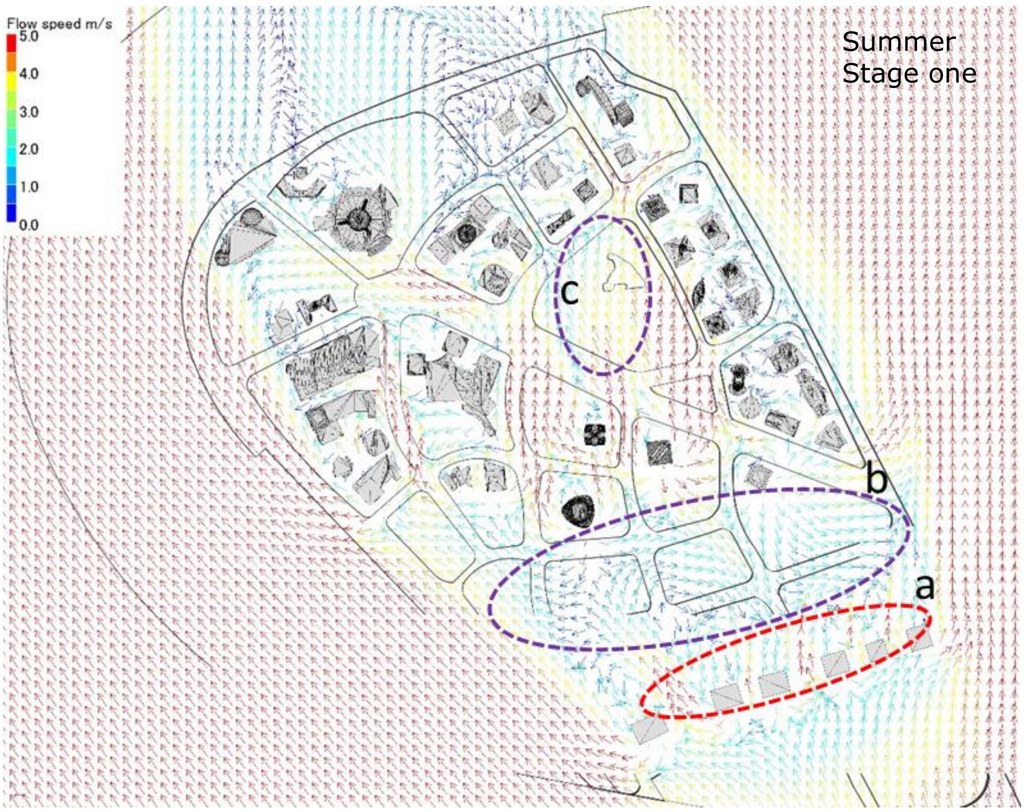
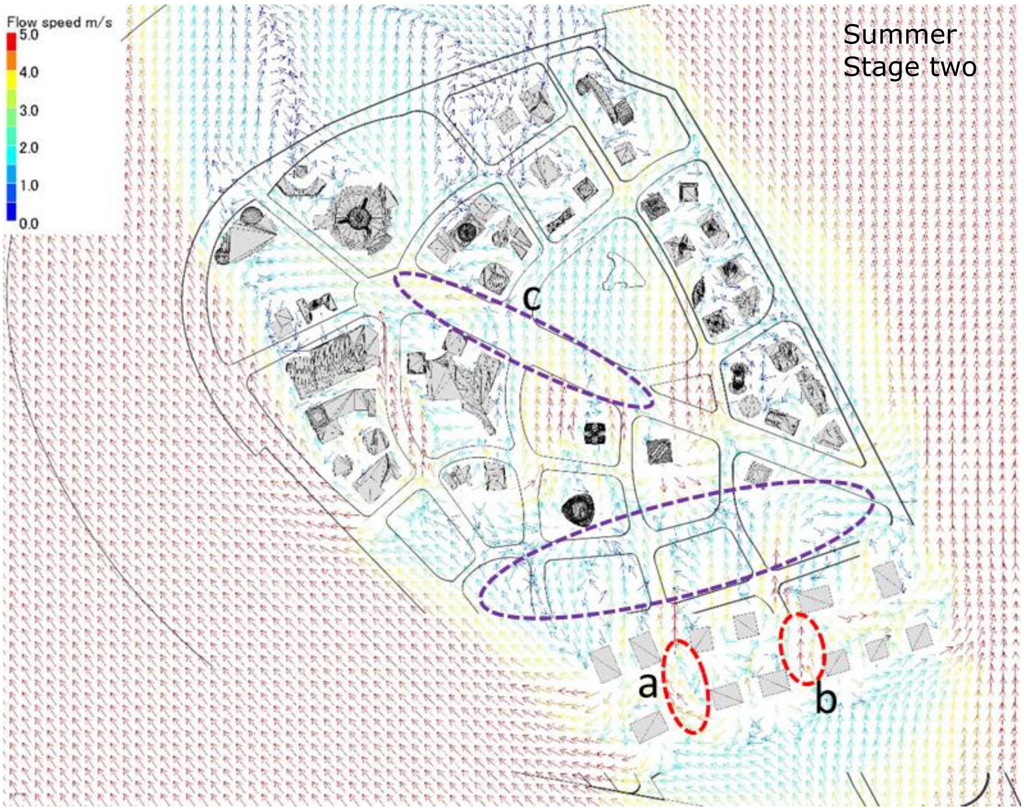


Figure 61: Outdoor pedestrian-level wind environment (Order A)

7.3.2 Order B: From outside to inside

Establishment of the proposed buildings from outside to inside promotes an alteration in wind environment (Figure 62). For stage one in summer, the outermost row of buildings is distant from the Shanghai Tower (approximately 400m), therefore, air flow is unfluctuating and devoid of any interference in area b. Consequently, the wind environment in the Central Park (area c) improves dramatically. Furthermore, in stage two, the area with stagnant or high-speed reduces in both initial and extended sites. In contrast, the new buildings in stage one and two affect the wind environment at the initial site in winter, despite the distance. Fresh high-speed wind zones are generated ahead of each row of buildings. Therefore, the high speed zone moves from b_stage one to a_stage one in winter, because wind affects the windward side of the new built constructions.



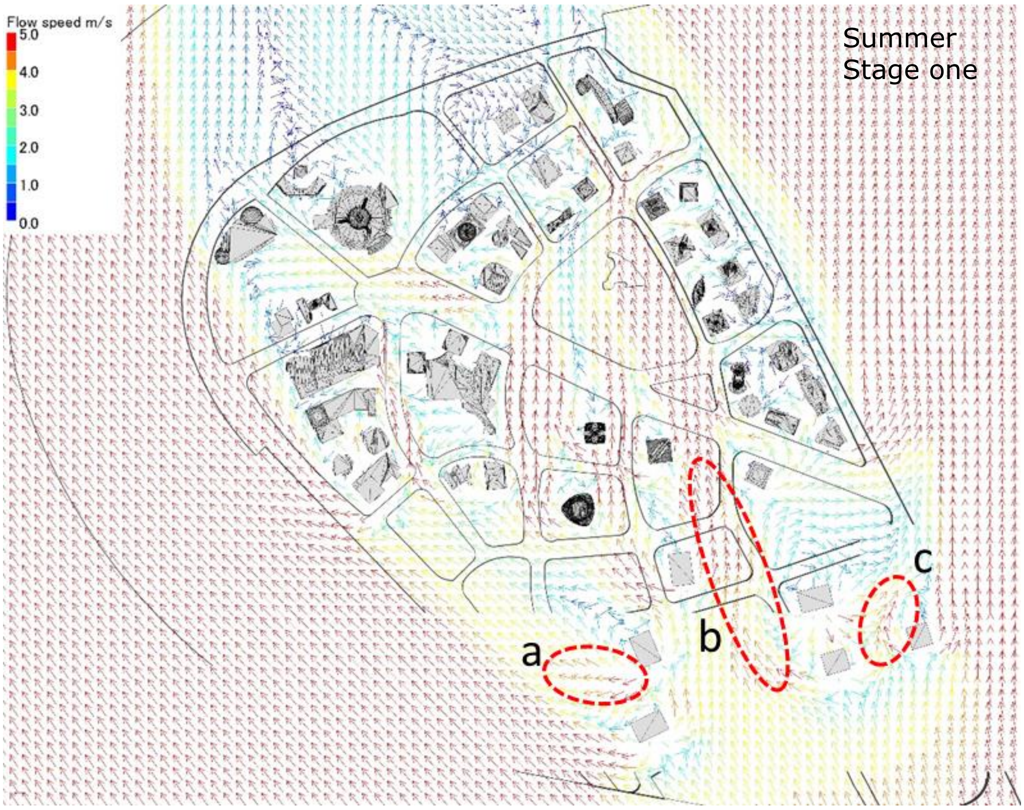

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Summer
Stage two
c
a
b

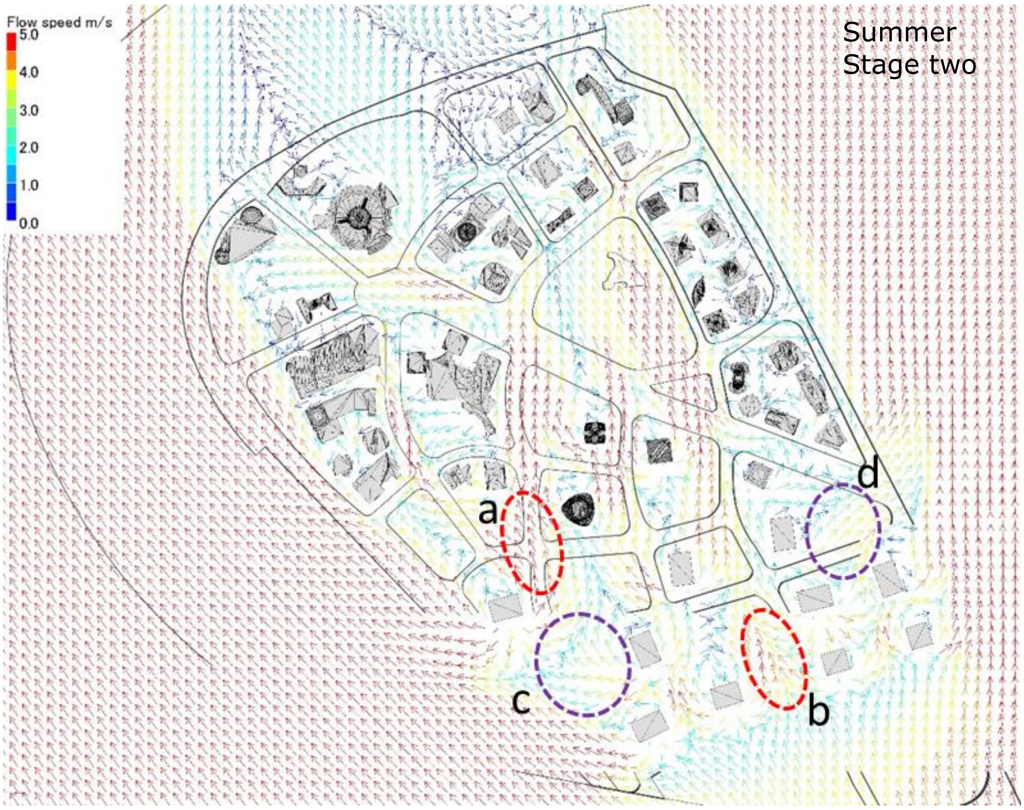

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Winter
Stage one
d
c
b
a

Figure 62: Outdoor pedestrian-level wind environment (Order B)

7.3.3 Order C: Mixed arrangement

The mixed arrangement construction order for building proposals is generally applied in reality (Figure 63) and renders the seizing of regularity to the surrounding wind environment immensely challenging. In summer, new buildings in the first stage improve some surrounding wind environment, such as area a, but it becomes uncomfortable when more buildings established in stage two (area c). On the other hand, according to the development of buildings in these stages, outdoor wind environment is becoming much more complex and elusory. Therefore, in winter, air speed in area a (stage one) reduces to a comfort range (shown in area b in stage two). In contrast, area c is going to become uncomfortable and maybe even dangerous from stage one to two. Besides, air flow in other areas changes significantly as highlighted. The random nature of wind direction and building completion stages may cause wind velocity to accelerate beyond acceptable levels or, alternatively, reduce it to stagnant levels, which may prove unhealthy for pedestrians. Furthermore, this order of construction completion impacts open spaces in both initial and extended sites.




Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Summer
Stage two
a
b
c
d


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
Winter
Stage one
a
b
c
d

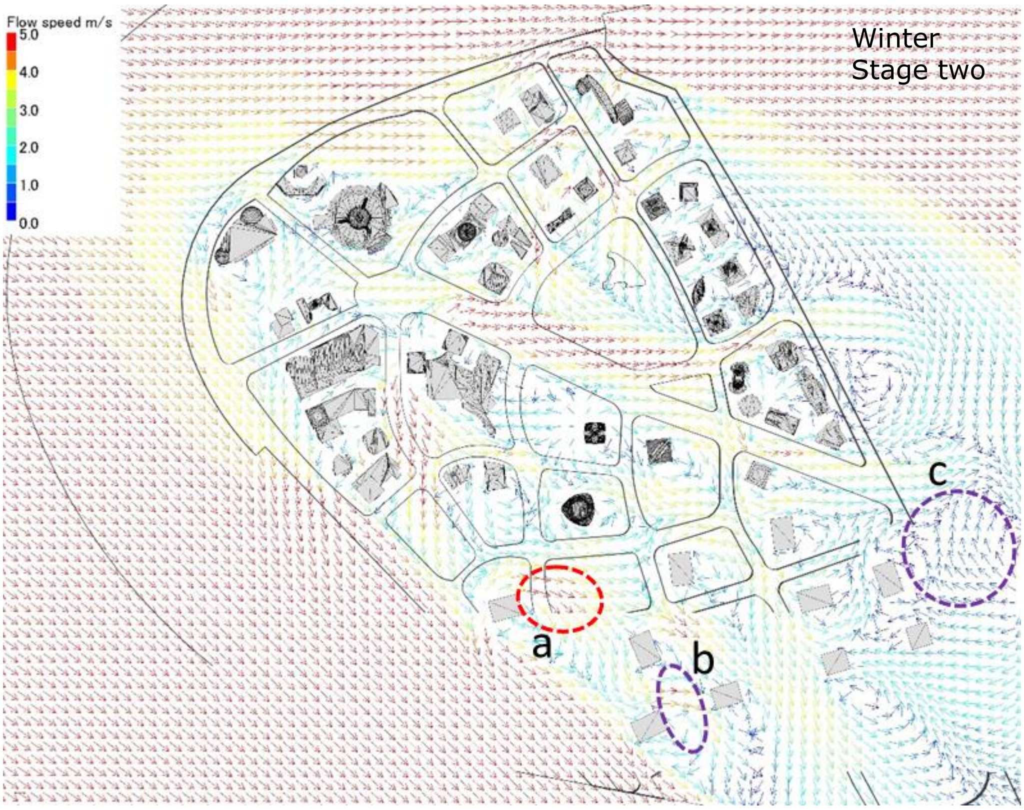


Figure 63: Outdoor pedestrian-level wind environment (Order C)

7.3.4 Summary

Outdoor wind environment is compared at different stages of development, varying construction completion times and changing seasons, such as summer and winter months. Furthermore, wind conditions are also compared at initial or existing and extended sites. Figure 64 demonstrates similarities and differences between the preliminary and final state as the year of 2014 and type A in the previous section, whereby the wind environment at each stage appears distinctive. The RCS is much higher in the extended site than the initial site at both stages and overall, order B improves pedestrian wind comfort most dramatically, suggesting that the development of proposed buildings from outside to inside is the paramount option. Moreover, this construction order will minimise impact noise pollution levels for people in the initial site. Furthermore, order A should be avoided for application if at all possible.

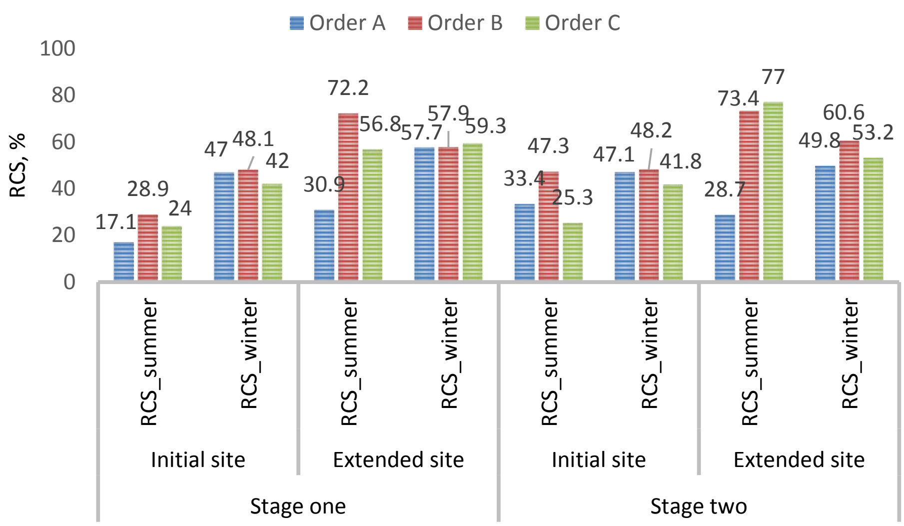


Figure 64: The comparison of RCS among three proposed urban design with different construction completion time

7.4 Summary and discussion

The focus on wind levels for the creation of an environmentally comfortable and healthy urban development is often discounted at the planning stage in exchange for greater eminence to marketability, profitability and visual appeasement. Such disregard emerged in the instance of Lujiazui district, which is at the core of developer design proposals for urban redevelopment. Comparisons with western expansions and oriental representative cities, in cahoots with a scattering of seminal architectural buildings, shape the foundations encompassing the strategy for urban development providing a vivifying, serene, healthy, cosmopolitan yet financially lucrative experience. Furthermore, sustainable urbanisation of the modern metropolis and its overall aura is also attributed to the presence of creative hubs for the public, which function in the maintenance of the culture of the city. Regardless, calculated arrangement of the urban building and street network is essential for establishing a beneficial wind and heat balance in urban open zones for the local pedestrians.

The ambiance in urban open zones is immensely impacted by the local climatic characteristics, which subsequently will determine the popularity of these spaces with individuals. For example, visitors are more likely to pay less visits to locations facing unfavourable weather conditions.

Building on this, this chapter has demonstrated that natural wind conditions at the pedestrian level can be significantly improved by two innovative methods: stepped building heights with well-designed arrangements and classifying building construction completion times with a certain order.

