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Optimized Open Space Design for Spatial Behavior based on Microclimate in Winter Cities

北方都市における空間利用行動のためのオープンスペースデザイン最適化手法の構築

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Abstract

Over the past few decades, the pursuit of urban life quality is increasingly important. How to create outstanding open space which satisfy different requirements of outdoor activities and create relatively comfortable sensation become the focus of attention. A burgeoning number of studies have researched the relationship between outdoor thermal comfort and outdoor activities influenced by microclimate as a goal in urban planning and design. However, almost of all the research were conducted at the warmer area with hot and humid conditions. Only few have focused on extreme situations in both hot and cold seasons. In addition, microclimate, behavior and space design are characterized by a separation among climatologists, behavior researchers and designers. It is also unrealizable to apply the research results to the space design because of the gap created by the interdisciplinarity.

Therefore, this study chooses the downtown central open space in northern China with extreme temperature difference during summer and winter and northern Japan with heavy snow and low temperature during cooling period to research the open space design. From microclimate perspective, taking people's comfort and spatial behaviors as criterions, field survey and wind simulations are used to discuss how the open space forms affect microclimate, thus affect comfort sensations and spatial behaviors. Optimized open space design guidelines are also put forward based on the above research.

The thesis consists 7 chapters as following:

Chapter 1 gives a general introduction about the research background including the definition and the classification of open space, the important role of open space in urban area, the research scale of urban microclimate and spatial characteristics of street canyon. Current research, development direction on such topics and the originality of this research which explain orientation of this thesis are presented in this chapter. Winter city is the main topic introduced in this chapter on dealing with the relationship between open space design and human behavior to pursue desirable outdoor open space in cold area.

Chapter 2 introduces the urban conditions in Shenyang and Sapporo, including geographical locations, climate characteristics, urban structures, and the reason for selecting these two cities on open space research. Shenyang has long severely cold

winter, relatively short summer and huge annual temperature range. Sapporo has long cooling period in the early and late winter. Since many similarities like locations, climate characteristics, living habits and different characteristics like urban layouts, spatial scales can be realized, these two winter cities have representative and typical research value for this thesis.

Chapter 3 figures out how the open space forms affect microclimate, thus affect comfort sensations and spatial behaviors by taking people's comfort and spatial behaviors as criterions in hot summer and cold winter in public open space in Shenyang. Results shows that microclimate obviously affected people's comfort. In hot season, shade and air-flow play crucial roles in outdoor comfort. People tend to stay outside in the shade and the area with higher air velocity. After sunset is popular period for outdoor activities. In cold season, at the same ambient temperature, lower air velocity will raise the comfort level. Shade also has influences on comfort sensation but do not affect spatial behaviors significantly.

Chapter 4 clarifies the relationship between outdoor environmental conditions and the behaviors of people in outdoor public spaces in three public spaces and analysis of the microclimate and sitting behaviors in these space during the cooling period (8 - 20 degree centigrade) in downtown Sapporo. At air temperature higher than 20 degree centigrade, the outdoor environment do not affect the spatial behaviors. At temperatures below 8 degree centigrade, almost no sitting behaviors are observed. Increasing sunlight and reducing the wind can extend the duration of use of outdoor public space during the cooling period in winter cities.

Chapter 5 conducts the wind tunnel and CFD (computational fluid dynamics) simulations to evaluate the open space in Shenyang and several assumptions about canyon orientation and building types are proposed. Depending on the results, figuring out the prevailing wind directions during hot and cold periods in a monsoon climate city and making the winter wind direction perpendicular to the main street will significantly improve wind comfort. The urban layouts which affect wind situation at pedestrian height are found to cause five types of airflow as followings: (1). Wind shadow area with native pressure created by high-rise buildings will reduce the wind speed at pedestrian height. (2). The skyway acted as a wind diverter causes the increased air velocity to under it. (3). Funnel effect formed by narrow street with buildings running continuously along both sides causes the accelerated air velocity. (4).

Roofs can resist head wind to create lower wind speed at pedestrian height. (5). The streamlining of the building edges changes the air duct area and causes a higher wind speed at the narrow section.