The ratio of wind comfort area to site area has been employed as a standard to compare the influence of diverse proposed urban design methods on the extended district:

- Overall, all four types of urban design improved outdoor wind comfort in summer at both initial and extended sites. Nevertheless, wind environments remained unchanged at the initial site in winter, whilst they improved somewhat at the proposed extended site;
- Improvements in the outdoor wind environment at the pedestrian level are optimised by the building arrangement of type A and followed closely by type C. Both these arrangement approaches are recommended to be applied in future designs at the extended site as they exude greater benefits over traditional designs. However, Type B should be avoided; and
- Based on the optimised design with type A, the proposed buildings are recommended to be developed from outside to inside in order to maximise wind comfort improvement during the construction process, if not consider about the economical and other factors.

CHAPTER 8 CONCLUSIONS

It has been noted that contemporary urban planning, design and architecture, in China but also worldwide, need to consider many aspects – environment, social, economic and cultural factors – so as to be able to properly deal with problems regarding the discrepancies emerging from the necessity to safeguard cultural and natural assets all the while meeting developmental demands. In particular, open spaces are gaining more and more recognition as being one of the essential elements that require special attention when devising the future urban plan.

A more comfortable microclimate can make urban planning more successful because it has the ability to encourage residents to walk, exercise, and take part in recreation in public open spaces as well as to take public transportation, rather than staying indoors or driving personal motor vehicles. Another fundamental matter is a city's ventilation in the summertime because it is pivotal for human thermal comfort: more and more people are asking for relieving air currents that are energy-saving and that dispel pollution at the same time.

Nonetheless, this is not easy to obtain since in high-density areas the efficacy of the air flows created at pedestrian-level is threatened by the frictional resistance exerted by urban surfaces, which in turn is determined by the degree of roughness possessed by said surfaces. For example in rapidly developing, high-density urban zones such as the Lujiazui district, where there are deep street tunnels, the air flows are quite low in speed but their circulation is considerably varied both in space and time-frames according to which wind profile and urban architecture prevail. This is especially true when analysing the impact of tall buildings on air currents in different climates because if in the winter the downward flows can result in uncomfortably cold, pedestrian-level winds that end up needing mitigation, in the summer they become a source for ventilation, useful to cool naturally an otherwise hot and humid weather. These currents, however, can be artificially manipulated and channelled based on need by shaping the city's morphology and street geometry accordingly. It is evident that this is for urban designers both a challenge and an opportunity as it is not easy to create a well-ventilated yet comfortable urban space. The aims of this thesis have been achieved, such as (1) with site meteorological data measured and outdoor questionnaire survey, local pedestrian thermal comfort criteria in Shanghai in winter is obtained while other case studies have been used to get a picture of the situation in summer; (2) outdoor wind environment in Lujiazui has been analysed by CFD that is validated by wind tunnel tests in HKU and assessed by wind comfort criteria; and (3) optimised urban design methods for the development in the extended area have been proved. The necessity was born out of a general lack of documentation on the subject, as very little practical information on simulations and researches carried out based on actual site models exists. Section 8.1 discusses in more detail the extent to which the research aims were met.

8.1 Summary of contributions

Chapter 4 focused on outdoor, pedestrian-level air flows around a series of tall buildings in high-density districts located within Sai Ying Pun, Hong Kong – the research was conducted with experimental and computational assessments. Two local prevailing wind directions were applied in the simulation in the wind tunnels and the CFD tool FlowDesigner was also employed. After comparing the results derived from these two methods, the maximum discrepancy appears to be at the centre of courtyards, whilst minimal variations are detected around building corners. As a matter of fact, the differences between wind tunnel tests and numerical simulations lie within 20% for the majority of the tested locations. Furthermore, they retain a similar order of magnitude and variation trend with a high correlation, which indicates the reliability of FlowDesigner in predicting the mean wind speed values in the vicinity of buildings in urban areas.

Chapter 5 examined why, according to the questionnaire and the site-monitored weather data obtained, microclimate is a very important parameter for thermal comfort. Based on those results, it was determined which attitudinal factors, experimental conditions and attires can be applied to the adaptation used to define said comfort. For instance, with Bin method and regression analysis in SPSS, air temperature, relative humidity, global radiation and wind all contribute to the variations presented on the comfort scale in winter: 1) the mean neutral T_a is 14.7℃ and the accepted temperature range is 7.7℃-21.8℃; 2) neutral global radiation is 856W/m^2; 3) neutral air humidity is 67%; and 4) neutral wind velocity is 0.55m/s with the accepted wind velocity range of 0-3.2m/s.

After that, a simulation of outdoor winds blowing around tall buildings erected with urban morphology developments in the Lujiazui district was divided into several stages according to constructions' completion time to show the influence on the air flow at pedestrian level. Therefore, the local wind comfort criteria have established that the wind velocity in the winter should be lower than 3.2m/s, while it is suggested to be between 2m/s and 5m/s in the summer.

Finally, by seeking urban design methods to create comfortable natural wind environments for pedestrians, two innovative techniques were presented: stepped building heights with well-designed arrangements and the classification of building construction completion times according to a certain order. These techniques have proved to be able to significantly improve the natural ventilation around current and proposed buildings in both existing and extended sites. For example, improvements in the outdoor wind environment at the pedestrian level are optimised by two types of building arrangement: parallel arrangement (type A) and enclosed arrangement (type C) facing the prevailing wind directions. Both these arrangement approaches are recommended to be applied in future designs at the extended site as they exude greater benefits over traditional designs. However, building heights opposite to the prevailing wind directions (Type B) should be avoided. Therefore, according to the optimised design with type A, the proposed buildings are recommended to be developed from outside to inside in order to maximise wind comfort improvement during the construction process, if not consider about the economical and other factors.

8.2 Limitations

This research mainly focused on the influence of tall buildings on the pedestrian-level micro-climate in Shanghai's Lujiazui district and recommended some new solutions for further urban design in extended sites. However, there are still some limitations to this thesis. For instance:

1) *Local meteorological data is not up-to-date*

In fact, at the beginning of this study the researcher of this investigation had sent a request to the Shanghai government and to the meteorological station, but to date no reply has been received yet, perhaps because they want to protect their information. For this reason, the meteorological data used in this thesis does not include the most recent years, which means that, for example, actual recent prevailing wind velocities may be different, as local urban developments can change them to a certain degree.

2) *The real applicability of this research*

   a) It has been said that outdoor thermal comfort criteria can be used as a reference in urban planning. However, it is currently only applicable in Shanghai, because of its unique geographical location, weather conditions and experimental conditions. Those conditions can however be obtained in other cities, as long as similar research methods, such as thermal comfort questionnaires, are adopted. Therefore, the wind and thermal comfort index in summer in Shanghai can also be assessed with the same methodologies.

   b) As a result, the design methods for proposed buildings in extended areas may not be adapted in other regions unless more relevant research has been completed, based on the actual current situation, for example through wind tunnel tests and CFD simulations.

3) *Deficiency of the proposed buildings:*

   In the previous two chapters about designing more tall buildings in the extended Lujiazui district, only the approximate location and the simple arrangement of the buildings are taken into consideration. Other aspects such as the layout distance, the diversity in the buildings' morphology (only cuboid is applied) and the total number of buildings were not given too much consideration, due to limitations of computing power and time.

All in all, the methods presented here can only be applied to a certain extent. Government officers and urban planners can nevertheless consider the suggestions given below with peace of mind before they make urban planning decisions.

8.3 Recommendations for future research

As previously mentioned, blending modern architecture with urban design has made it possible to increase or decrease air flows according to need, in order to provide adequate thermal comfort in the open spaces and between buildings found in big cities by manipulating certain climatic conditions. However, to fully understand the real advantages obtained from this procedure it would be helpful first of all to comprehend the importance that people give to certain physical conditions. People require sunshine during cold days to feel warm and cosy, but they may also want to avoid being under the blazing sun, if only for a short time during the summer. In the future studies, the effect of sunlight can be simulated by using software such as Ecotect, to improve outdoor thermal comfort on a street level.

Therefore, the goal will be to integrate systems that consider the material of buildings' facades, the ground on which they are erected, the lawn and trees around them and their radiant reflectance, the size and location of the plants and their shade, the vehicle's flow rate and the related anthropogenic heat sources as well as air pollution in the targeted site for a comprehensive outdoor thermal comfort assessment method.

This thesis considers only the influence of the urban and building morphology on the outdoor wind environment at the street scale. The effect of small-size objectives can be studied in future research for further optimization in some specific areas. For example, the location and density of trees may reduce or improve the pedestrian's thermal and wind comfort. Therefore, due to the dreadful air pollution experienced in many cities recently, wind health should also be considered in addition to the wind comfort and safety assessment, and contained in the government criteria imperatively. For example, simulating the diffusion of contaminant, such as Particulate Matter 2.5 (PM2.5), is conducive to determining the new minimum wind velocity at street level.

The reason for analysing microclimates is that researchers want to generate interest in and focus on procedures and systems able to enhance urban designing all the while having peace of mind since architectural plans devise landscape modifications by manipulating thermal and aerodynamic conditions. In order to make improvements with sensibility, all the different disciplines employed in the process, such as architecture, climatology or biometeorology, should be given equal importance and they should communicate effectively in order to be able to work together for the same goal.

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Appendices

Appendix 1: Review of outdoor thermal comfort studies from behavioural aspects in the last decade (Chen and Ng, 2012)

City and climate	Urban area	Season	Survey method	Thermal comfort assessment	Analysis method	Behaviors	Factors determining comfort	Levels of consideration	Source
Cambridge, UK; Temperate	Open spaces	Spring, summer, winter	Interview, attendance counting	PMV/PPD	Regression, frequency distribution	Attendance	Environmental stimulation, thermal history	Physical, physiological, psychological	Nikolopoulou, Baker, and Steemers (2001)
Montreal, Canada; Temperate	Plazas, public squares	Spring, summer, autumn	Observation, presence counting	No	Multiple regression, ANOVA test	Sitting, standing, smoking	Temperature, sun	Climatic	Zacharias, Stathopoulos, and Wu (2001)
Gothenburg, Sweden; Temperate	Urban park	Summer, autumn	Interview, questionnaires, vote	PMV	Regression, frequency distribution	Stay and rest	Microclimatic condition, thermal expectation	Physical, physiological, psychological	Thorsson, Lindqvist, and Lindqvist (2004)
Kassel, Germany; Temperate	Open spaces near a bistro	Spring, summer	Observation, presence counting	PET	Regression	Attendance	Temperature, solar radiation, wind speed, expectation	Physiological, expectation	Katzschner (2006)
Satellite city of Tokyo, Japan; Temperate	Park, square	Spring	Interview, questionnaires, unobtrusive observation	PET	Frequency distribution, regression	Various	Weak relation	Physiological, social	Thorsson et al. (2007)
Athens, Greece; Temperate	Neighborhood square, seashore place	Four seasons	Interview, questionnaires, observation	No	Regression	Presence, sitting	Temperature, solar radiation	Meteorological, social,	Nikolopoulou and Lykoudis (2007)
Gothenburg, Sweden; Temperate	Square, park, courtyard, plaza	Four seasons	Observation, interview	No	Multiple regression	Attendance, various behaviors	Clearness, temperature, wind speed	Meteorological, functional, psychological	Eliasson et al. (2007)
Taichung, Taiwan; Subtropical	Public square	Four seasons	Observation, questionnaires	PET	Regression	Attendance	Temperature, solar radiation	Physiological, psychological, behavioral	Lin (2009)

Appendix 2: Questionnaire Survey (English vision)

This independent research project focuses on the outdoor pedestrian thermal environment in Lujiazui, Shanghai, and it may refer to individual thermal sensation, which includes your own perception of the solar condition, wind velocity, air humidity, ambient temperature and overall comfort. From the results of a questionnaire survey, it aims to establish criterions of outdoor thermal comfort in urban areas and guide the Chinese government and urban planners to generate better codes for a healthier pedestrian level environment.

I would be greatly appreciated if you would help me to complete this simple voluntary questionnaire. It will only spend you about 10 minutes. In completing the questionnaire, please be honest and there are no right or wrong answers. The questionnaire is completely confidential to the research team at the University of Nottingham. All the information collected will be summarised anonymously, which means nothing can be traced back to you.

In order to participate in the research, you will need to give your informed consent. By ticking the box below, you are indicating that you understand the nature of the survey and that you agree to help us. Please tick the box if you agree to take part: ☐

I understand that all information I provide will remain anonymous and kept in accordance with the Data Protection Act, UK (1998). I understand that I have been provided with an explanation of the survey in which I am participating in and have been given the name and contact details of an individual to contact if I have questions about the research. I understand that participation in the survey is voluntary and that I can withdraw at any time.

Thank you very much for your help.

The questionnaire is completely anonymous. So please do not write your name on it. But if you would like any more information about the research project, or if you would like to know the overall results of the project, please contact me:

Jiawei Yao

Email: laxjy9@nottingham.ac.uk

The Department of Architecture and Built Environment, Faculty of Engineering

University of Nottingham, UK

Or, if you wish, you can leave your telephone number or email address below, and I will contact you. This personal information will be kept completely separately from the attached questionnaire, be stored safely and remain confidential.

Email address: ……………………………………… Tel: ………………………………

Outdoor pedestrian thermal comfort questionnaire survey in Lujiazui District

NO.□□□□

Part One:

Gender: Male / Female Age: 18 ~ 29 / 30 ~ 49 / ≥ 50

Nationality: Chinese / non-Chinese

Occupation: Student / Work / Unemployed

Clothing level (please tick what you are wearing):

A. Underwear	**Clo**	**C. Sweaters**	**Clo**	**F. Socks**	**Clo**
T-shirt	0.08	Sleeveless, thin-thick	0.13-0.22	Ankles-high Athletic socks	0.02
Full slip	0.16	Long-sleeve, thin-thick	0.25-0.36	Calf-length socks	0.03
Long underwear top	0.2			Panty Hose	0.02
Long underwear bottom	0.15	**D. Coat**	**Clo**		
		Leather jacket	0.46	**G. Shoes**	**Clo**
B. Shirt and Blouses	**Clo**	Cotton-padded clothes	0.6	Sandals	0.02
Sleeveless, scoop-neck blouse	0.12	Down jacket	0.69	Leather shoes	0.08
Short sleeve, dress shirt	0.19			Boots	0.1
Long sleeve, dress shirt	0.25	**E. Trousers and Coveralls**	**Clo**	Sport shoes	0.12
Long sleeve, flannel shirt	0.34	Walking short	0.15	Snow boot	0.2
Long sleeve, sweat shirt	0.34	Trousers and Coveralls	0.24		
		Sweat pants	0.3		

1) **Have you done this questionnaire before?**

Yes / No

2) **In your opinion, is it important to consider about thermal comfort in this area?**

No important	Never think about it	Important	Quite important

3) **What was the most recent time you came to Lujiazui district, Pudong?**

The first time	Every day	Within 1 week	Within 2 weeks	Within 1 month	Within 1 year	Within 3 years	3 ~ 6 years	6 ~ 9 years	More than 9 years

4) **With the increasing number of tall buildings have been completed, do you think the current outdoor environment is more comfortable than last time you came here?**

Less comfortable	I do not know	More comfortable	I do not remember	No change

Which factors affect you to feel more or less comfortable? (multiple choice)

Air quality	Landscape	Body health	Temperature	Air velocity

Or others:__________

5) **Have you been staying in Shanghai during the past 6 months?**

Yes/ No

6) **In the past 15 minutes, have you been to (or stayed in) indoor spaces with air-conditioning or heating system (including bus, taxi, underground, etc.)?**

Yes / No

7) **What were you doing during the past 15 minutes? (multiple choice)**

Waiting for people or cars	Resting	Standing	Sitting	Working	Shopping	Doing exercises	Walking

8) **Why did you use this particular place?**

In shade	Under tree-cover	Under sunshine	Breezy	Fresh air	Have an appointment	No particular reason	Going to school or work	Close to home or station	Pass by

9) **How do you feel in terms of thermal perception?**

Very Hot	Hot	Too warm	Neutral	Too cool	Cold	Very cold
3	2	1	0	-1	-2	-3

10) **How do you feel in terms of thermal perception about the surrounding environment?**

Yes / No

11) **How do you feel about the exposure to the sun?**

Sun makes me uncomfortable	Neutral	Not enough
1	0	-1

12) **How do you feel about the wind?**

Stagnant	Too still	Slightly still	Neutral	Slightly windy	Too windy	Much too windy
3	2	1	0	-1	-2	-3

13) **How do you feel about the air humidity?**

Too humid	Neutral	Too dry
1	0	-1

14) How is your skin wetness?

Drops of sweat	Moist	Neutral	Dry	Very dry
2	1	0	-1	-2

15) Overall, what is your feeling about this place?