Chapter 6 indicates the climate-responsive open space approaches. The suitable outdoor microclimate situation and activity time during hot summer, cold winter and cooling period are clarified. Combining with the results of field surveys and wind simulations, this chapter gives comprehensive conclusions on how the open space forms affect microclimate, thus affect comfort sensations and spatial behaviors. In the research area, funnel shape entrance and skyway will bring higher wind speed, thus make people feel comfortable in summer. Building corners, high-rise and low-rise building groups will reduce the wind speed resulting higher comfort sensation in winter. The roof and podiums can also resist the head wind. Shade formed by roof , building structures and landscape facilities will make the open space attractive.

Chapter 7 proposes optimized open space design guidelines from the general perspective to specific design details with examples. First, thinking mode of open space evaluation is put forward. Secondly, the optimization street canyon layout including ideal type, orientations and desirable microclimate situations are introduced. Based on the above proposals, specific design methods are given from 3 aspects as followings: (1). In the wind and buildings part, the wind situations of isolated high-rise building and building groups, channeling effect, downwash effect, stepping effect are clarified. (2). In the human and open space part, the paths of outdoor activities and the spatial scale should be noticed during the open space design. (3). In the human and environment part, design strategies with comfortable microclimate creation, landscape facilities arrangement like roofs, skyways, sun rooms, waterside and vegetation are introduced with several examples to explain the guidelines.

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1. Introduction: research background, purposes and framework

1.1. Research background

1.1.1. Definition of open space

Space is mainly formed by the relationship between objects and people who feels the objects. The outdoor space comes from the limitation of continuous natural space. This space limitation is called “positive space”, it is created for satisfying the intention and function from users. In the profession of architecture, this outdoor space can be defined as “architecture without roofs”, that is, land is realized as the architecture, the indoor space is with roofs and the outdoor space is without roofs [1].

Urban space can be defined as the interspace formed by buildings in city. This space is restricted by different facades of buildings. The definiteness of the geometric and aesthetic feature of the space makes people understand that this kind of outdoor space is urban space [2].

Public open space is a social space that is generally open and accessible to people. Roads (including the pavement), public squares, parks and beaches are typically considered public space [3].

The open space in this research can be defined as the public place is not regard transportation as the only object and service for universal citizens. The open space affected by natural factors, like meteorological environment can be judged the quality by people's feedback including comfort sensation and spatial behavior.

1.1.2. Important role of open space in urban area

Open space that accommodate the daily social activities of both pedestrians and stationary people play an important role in cities. The goals of open space design are gradually evolving toward attracting more people to stay outside door and enhancing the spatial utilization [4-7].

The outdoor open space together with the indoor space compose the subject of space of city life. As people's health awareness gradually strengthened, growing number of people arrange their leisure time in the outdoor space. At the same time, various types of outdoor activities appear on the outdoor space. City parks, square and wide city streets gradually become the main place for people's activities after work and dinner. People choose such kinds of place for exercise and fitness, buying and selling, and to communicate with others.

A good open space should not only provide suitable place for citizens to play outside, but also accommodate various possibilities of activities.

1.1.3. Open space classification based on the architectural typology

From the building morphological types, Robot Krier mentioned 4 types of space in his book "*Architectural Composition (1988)*" (Fig. 1-1), they are circles, squares, triangles and irregular shapes. After a series of logical transformations, innumerable variations of spatial

types are generated. The conversion logical of space are al following: addition, penetration, bucking, breaking, accentuation of the perspective and effect of depth and distortion [8].

In the book "*Urban Space (1979)*", Krier believes that the composition of streets and squares, and the interrelationship between them determines the scale and the geometric properties of the urban space. The square is the first way humans use the city, which can be defined as the open space which is surrounded by houses and providing enough interior space to effectively contain barriers to external disturbances [9]. Streets are an important part of the urban space that connects each element of city. In the two elements of streets and squares, Krier categorized urban space in his "Practical Typology" theory (Fig. 1-2).