Very comfortable	Comfortable	Neutral	Uncomfortable	Very uncomfortable
2	1	0	-1	-2

Part B (complete by observer):

B1. Date:_______________

B2. Time:

B3. Weather: Sunny / Cloudy / Rainy

B4. Is the participant shaded: YES / NO

B5. Survey location:

Appendix 3: Questionnaire survey (Chinese vision)

本问卷是关于上海陆家嘴地区室外行人热舒适度的调查研究，主要是收集关于您身体的热感觉参数（包括太阳辐射、风速、空气湿度、温度和您对周围环境的舒适满意度）。这份调查问卷最终可以帮助我们建立该地区的室外热舒适性的各项标准并在未来帮助政府和规划部门为居民提供更健康舒适的环境。

非常感谢您能在百忙之中抽出时间填写这份问卷调查。填写此问卷最多只需要占用您 10 分钟时间。本问卷的问题均为询问您的个人感受，没有对错之分，请结合您的工作经历和工作中的体会给予回答。本问卷采用不记名方式访问, 所有的信息仅供英国诺丁汉大学调研项目的专业研究人员使用, 所有资料绝不对外公开。您的宝贵意见将对本研究有极大的帮助。

您需要签署知情同意书进而参与此次问卷调查。当您在下面的方格中打勾就表明您了解此调研问卷的目的和性质并且同意帮助我们回答问卷。如果您同意参与，请在右边的方格中打勾：□

> *我了解我提供的所有信息将保持匿名，并根据英国的《数据保护法》（1998 年版）的规定保存。我已经理解了此问卷调查的目的和性质。如果我有关于此研究的疑问，我知道我可以联系的人的名称和详细联系方式。我了解参与此调研项目是完全自愿的，我可以在任何时候终止。*

如果您想了解关于此调研项目的更多信息或调研项目的最终结果，请联系我：

姚佳伟（英国诺丁汉大学建筑与环境学院）

电子邮箱: laxjy9@nottingham.ac.uk

或者，如果您愿意，您也可以把您的电子邮箱和电话填写在下面，我将会与您取得联系。这些个人信息将与问卷分开保存，所有个人信息在此次调研结束后全部销毁。

电子邮箱:________________________ 电话号码:____________________

室外行人热舒适性调查问卷

第一部分

NO.□□□□

性别：男 / 女　　　　年龄：18 – 29 / 30 – 49 / ≥50

国籍：中国 / 非中国　　　　职业：学生 / 工作 / 待业 / 退休

您身上所穿衣服指数（请在选项上划出）：

A. 内衣	Clo	**C. 毛衣**	Clo	**F. 袜子**	Clo
T-恤衫	0.08	毛衣背心	0.13-0.22	短袜	0.02
长裙	0.16	长袖毛衣	0.25-0.36	小腿高的袜子	0.03
棉毛衫	0.2			连裤袜/丝袜	0.02
棉毛裤	0.15	**D. 外套**	Clo		
		皮衣	0.46	**G. 鞋子**	Clo
B. 衬衫和短衫	Clo	棉衣	0.6	凉鞋	0.02
无袖背心	0.12	羽绒服	0.69	皮鞋	0.08
短袖衫	0.19			普通靴子	0.1
普通长袖衫	0.25	**E. 裤子**	Clo	运动鞋	0.12
带绒长袖衫	0.34	运动短裤	0.15	雪地靴	0.2
长汗衫	0.34	薄长裤及连体工作服	0.24		
		厚长裤	0.3		

1) 您以前做过同类型的问卷吗？

做过	没有做过

2) 以您的经历和观点，您觉得在城市规划中考虑室外行人的热舒适性是否重要？

一点都不重要	从来没有考虑过	重要	非常重要

3) 您多久前来过浦东陆家嘴？

这是第一次（跳过第四题）	一周内	一个月内	一年内	三年内	三到六年	六到九年	超过九年

4) 随着越来越多的高层建筑在陆家嘴竣工，您认为当前的室外环境是否比您上次来的时候更舒适呢？

不舒适	不知道	舒适

5) 过去的 6 个月内，您是否一直待在上海？

是的	没有

6) 在刚才的 15 分钟里，您是否去过有空调或暖气的室内空间（包括公交车，出租车，地铁等）？

是的	没有

7) 在过去的 15 分钟里，您主要的行为是？（可多选）

在等人或等车	休息	站立	坐着	工作	购物	锻炼	其他（请列举）

8) 您为什么选择坐在/站在这个地方？（可多选）

阴影下	树下遮阳	晒太阳	享受舒适的微风	呼吸新鲜空气	与别人约定的地点	没有特殊原因	去学校或工作的时候经过	离家或办公室或学校或站台近	其他（请列举）

9) 您对当前环境的热感觉？

非常热（+3）	热（+2）	非常暖和（+1）	正合适（0）	有点凉（-1）	冷（-2）	很冷（-3）

10) 您前额是否直接暴露于太阳光（是否戴帽子）？

是的	没有

11) 您现在对于直接暴露在阳光下的感受是？

太阳让我很不舒服	正合适	还不够，我需要更多的阳光

12) 您现在对于风的感受是？

没有风	几乎没有风	偶尔一丝风	正合适	微风	大风	狂风

13) 您对于现在空气湿度的感受是？

太湿了	正合适	太干了

14) 您皮肤的湿润情况是？

流汗	潮湿	正合适	干	非常干

15) 总体而言，您如何评价这个地方的热环境？

非常舒适	舒适	正合适	不舒适	非常不舒适

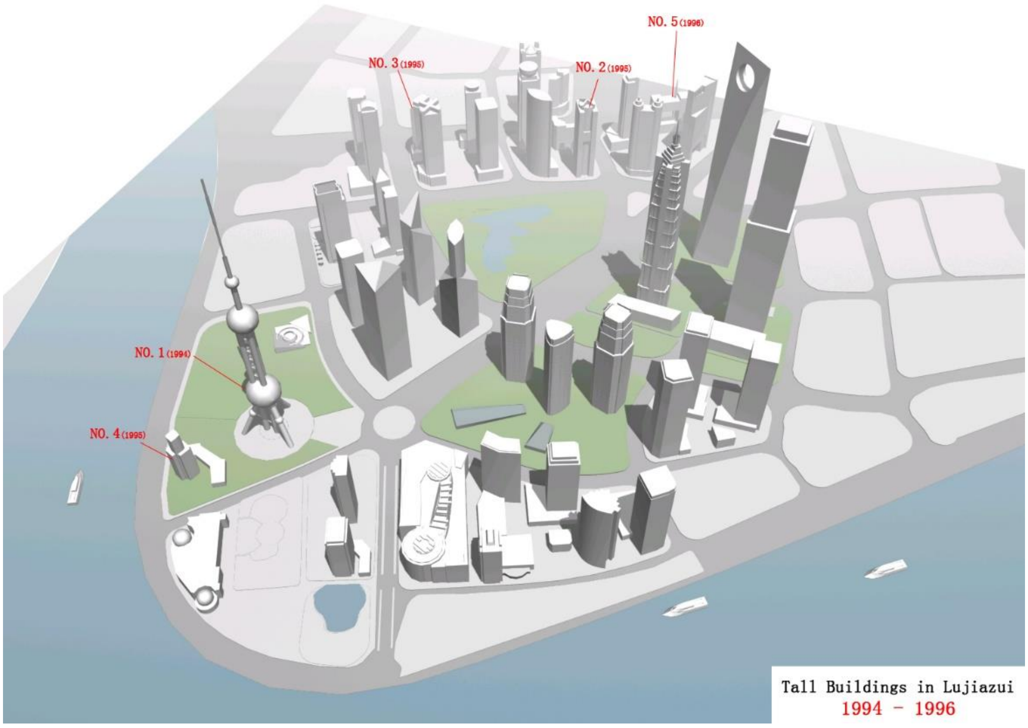
第二部分（由观察员所得）：

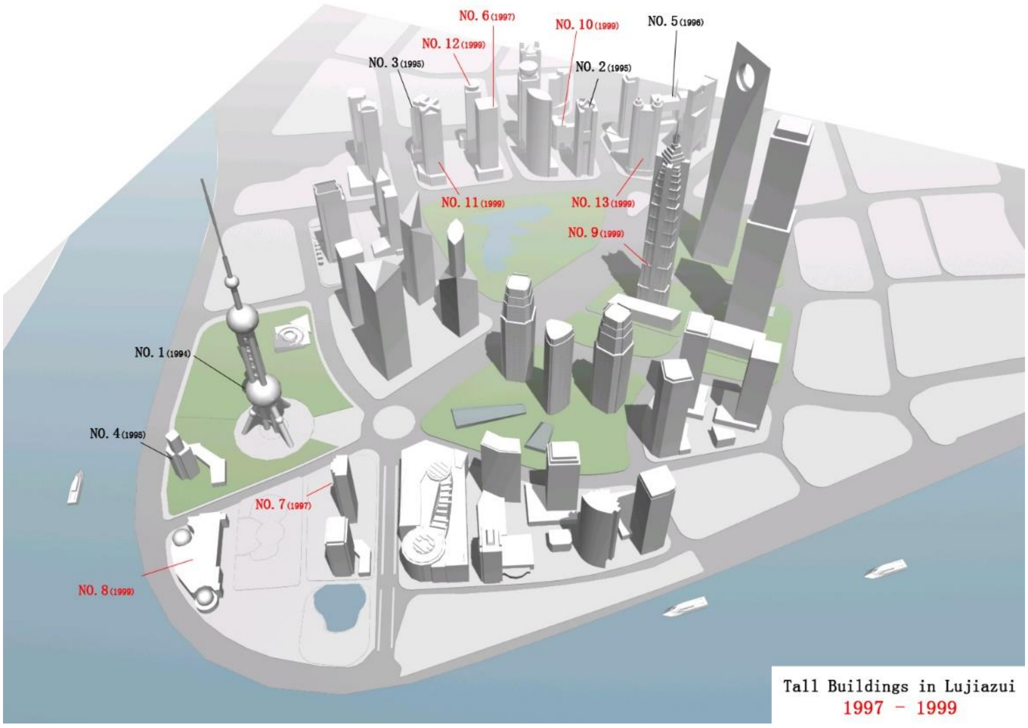
B1. 日期:_______________ B2. 时间:_______________

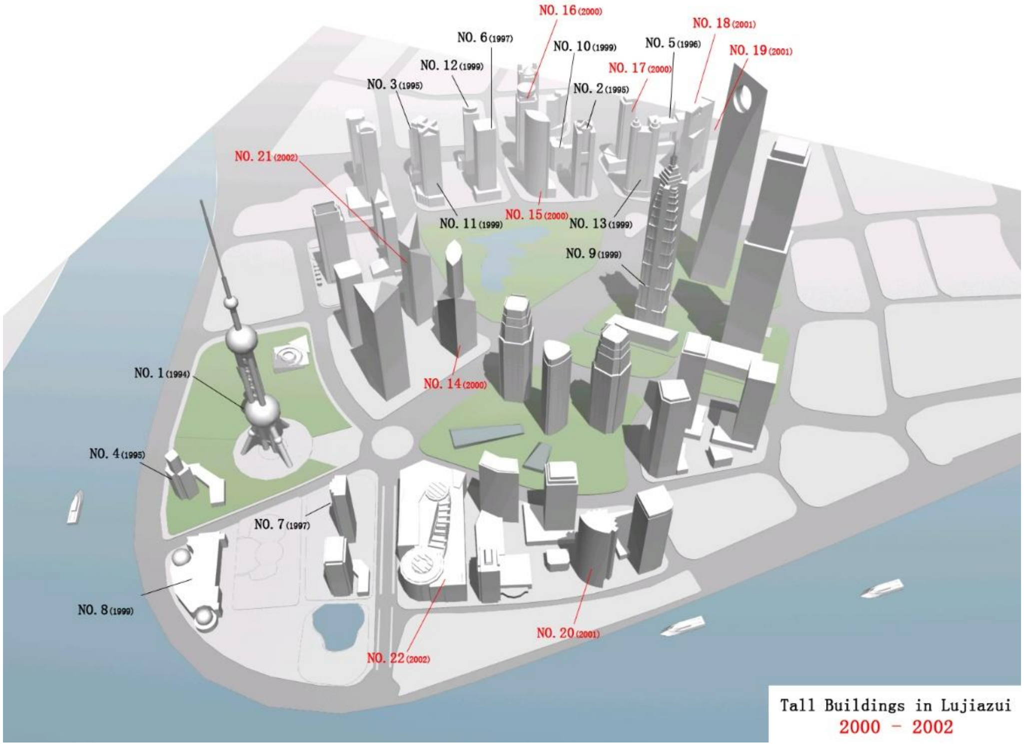
B3. 天气：晴 / 多云 / 雨天或阴天 B4. 被测者是否在阴影下:是 / 否

B5. 问卷地点:

Appendix 4: Development of tall buildings in Lujiazui New District during 1996 to 2014



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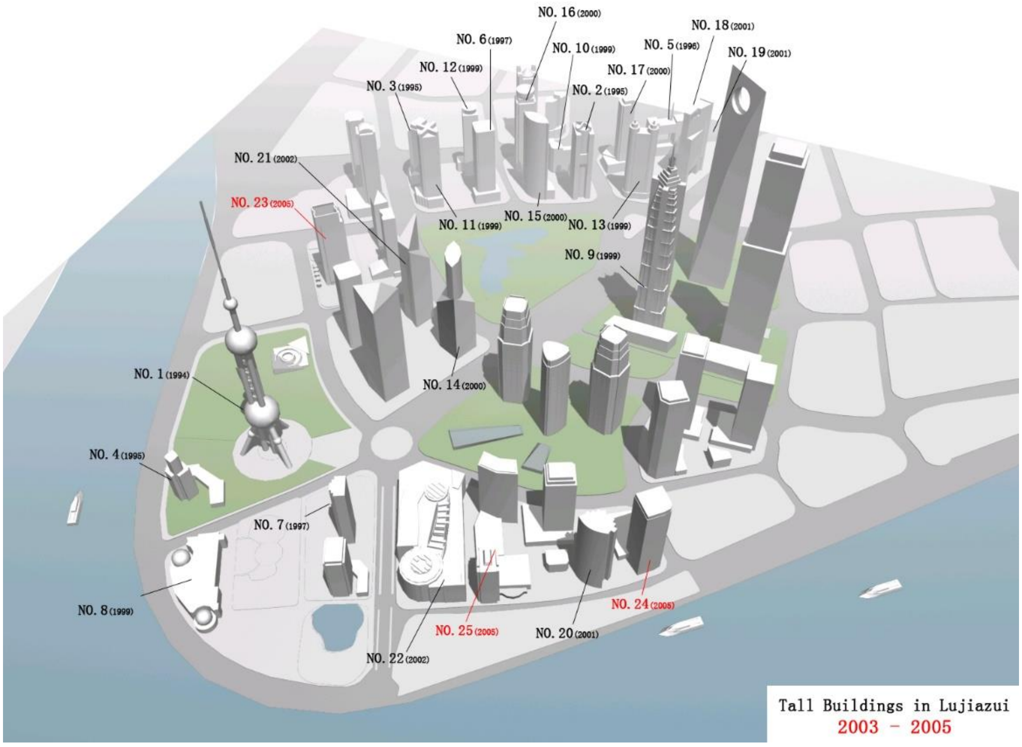
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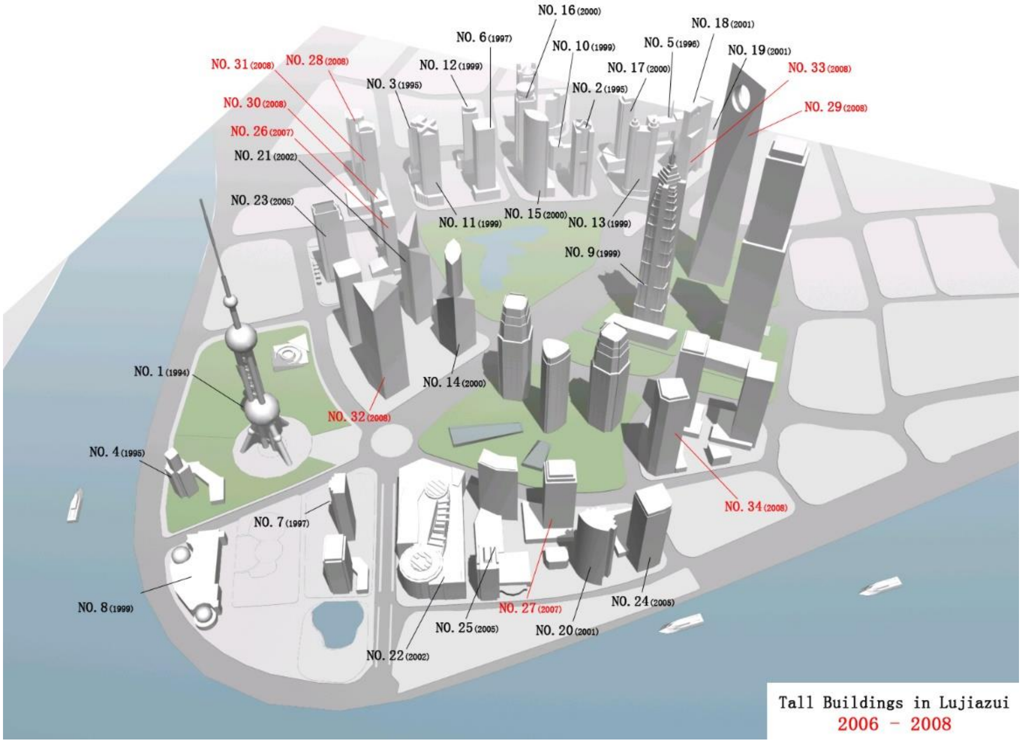
Tall Buildings in Lujiazui
2003 - 2005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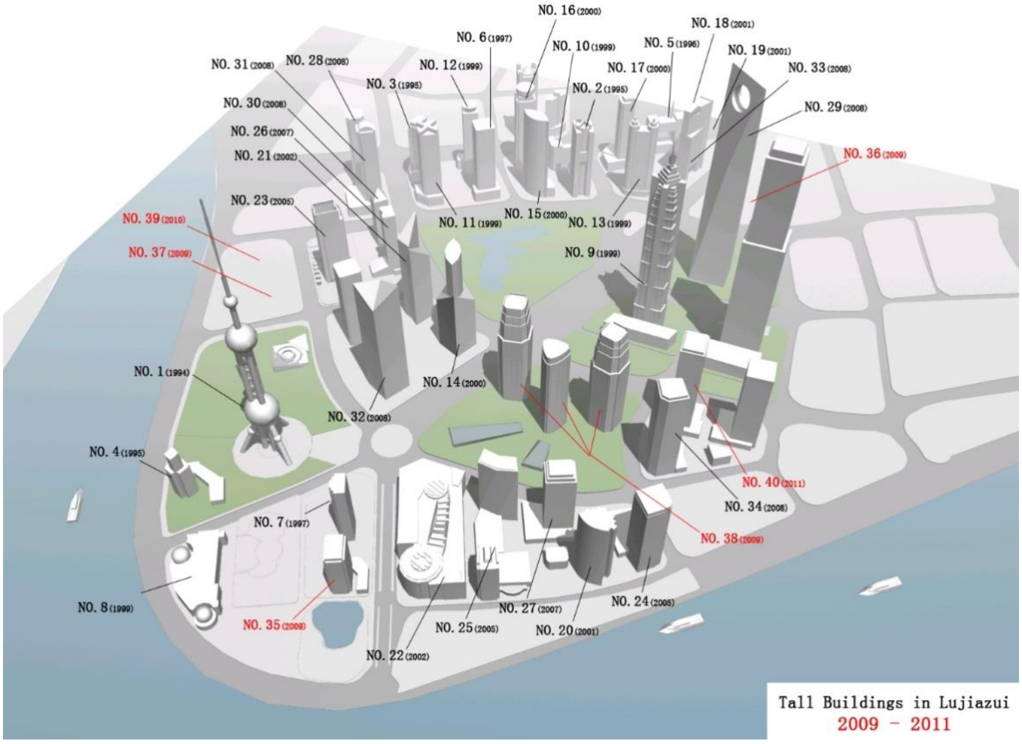
Tall Buildings in Lujiazui
2006 - 2008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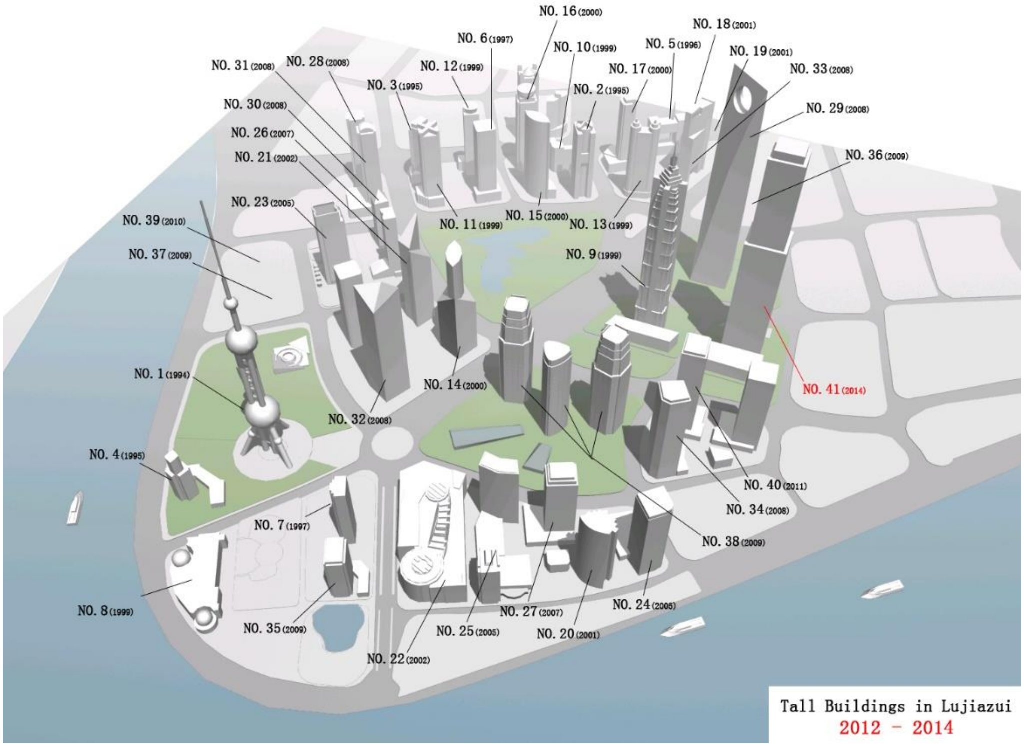
Tall Buildings in Lujiazui
2009 - 2011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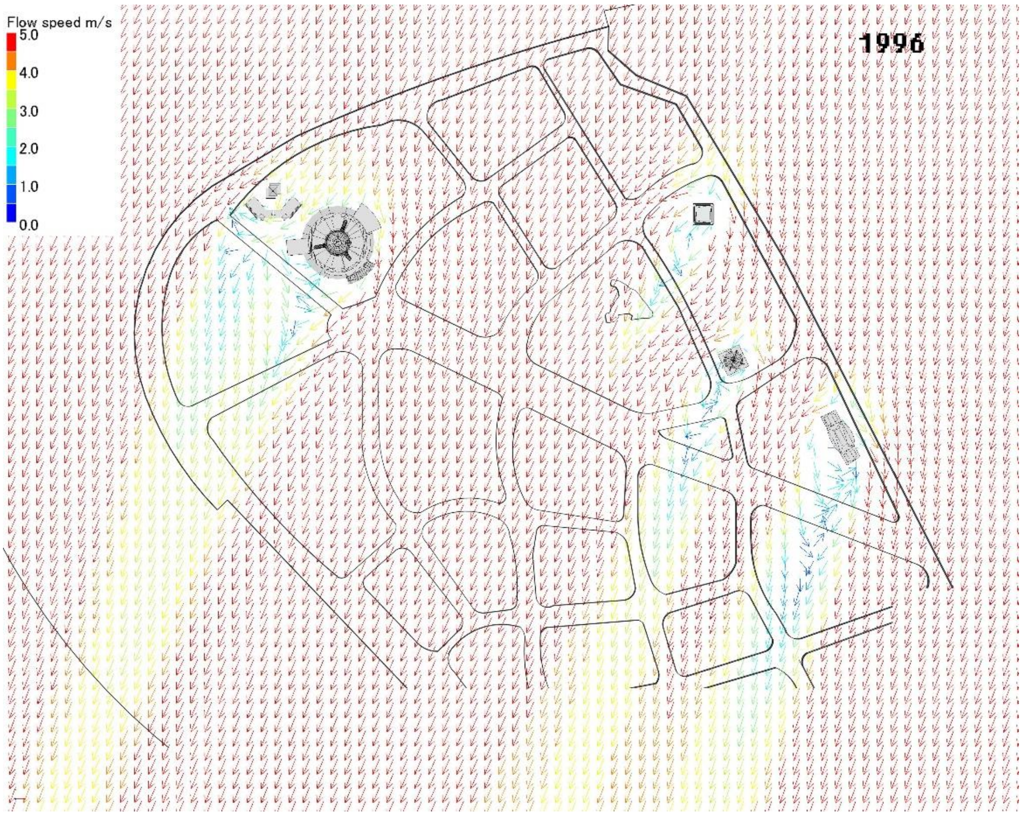
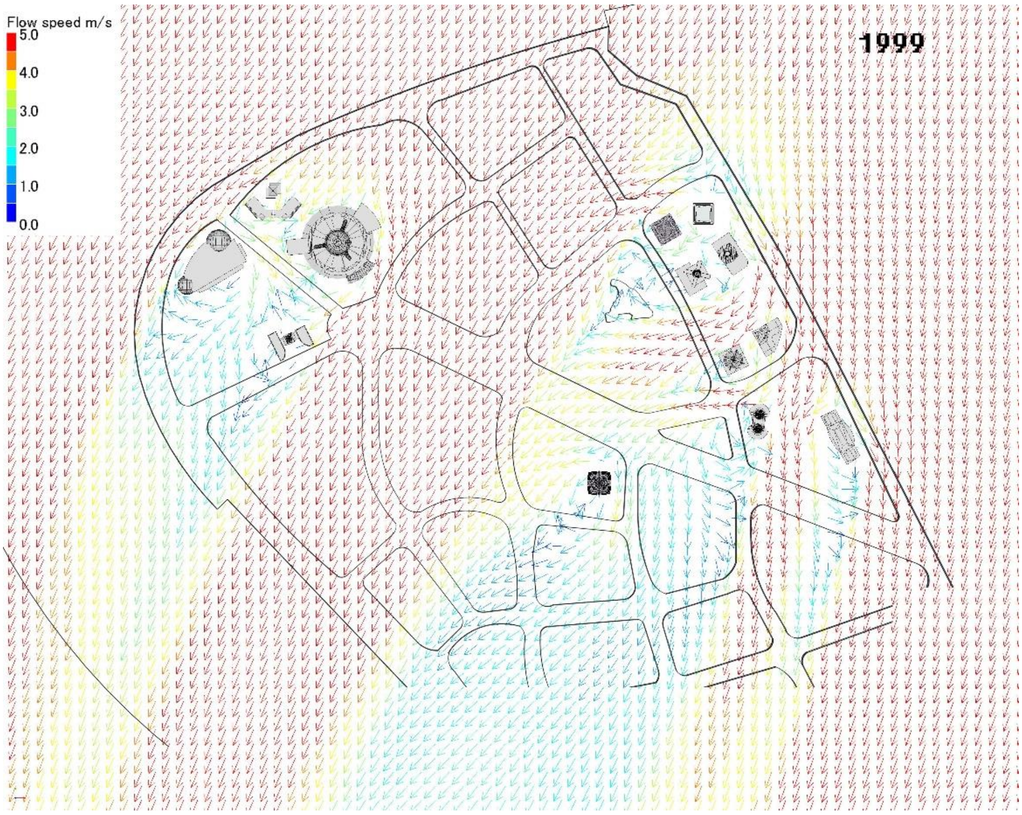
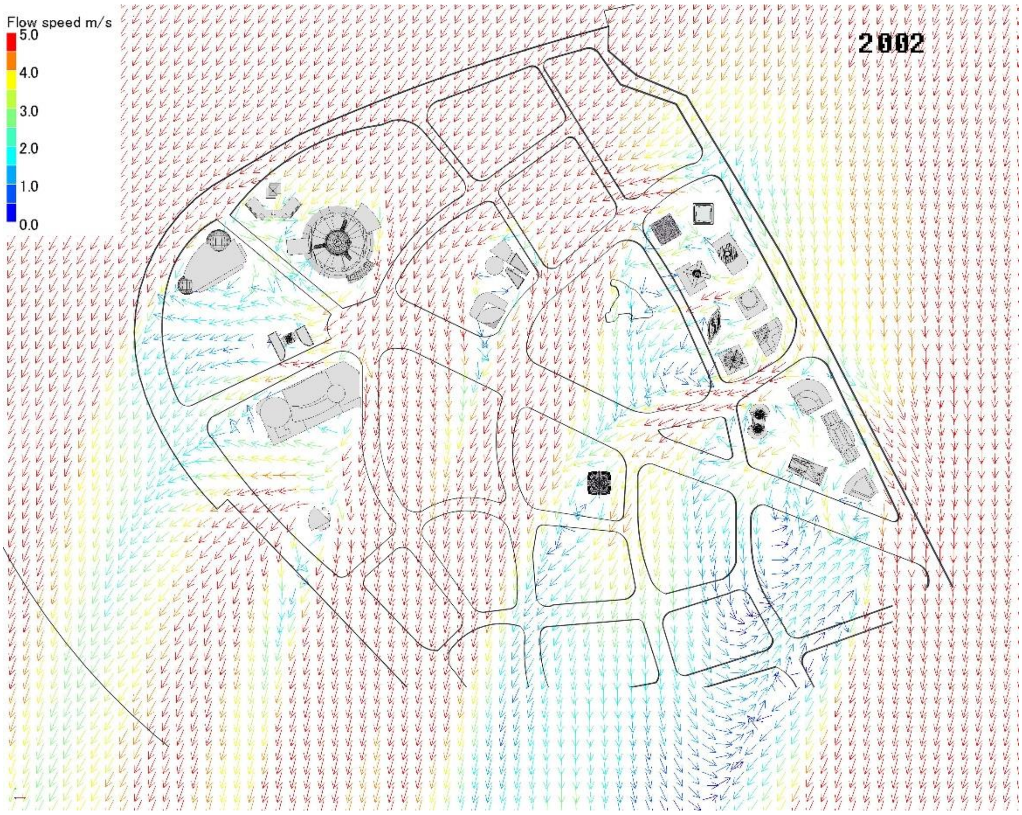
NO. 40 (2011)
NO. 34 (2008)
NO. 7 (1997)
NO. 38 (2009)
NO. 27 (2007)
NO. 24 (2005)
NO. 8 (1999)
NO. 35 (2009)
NO. 25 (2005)
NO. 20 (2001)
NO. 22 (2002)
Tall Buildings in Lujiazui
2012 - 2014

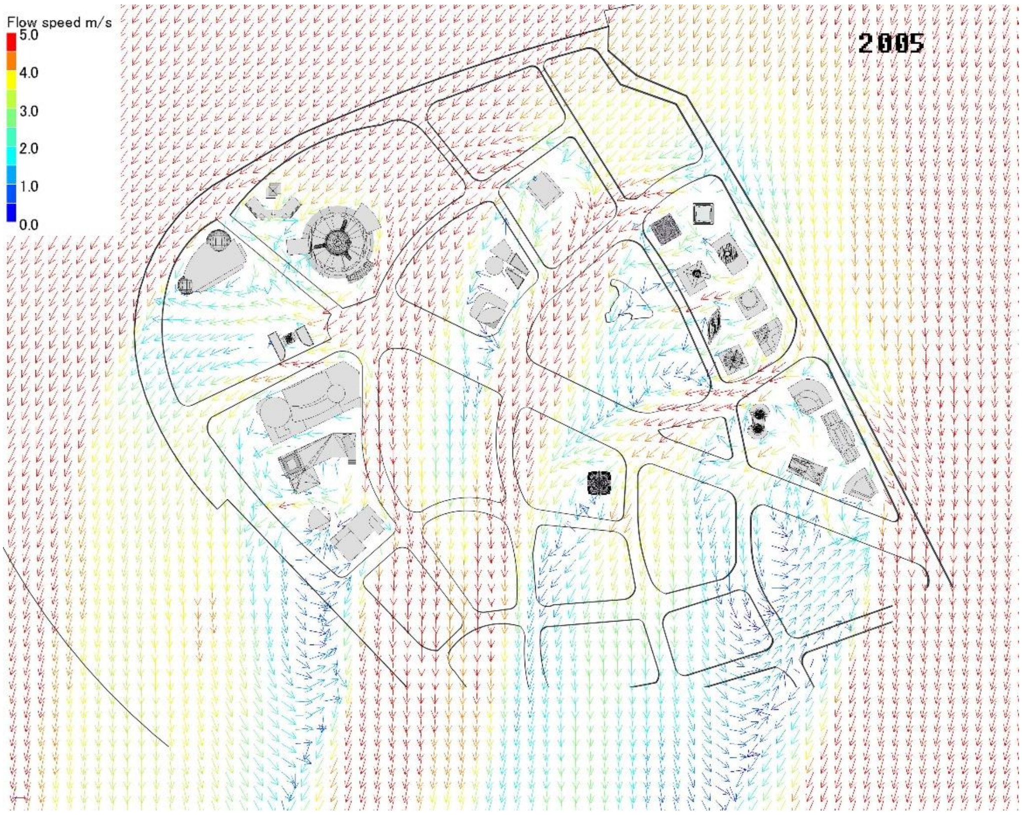
Appendix 5: CFD simulation of pedestrian-level outdoor wind environment during 1996 to 2014 in Lujiazui

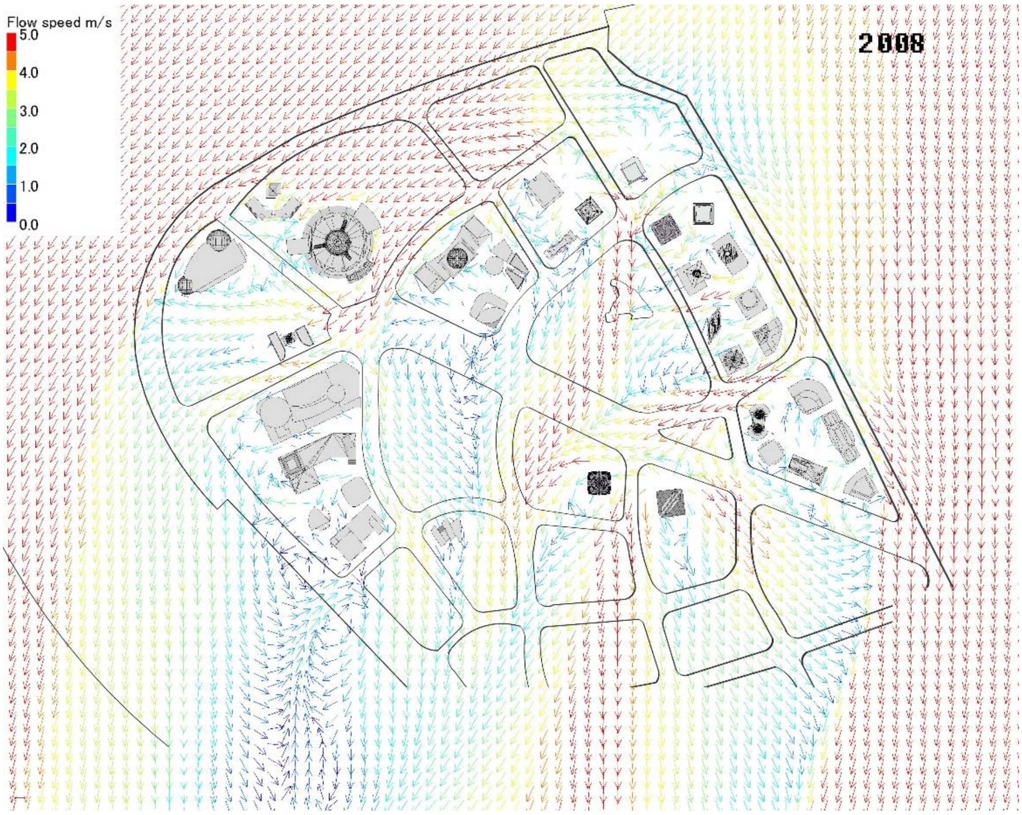
Appendix 5.1 Outdoor wind flow with wind direction at NNE