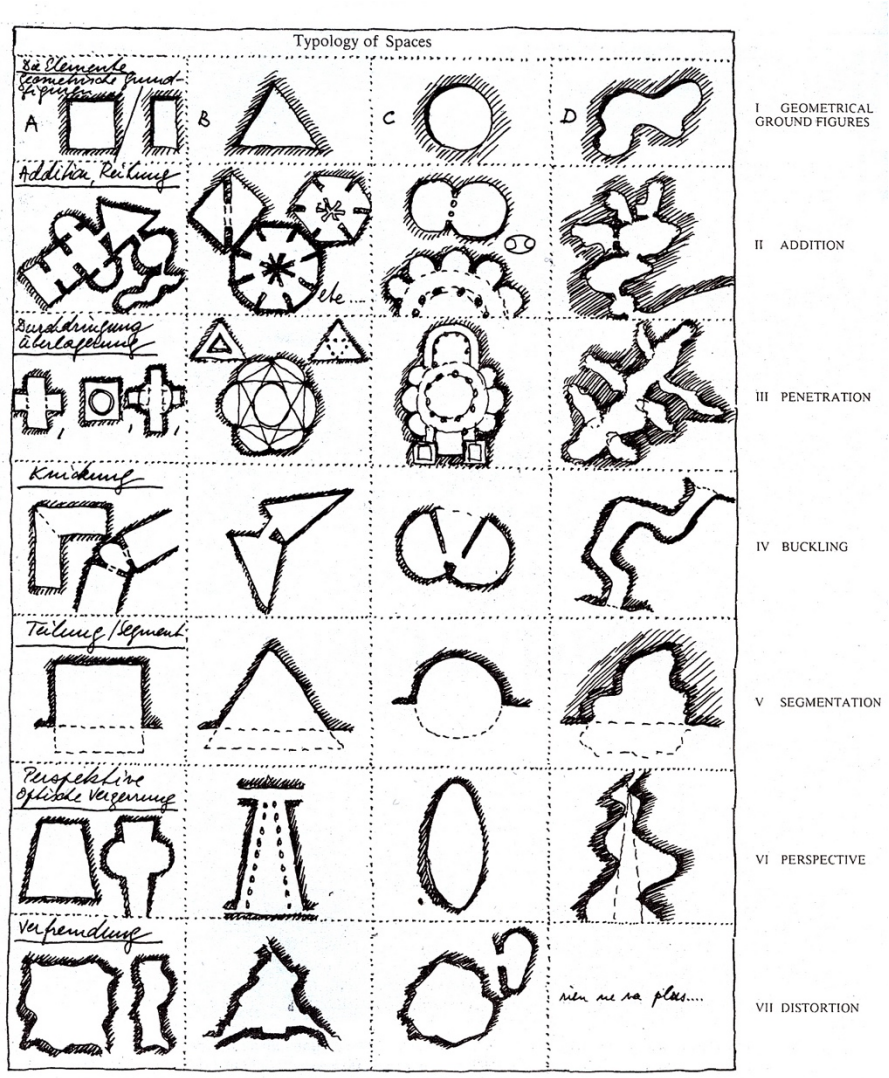


Figure 1-1 Typology of Space, R Krier [8] (revised by author)

While R. Krier modestly argues that this is only the tip of the iceberg of human creative thinking, the large number of examples shows that his theory is extremely broad, very universal and plays a crucial role in the morphological understanding of open space.