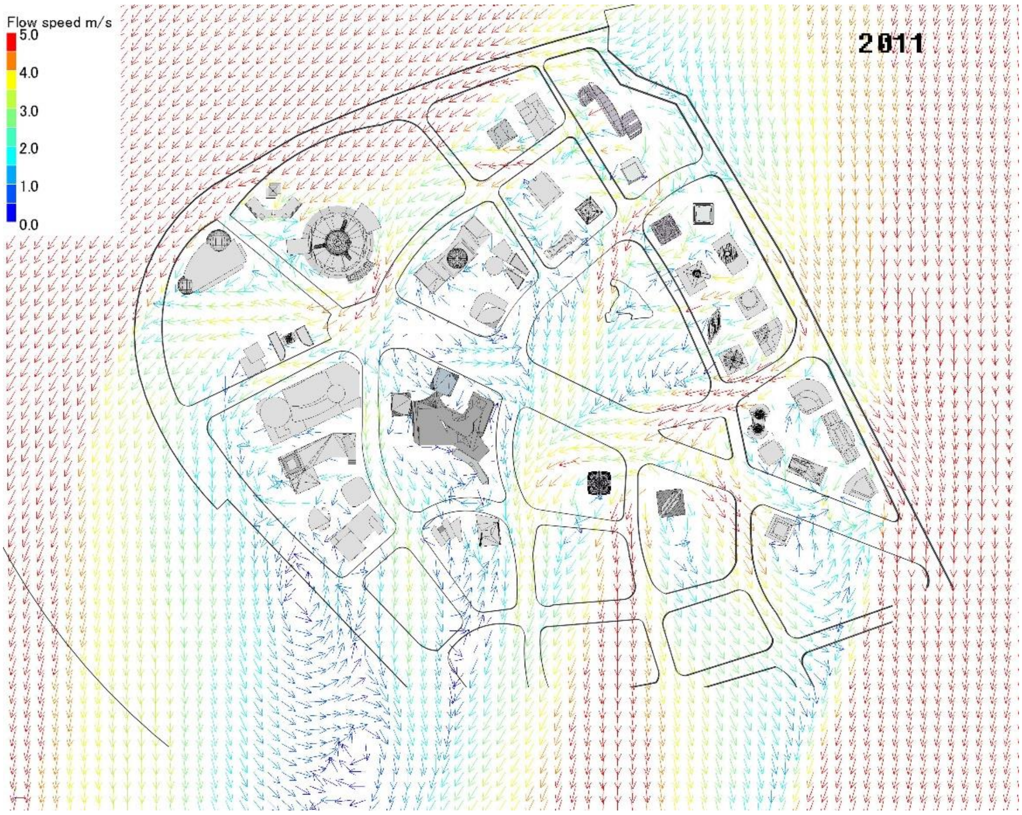


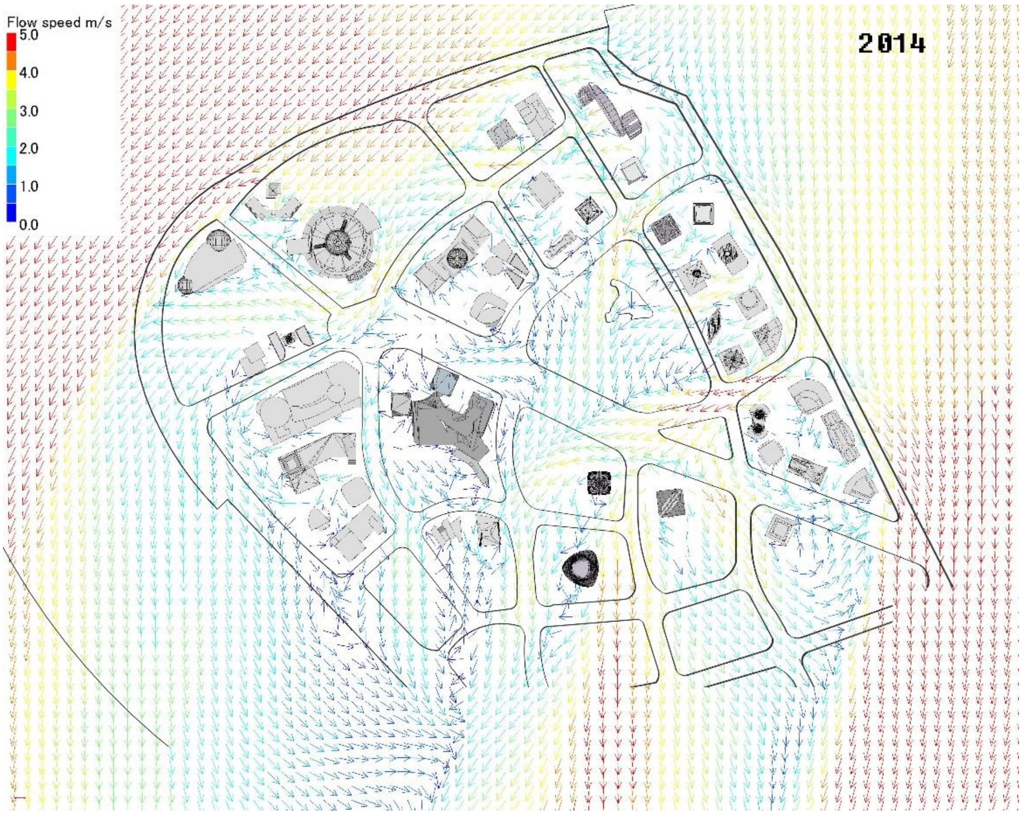

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
1999


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2002

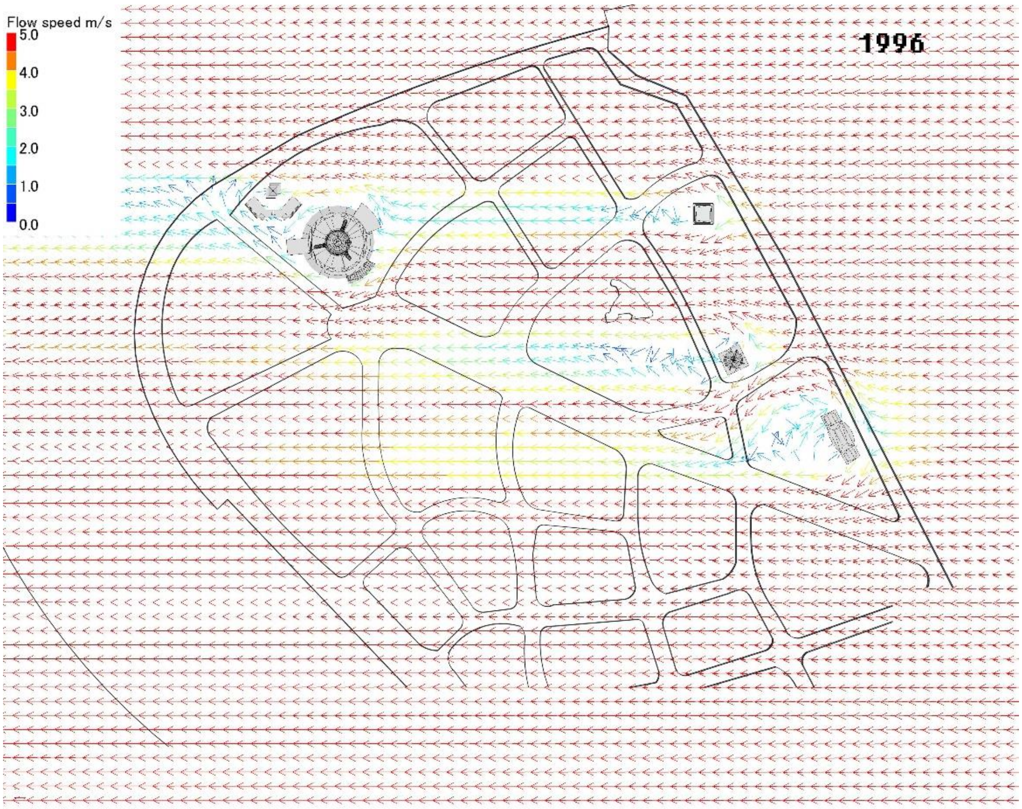

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2005

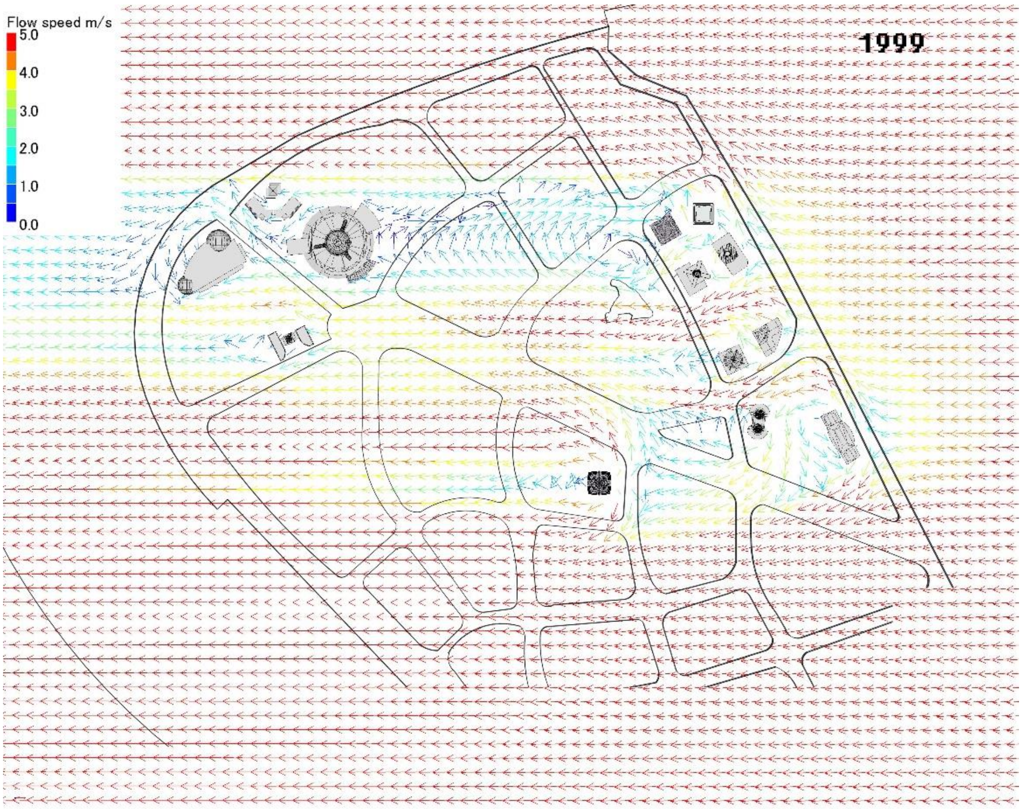

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2008

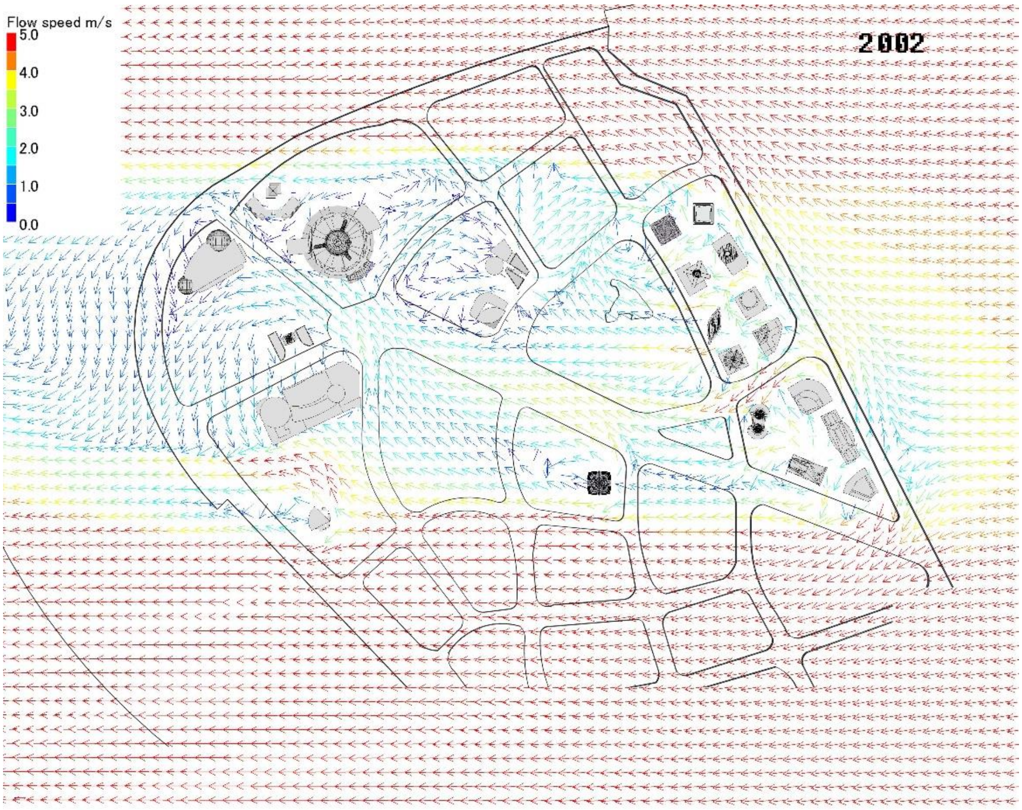

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2011

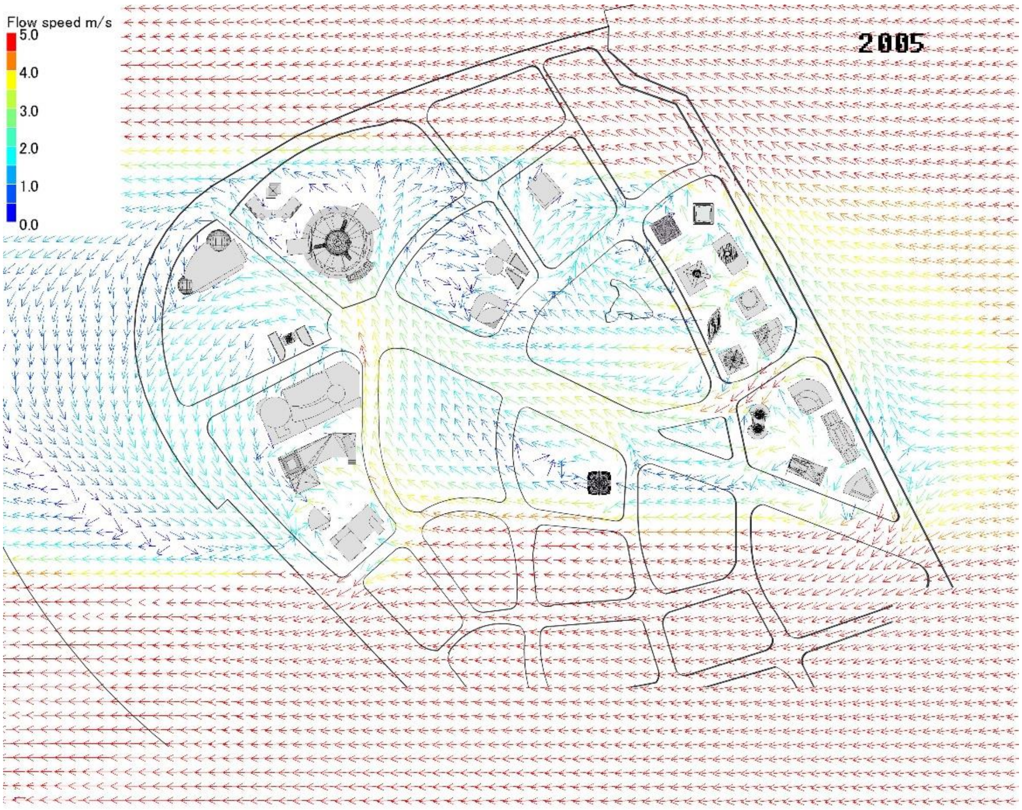

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2014

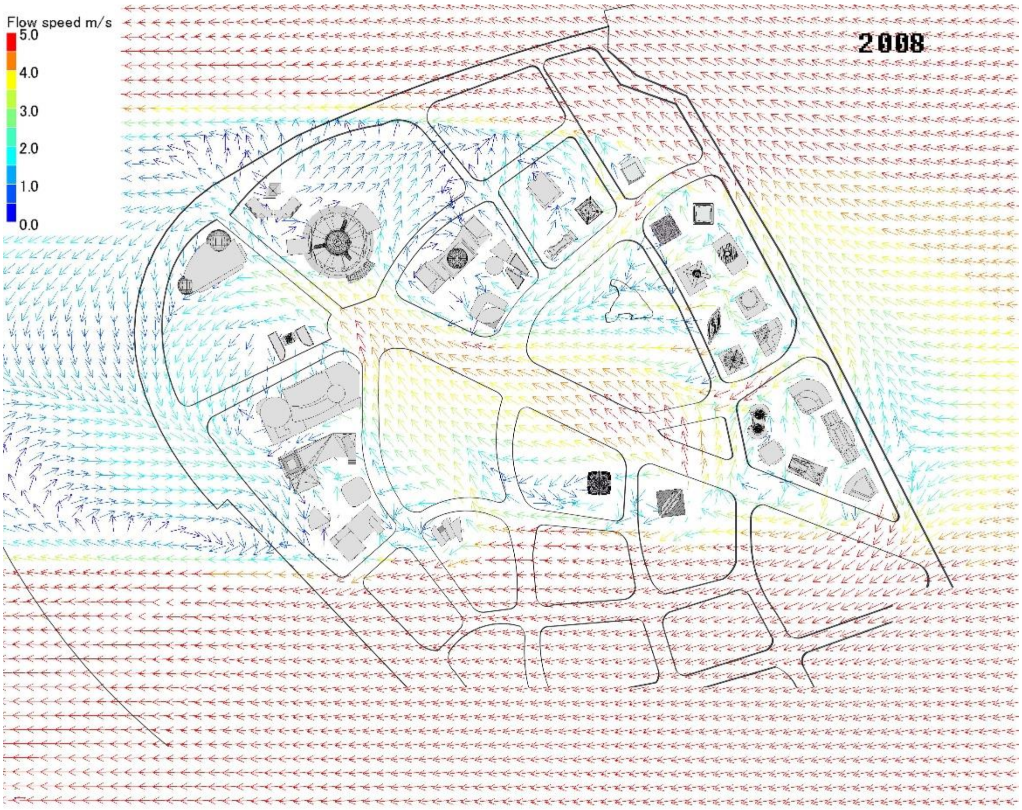
Appendix 5.2 Outdoor wind flow with wind direction at E

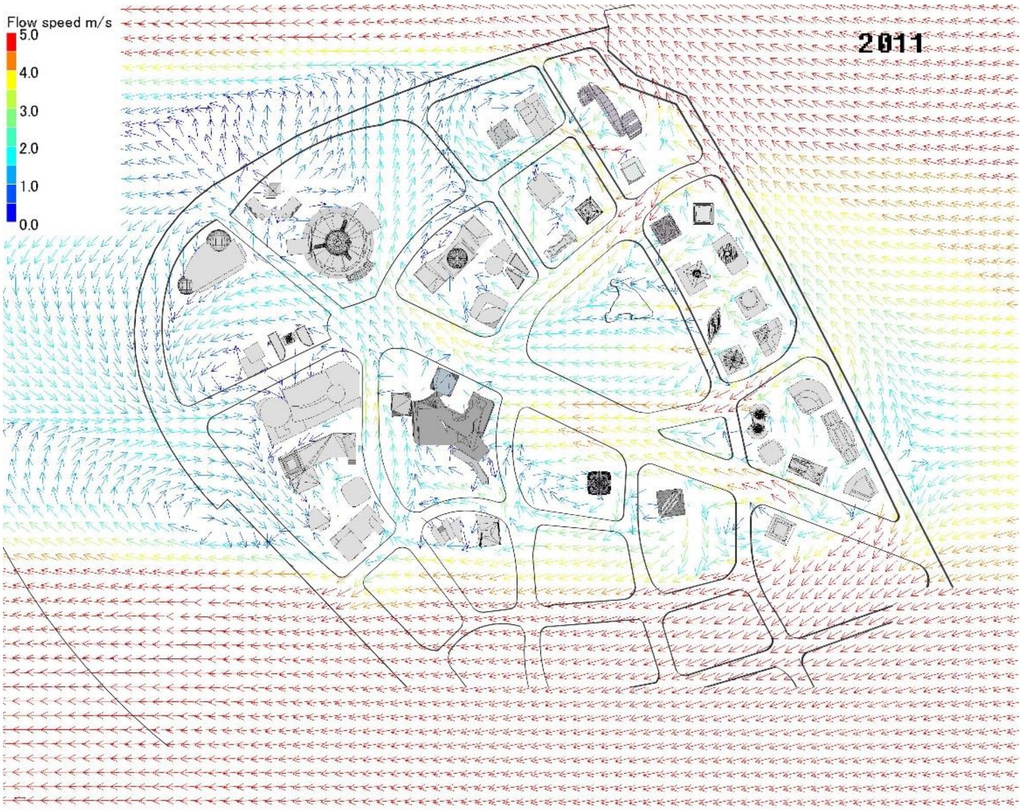


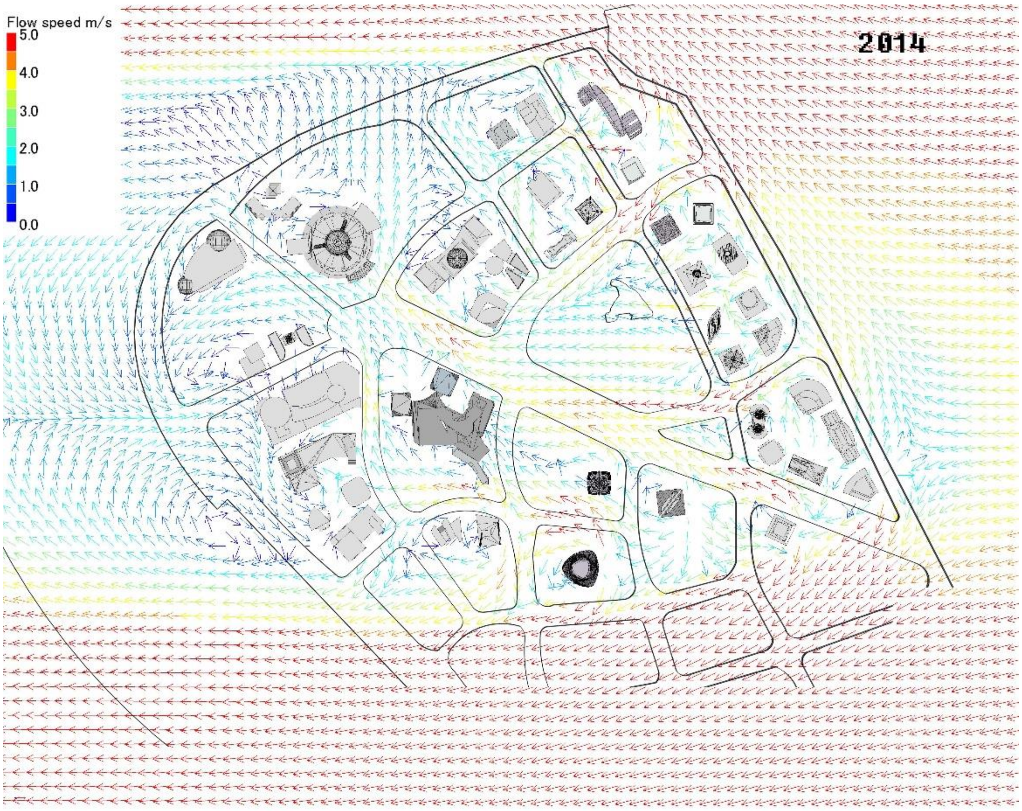



Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2002

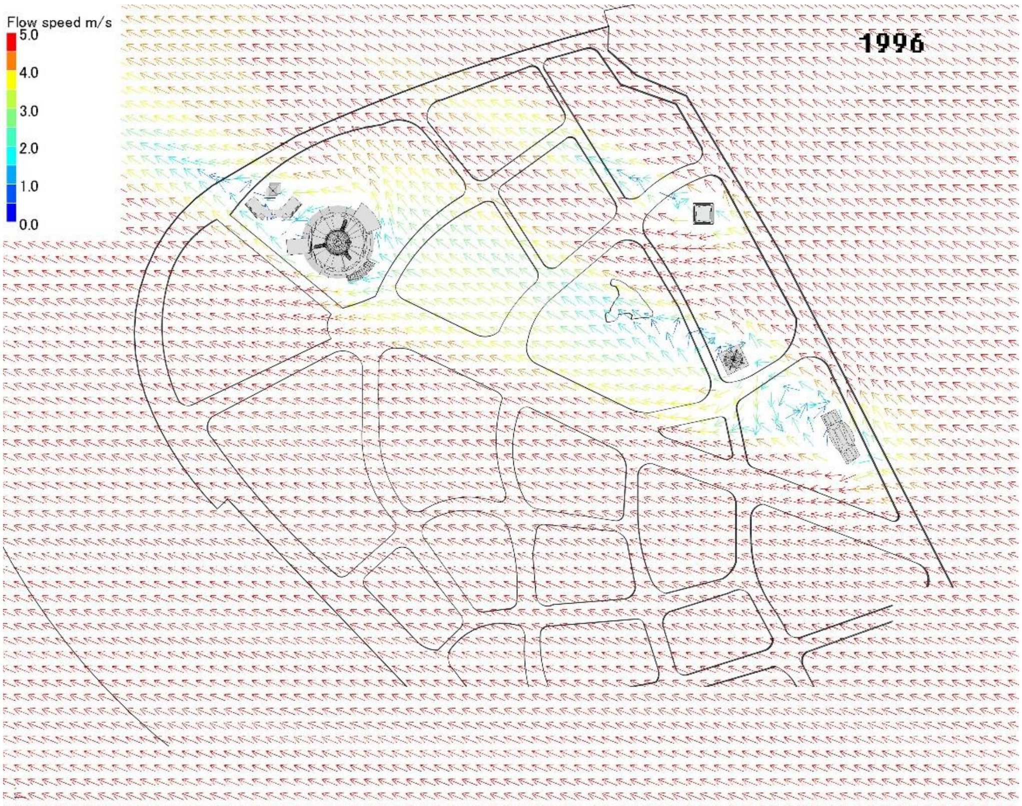

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2005

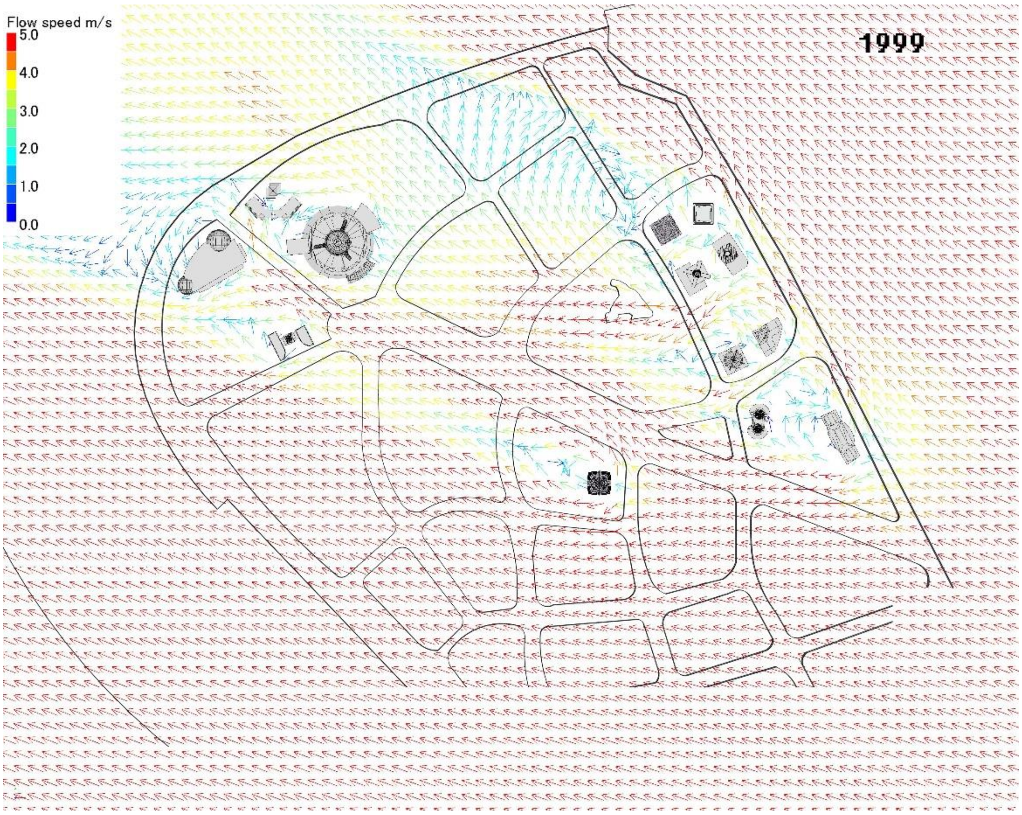

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2008

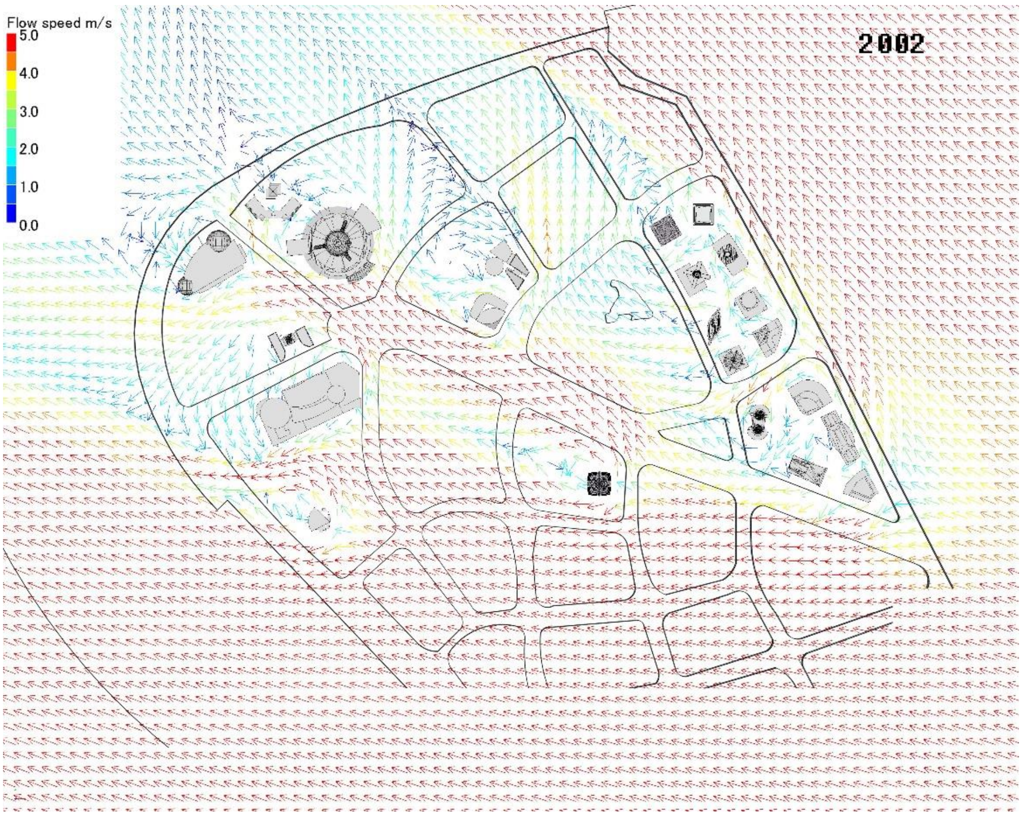

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2011

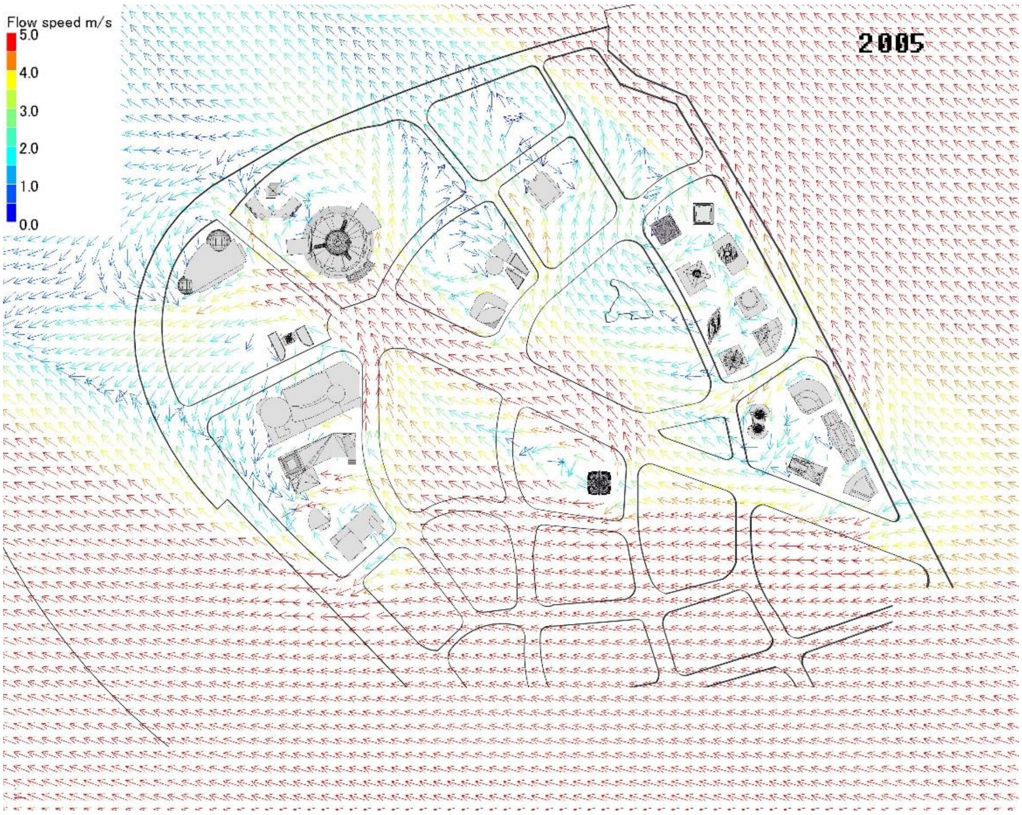


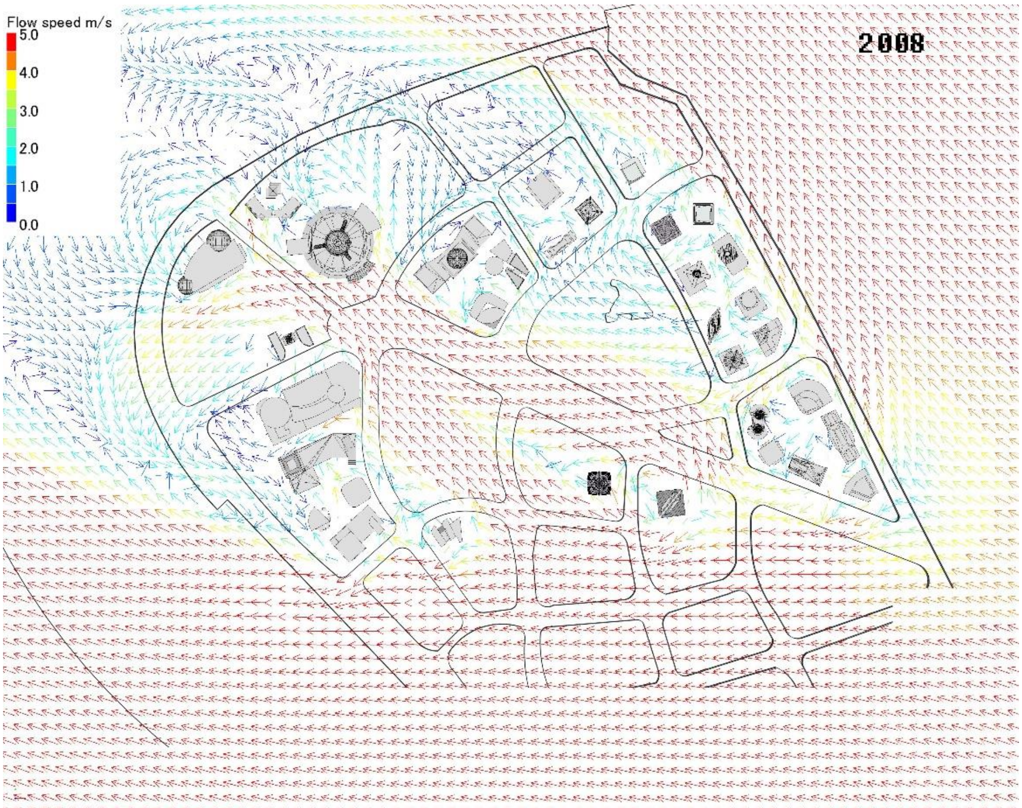
Appendix 5.3 Outdoor wind flow with wind direction at ESE