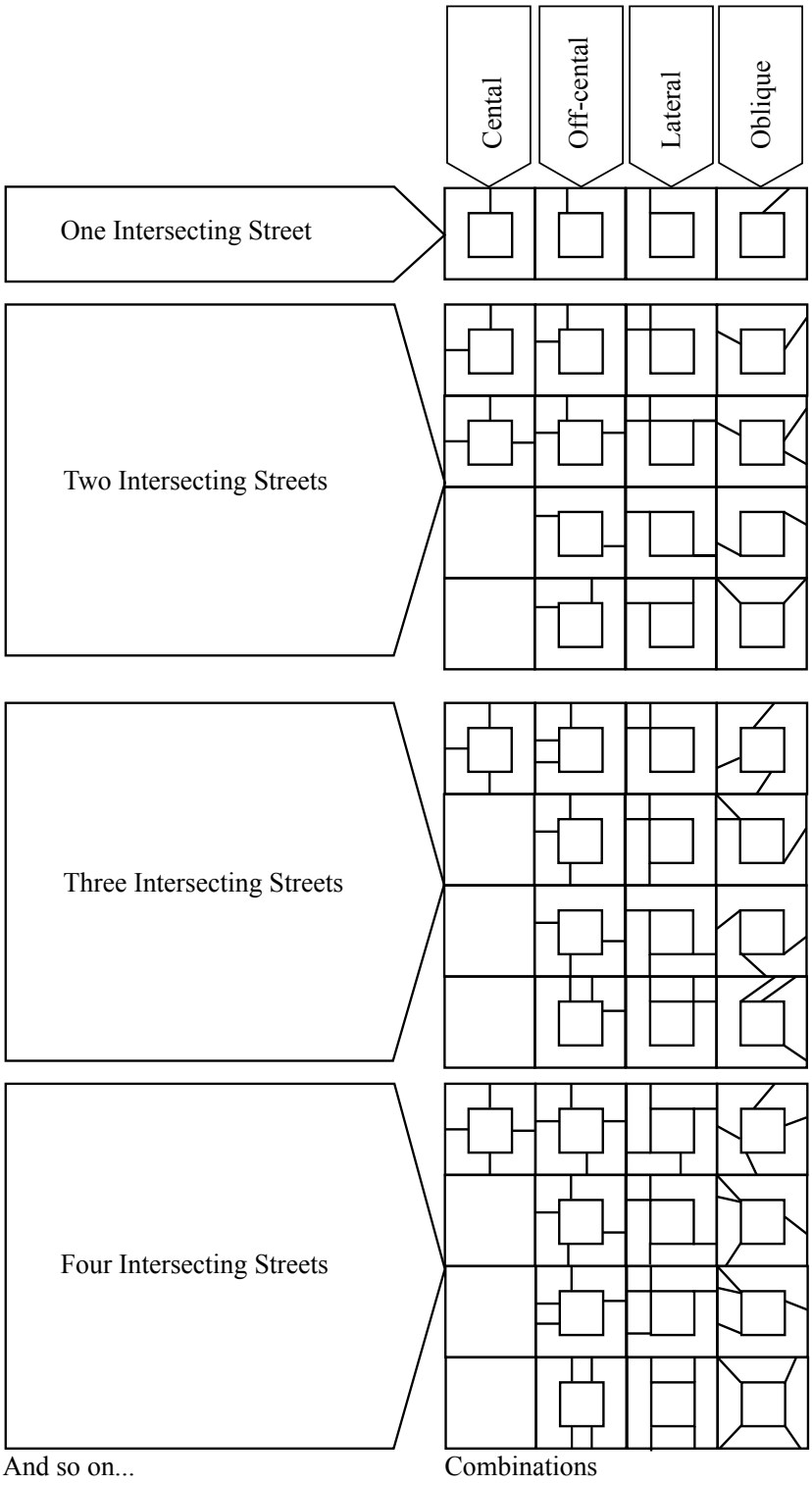


Figure 1-2 Typology of the intersection of the street and square[9] (revised by author)

Marcus & Francis (1998) classified the types of city central open space as street squares, building entrances, urban oases, transportation squares collecting and dispersing, and large-scale public square [10]:

Street square is joined with pedestrian way and near the street, it occupies a small part of public open space. Sometimes, the street square is the appropriately widen parts of the pedestrian way. Sometimes, it is the extension of the pedestrian passage way next to the building. This kind of space is mainly used for resting a while, waiting for someone or watching.

Building entrance provide a nice-looking place for the people who will enter the building. Normally, although this is private place for the users of the building, generally it is open to public.

Urban oasis is defined as the square with large area of vegetation. It looks like a garden or a park. To separate from the city noisy and other activities, in most of cases, it is located at separate place far away from the street.

Transportation square is heavily used as multi-modal transport interchange for people collecting and dispersing.

Streets as a commercial centre for squares, pedestrians and buses, it is possible to play a role of plaza if streets are forbidden vehicles to pass by. The pedestrian mall is often located in the old town and consists of several contiguous blocks, entirely or mainly for walking.

Large public square is next to multiple land uses which can appeal to a wider audience and a wider variety of users. Such areas are generally larger and more flexible.

Street canyons can be considered one of the main types of urban space. The term “street canyon” refers to narrow street with buildings running continuously along both sides [11]. Urban canyons are an important and basic part of urban climatology and urban design [12-14]. The urban canyon is defined as the space composed of the street and its flanking buildings [15 16] and it can be classified into three types based on the aspect ratio (D/H): regular canyon (an aspect ratio of approximately 1), avenue canyon (aspect ratio < 0.5) and deep canyon (an aspect ratio of approximately 2) [17]. In most cases, the commercial zones are planned in a central area, densely populated and convenient

traffic area. These properties lead to its crucial status in the overall city. For the design study based on people's sensation and behavior, researching the commercial area always has more obvious applications and value because of its abundant samples and leading role of outdoor life for people [18].