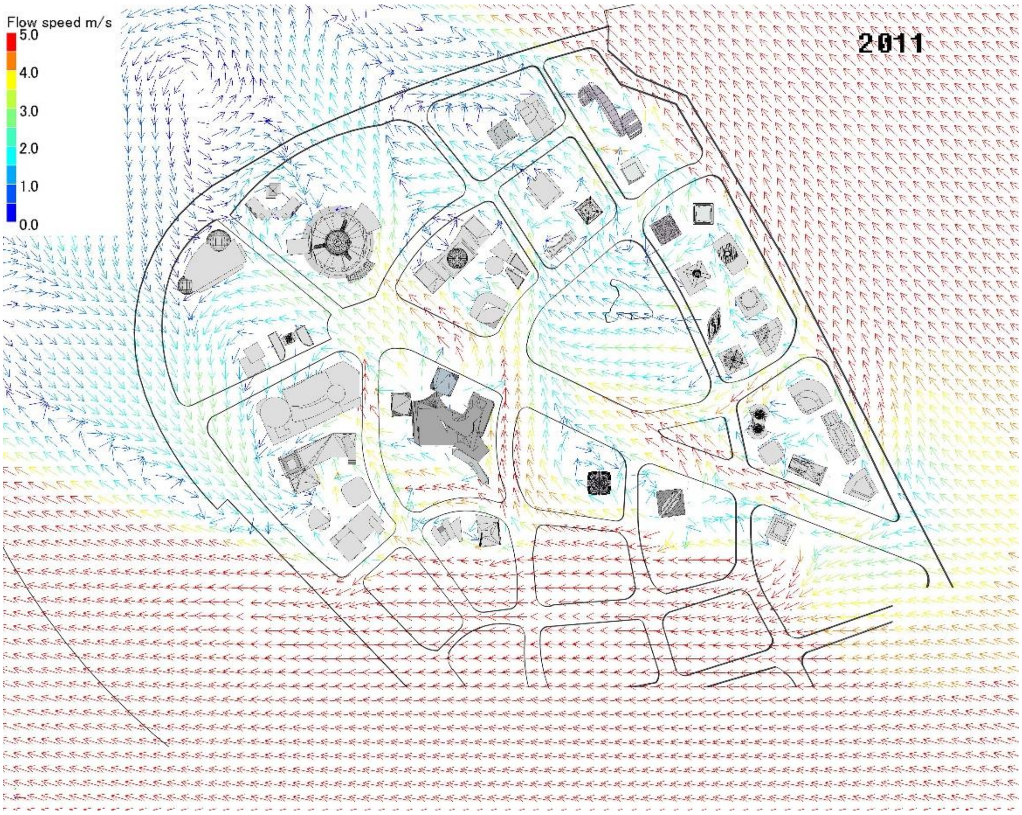


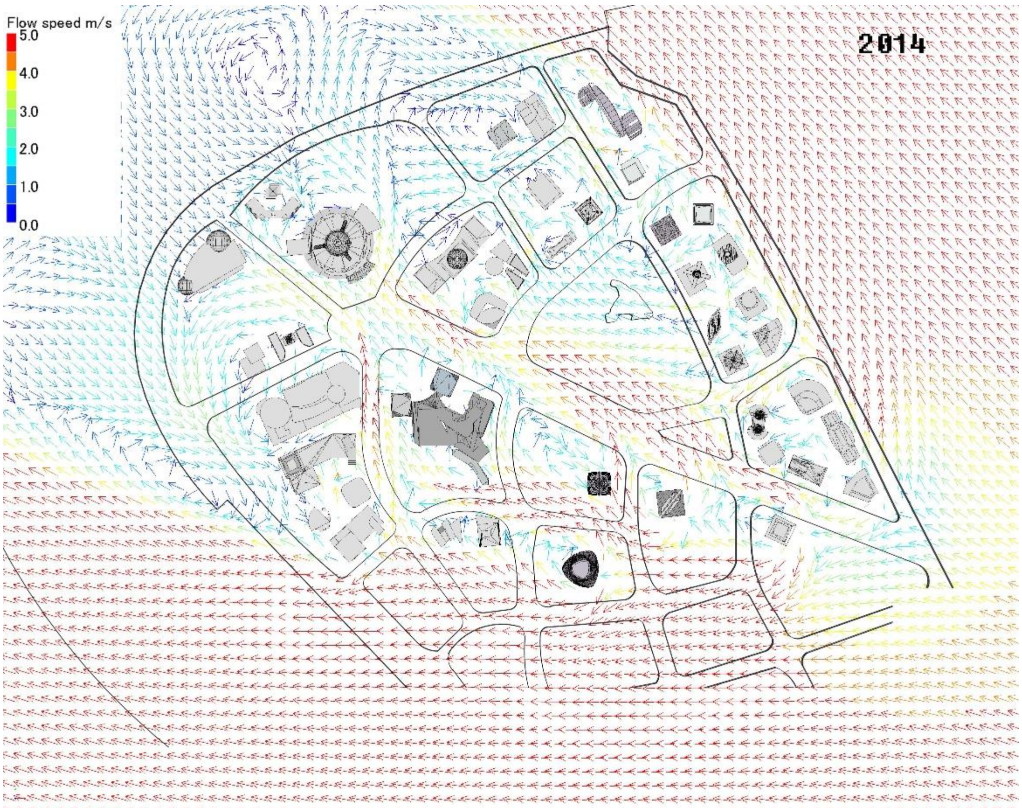

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
1999


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2002

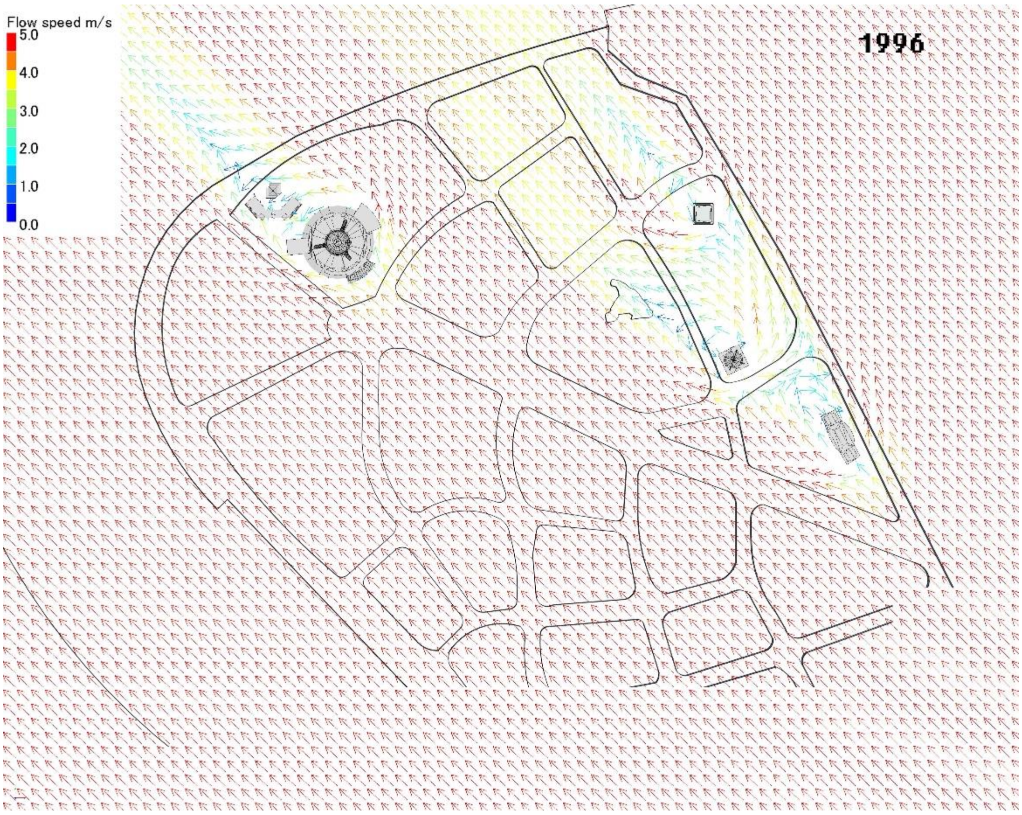

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2005

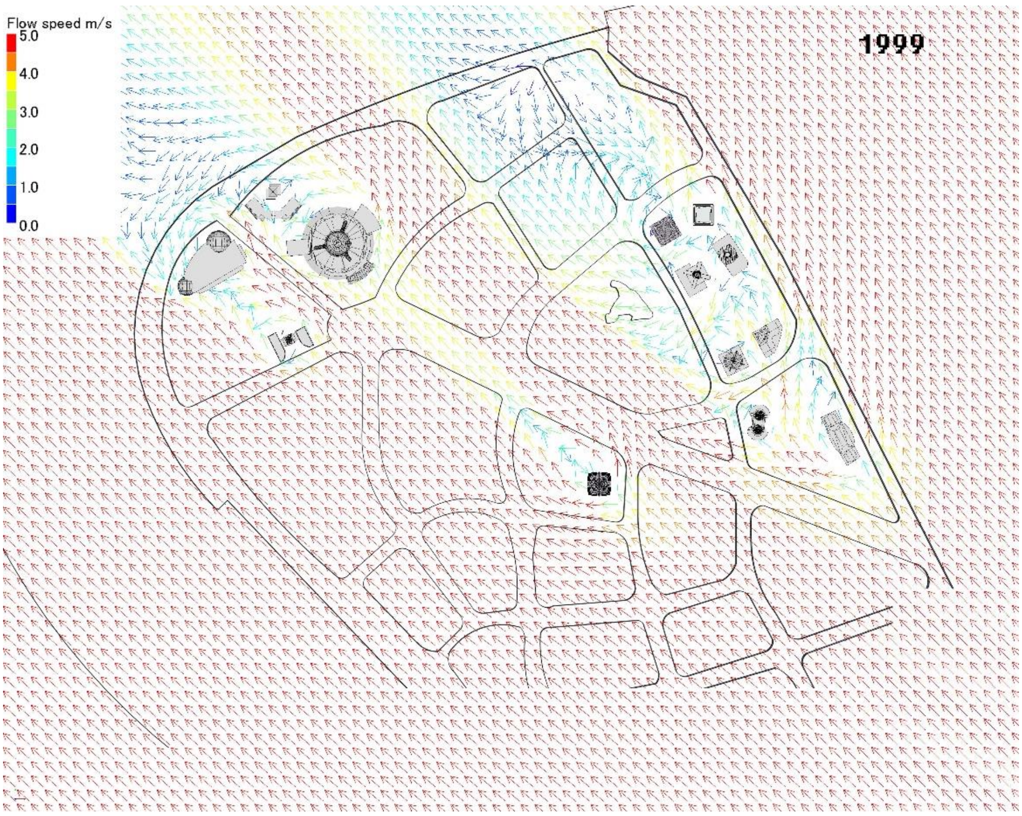

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2008

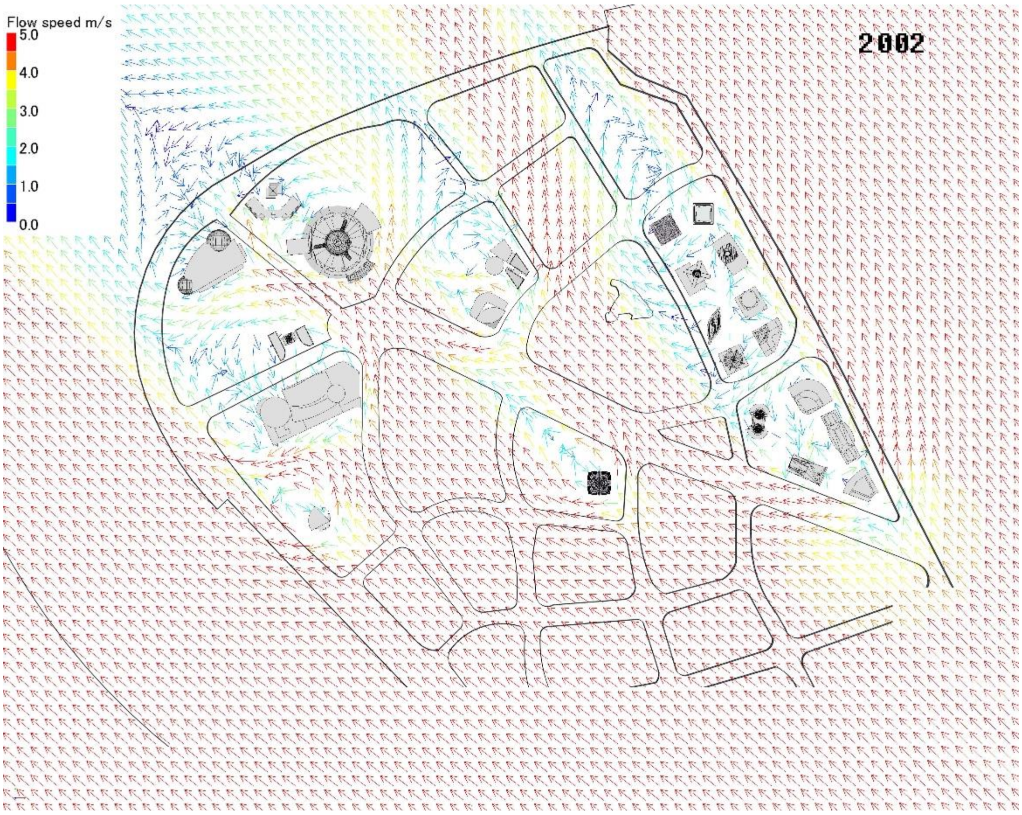

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2011

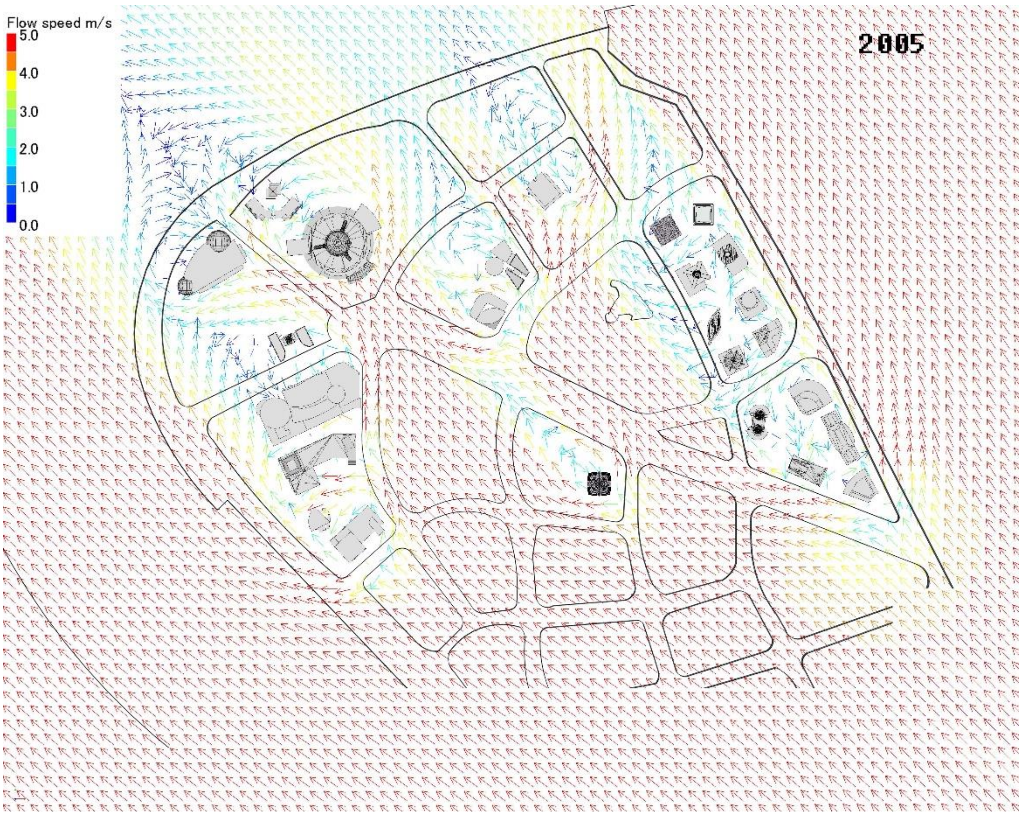

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2014

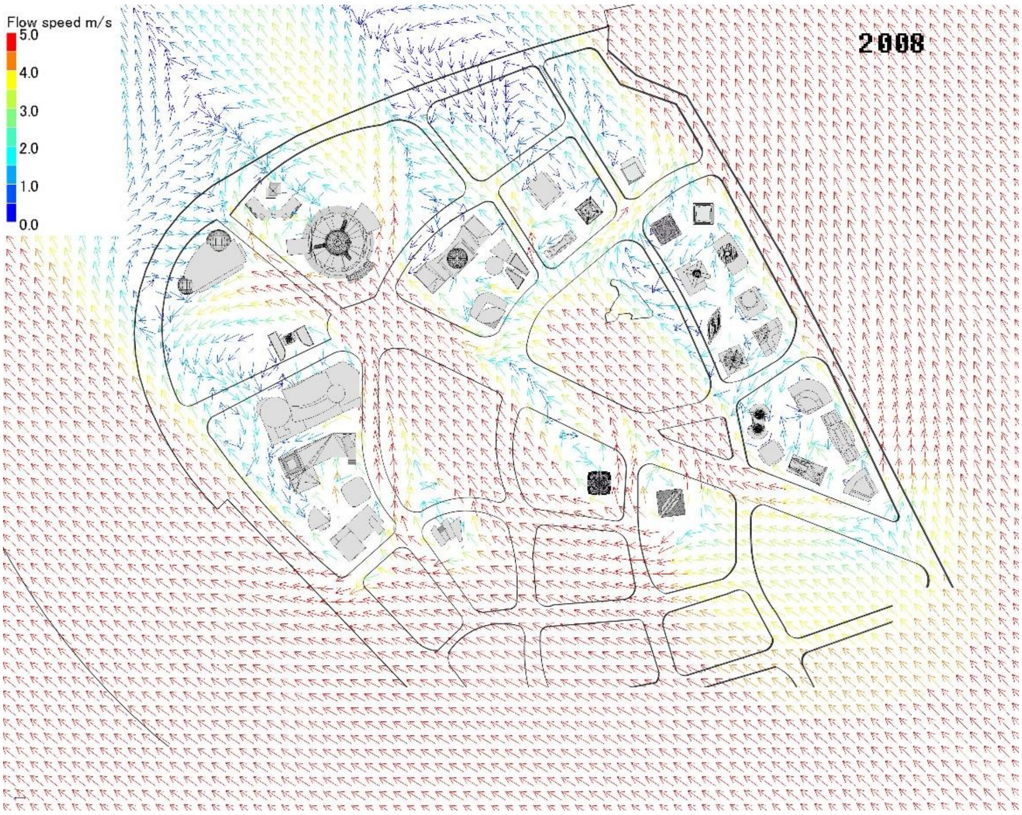
Appendix 5.4 Outdoor wind flow with wind direction at SE