1.1.4. Microclimate and space

Man-made space is the resistant result of natural environment by people. Different regional climate conditions bring up different human culture with colorful space types. The man-made space was given the basic function of resisting severe natural environment. The human community built by buildings is incessantly responding the influence from the natural environment by climate conditions. Ralph Erskine pointed out that, "*Without climate issues, people do not need buildings anymore.*" [19].

The terminology "*micro-climate*" first appeared in the 1950s in publications such as "*Climates in Miniature: A Study of Micro-Climate Environment* (Thomas Bedford Franklin, 1955)" [20].

From the American Heritage Science Dictionary, the definition of microclimate is "*The climate of a small, specific place within a larger area. An area as small as a yard or park can have several different microclimates depending on how much sunlight, shade, or exposure to the wind there is at a particular spot.*" [21] Among many factors that determine the quality of outdoor space.

1.1.5. Microclimate scale in urban space

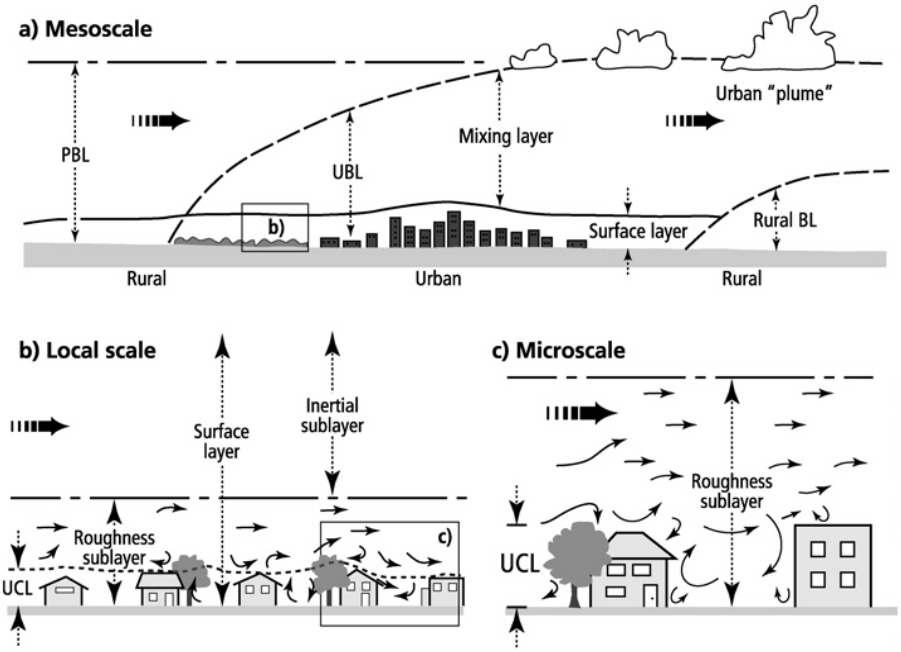


Figure 1-3 Schematic of the urban boundary layer including its vertical layers and scales. 'UBL' stands for Urban Boundary Layer, and 'UCL' for Urban Canopy Layer (revised by Oke and Rotach after a figure in Oke, 1997 [22]).

Urban boundary layer（UBL）can be realized as whole part of the lowest atmosphere which is affected by the surface feature of the established terrain in urban environment (Fig. 1-3 a). In general, UBL is about ten times higher than established terrain.

In the UBL, from top to button in turn are the "mixed layer" and "surface layer". In the surface layer, from the top to button are "inertial sub-layer" and "roughness sub-layer". The lowest part in the roughness sub-layer is the "Urban canopy layer (UCL)".

In the mixed layer, the atmosphere activities affected by the urban surface, but do not reflect urban surface form. Mixed layer also affected by the atmosphere stability factor and the magnitude of the urban effect.

The surface layer located at the 4 to 5 times of the height from ground to buildings average height (Fig. 1-3 b). It forms from the surface with urban properties where the air flow by. The surface with urban properties include the roughness created by the sharp edge of

the city and the hot air flow produced by the city. The vertical profile of wind speed follows a systematic logarithmic in this layer.

Roughness sub-layer is the lowest atmospheric layer immediately adjacent to a surface covered with relatively large roughness elements such as stones, vegetation, trees, or buildings. The roughness sublayer extends from the surface up to about two to five times the height of the roughness elements and includes the canopy layer.