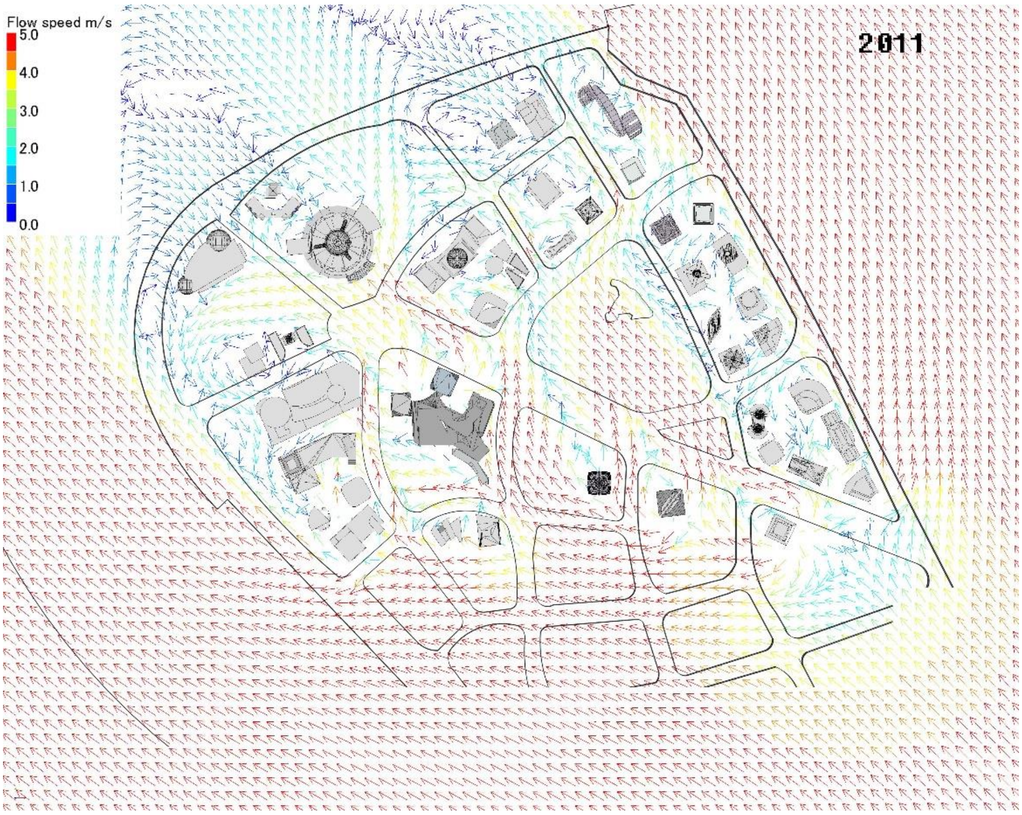


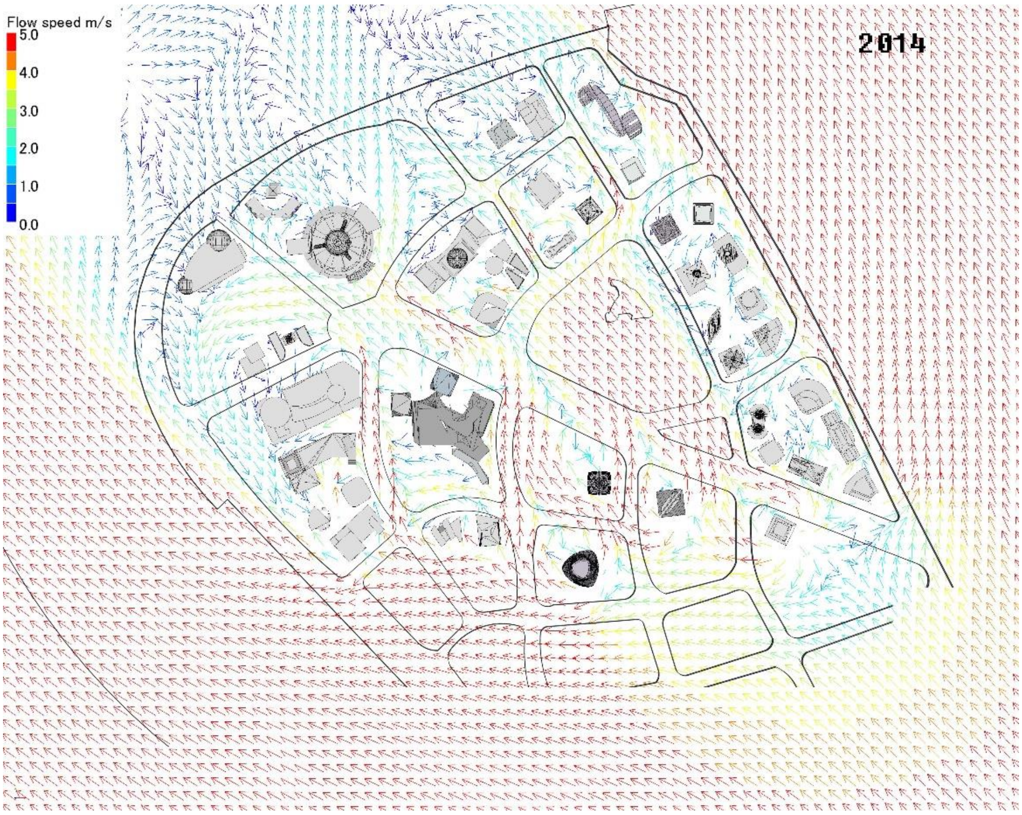



Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2002

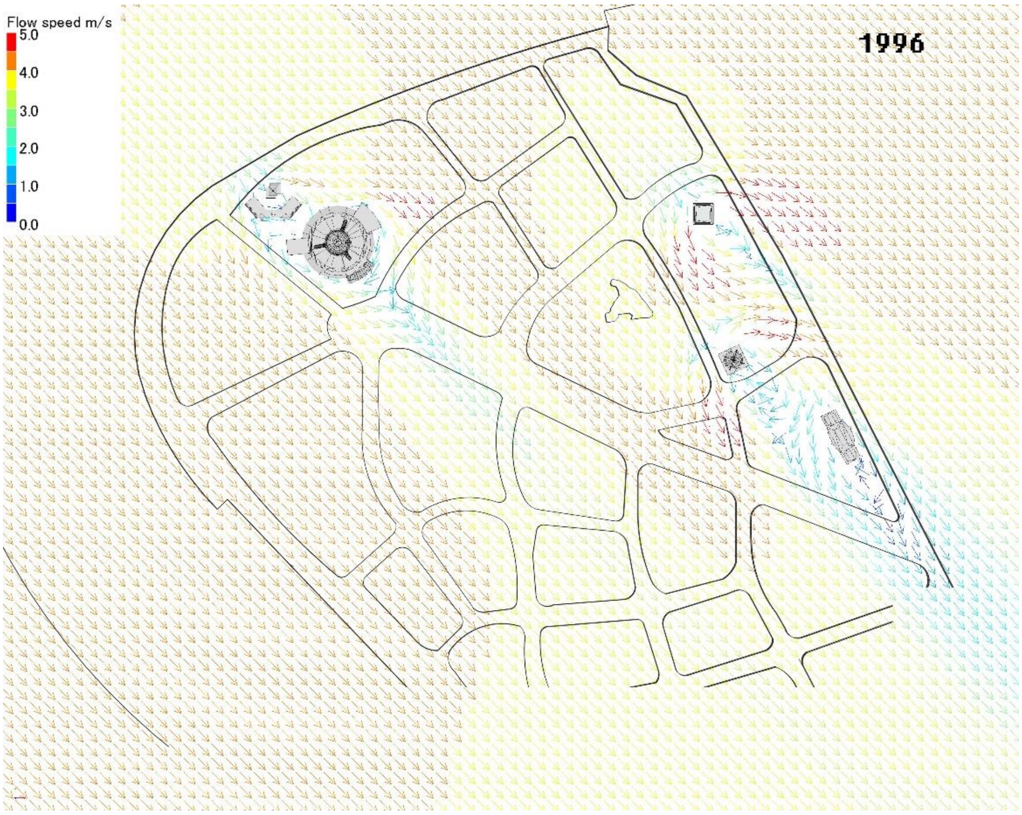

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2005

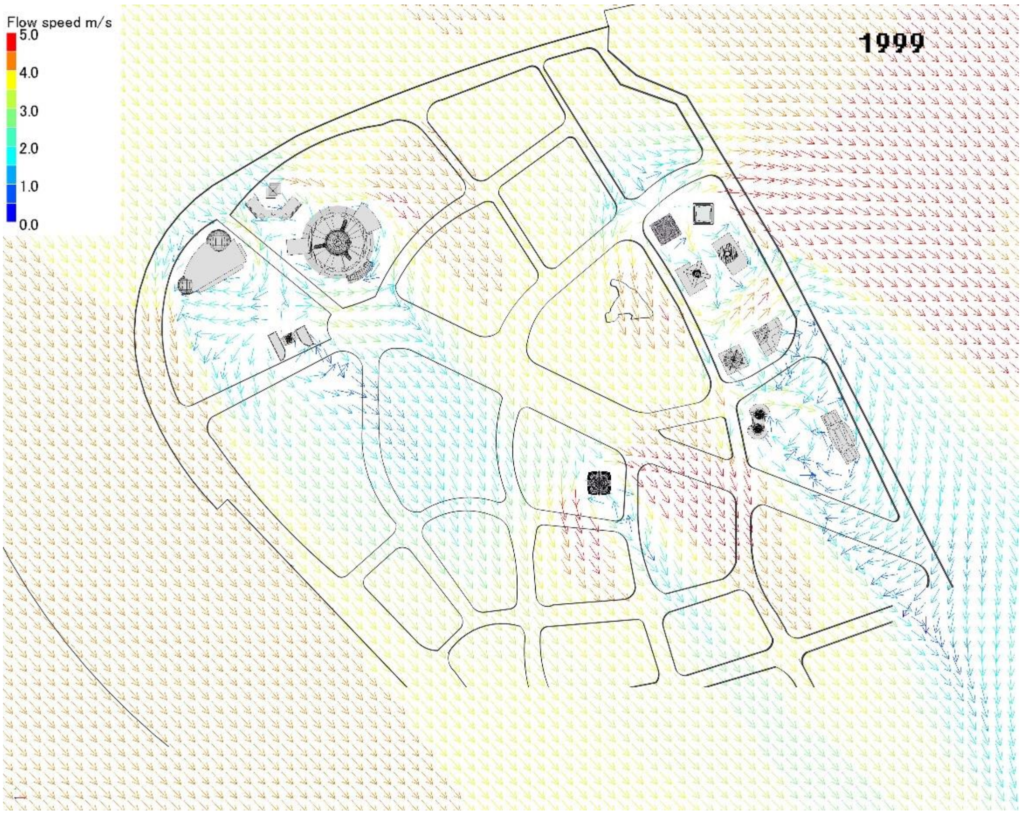

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2008

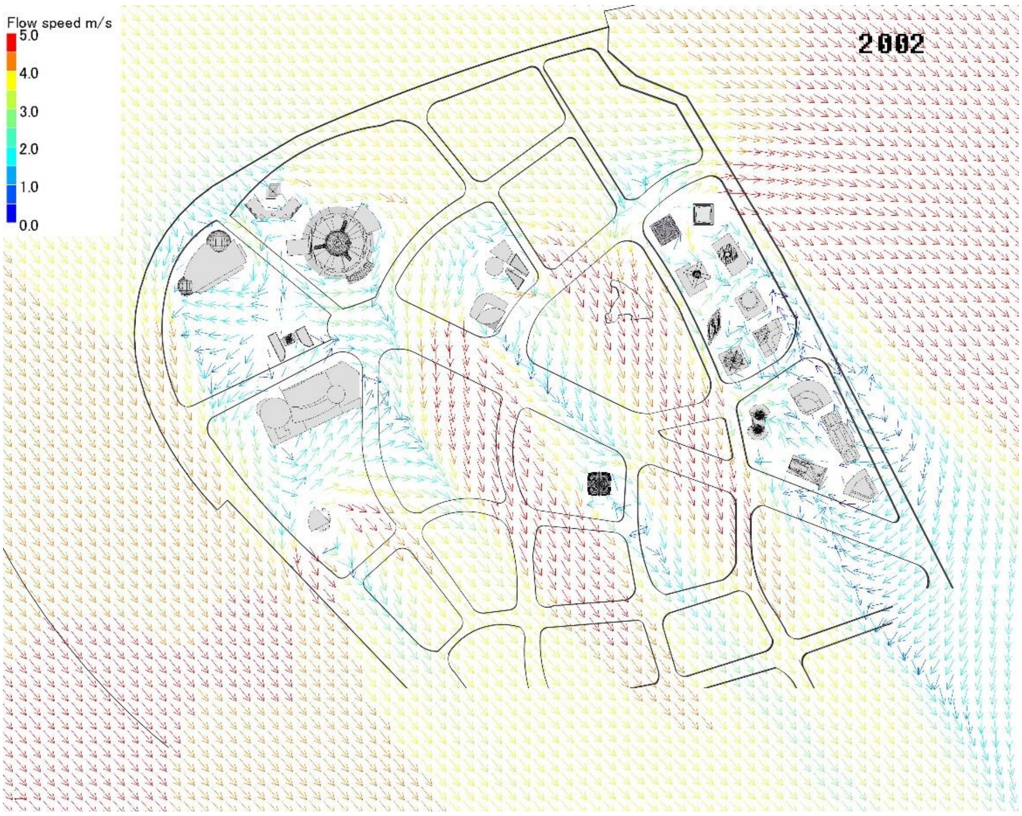

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2011



Appendix 5.5 Outdoor wind flow with wind direction at NW

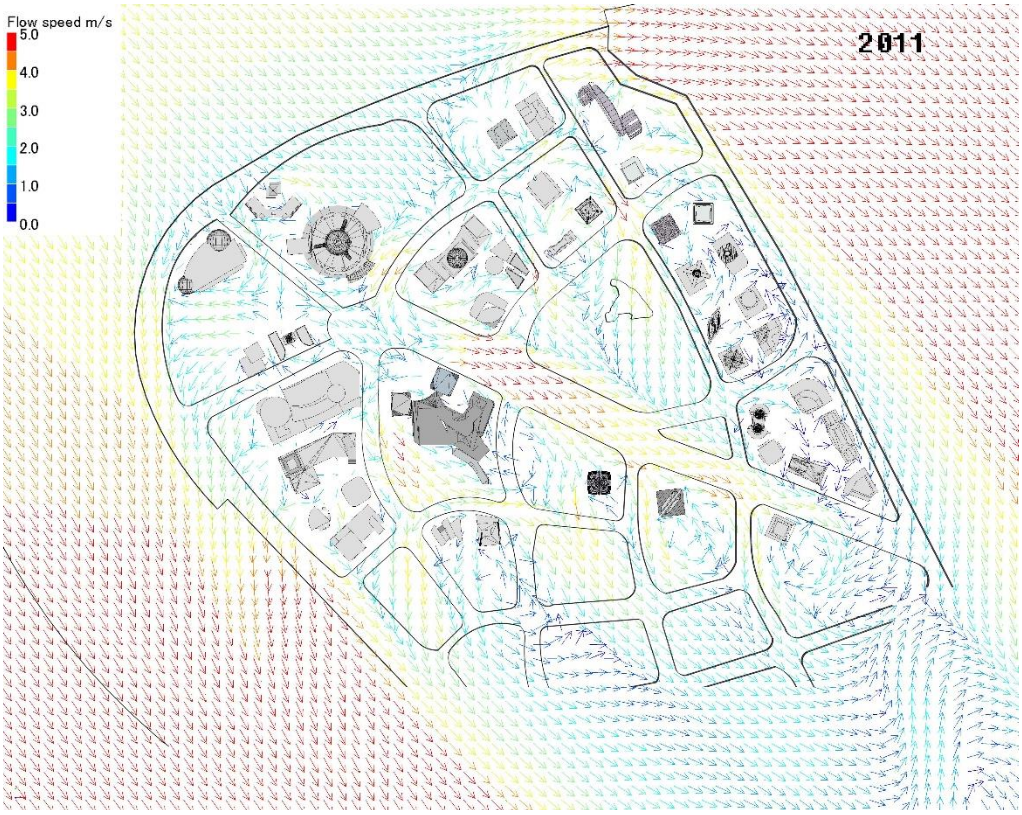


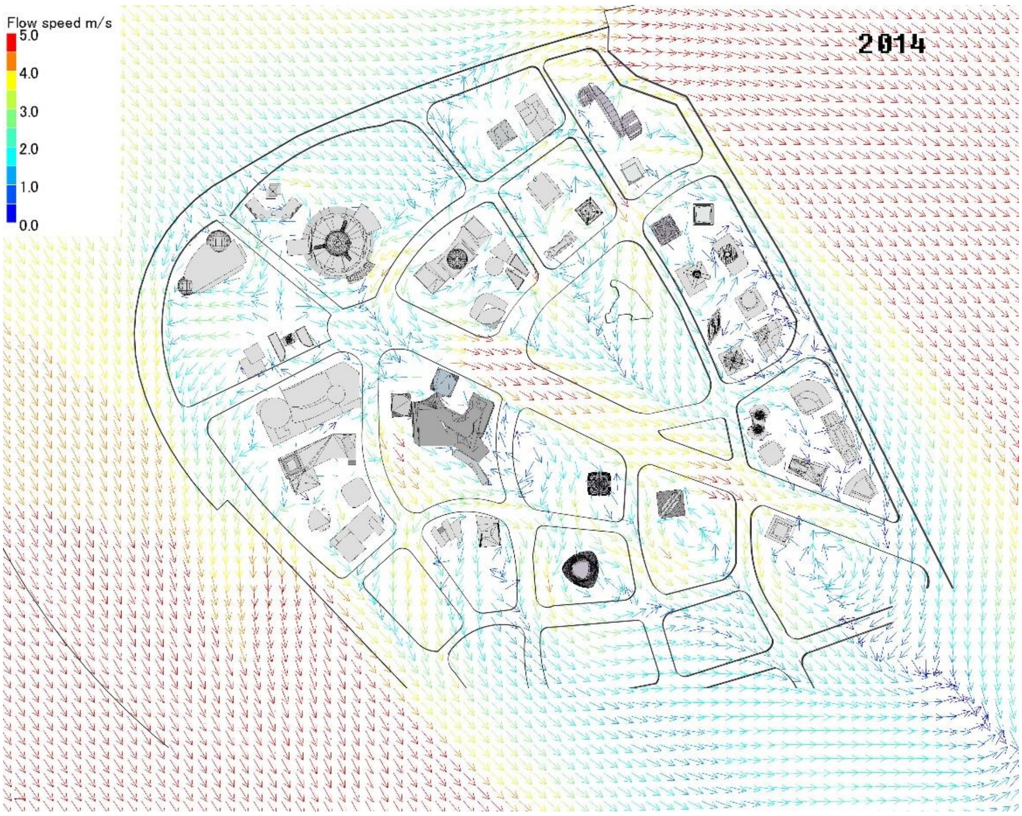

Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
1999


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2002


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2005


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2008


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2011


Flow speed m/s
5.0
4.0
3.0
2.0
1.0
0.0
2014