Urban canopy layer (UCL) (Fig. 1-3 c) is the layer of air in the urban canopy beneath the mean height of the buildings and trees. Its climate is dominated by microscale processes due to the complex array of surfaces (their orientation, albedo, emissivity, thermal properties, wetness, etc.). It is a zone of multiple reflection and emission, wakes and vortices, especially in the urban canyons.

Because of the inherently multidirectional of UCL, unique microclimate condition will establish in any given urban space. The air temperature, air flow, radiation balance and other climate factors are affected by physical condition and regional environment of urban environment. This research is on the basis of this space layer.

1.1.6. Microclimate and people

People's sensation is significantly affected by the microclimate when they are directly exposed to the outdoor environment.

The heat balance of a human can be used to explain and evaluate the people's sensation affected by the microclimate. Fanger first conducted that the thermal comfort is depended on the mean skin temperature ($\overline{T}_{sk}$) and sweat rate which related to the activity level. [23] The energy budget equation developed from the principle of heat transfer and human physiology was created by Hoppe called Munich Energy-balance Model for Individuals (MEMI) [24]. It defined as the balance of the human thermal maintained by skin temperature, core temperature and sweat rate.

It can be written as:

$$M+W+R+C+E_D+E_{Re}+E_{Sw}+S=0 \quad (1)$$

where M is the metabolic rate (internal energy production by oxidation of food), W is the physical work output, R is the radiative exchange, C is the major energy streams being convective heat loss, E_D is latent heat flow to evaporate water into water vapor diffusing through the skin (imperceptible perspiration), E_{Re} is the sum of heat flows for heating and humidifying the inspired air, E_{Sw} is the heat flux due to evaporation of sweat, S is the storage heat flow for heating or cooling the body mass.

In the Eq.1, all the physical factors will affect the heat exchange through the skin surface [25].

The other way of thinking the energy balance of a human being in an urban space is the radiation which can be realized as a highly variable, often dominant and component of the energy balance in urban open space. The total net exchange of radiation R_n between human being and urban space can be written as [26-28]:

$$Rn=(K_{dir}+K_{dif}+K_h+K_v)(1-\alpha_s)+L_d+L_h+L_v-L_s \quad (2)$$

Where K_{dir} is the direct short-wave radiation incident on body, K_{dif} is the diffuse short-wave radiation incident on body, K_h is the indirect radiation incident on body, reflected from horizontal surfaces, K_v is the indirect radiation incident on body, reflected from vertical surfaces, α_s is the albedo of skin or clothing, $1-\alpha_s$ is the proportion of all incident short-wave radiation that is absorbed by the body, L_d is the long-wave radiation incident on body, emitted downwards by the sky, L_h is the long-wave radiation incident on body, emitted by horizontal surfaces, L_v is the long-wave radiation incident on body, emitted by vertical surfaces, L_s is the long-wave radiation emitted by body to environment.

A number of biometeorological indices have been developed to describe human thermal comfort level by linking local microclimatic condition and human thermal sensation [29]. Most of these studies conducted based on the thermal balance conditions between human bodies and outside environment by exposing the human body in the

outdoor environment for a relatively long time. This type of research on the relationship between microclimate and human body is called “Steady-state assessment methods”. The biggest problem with this type of research is that the dynamic processes that the body adapts to the thermal environment cannot be described. Research built outside the above hypothetical states is called “Non-steady-state assessment method”.

Predicted Mean Vote Index (PMV) [30] is the average thermal comfort feedback indicators based on a large number of experiments. It has seven levels, and was applied to ISO1994 [31]. They are +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, 1 = slightly cool, 2 = cool, 3 = cold.

In generally, it is used to evaluate the indoor environment, it is also used on the outdoor environment evaluation and confirmed by many case studies [32-34].

The Physiological Equivalent Temperature (PET) [35] is a thermal comfort index based on degrees Celsius as rulers and units. It is easy to be understood by people without relative knowledge. PET is based on the Eq.1, it evaluates the complex outdoor environment factors equivalent to the simple indoor thermal balance, and then, making the PET indicator can be used in outdoor environments. PET and MEMI have been used in many studies [36-40].

1.1.7. Winter City: General information and the necessity of study

The city located in the cold region can be realized as “winter city” which is widely accepted was defined by the WWCAM (The World Winter Cities Association for Mayors) as one that faces harsh winter climatic conditions, including heavy snowfalls and cold temperatures (Fig. 1-4). A winter city also has an annual snow accumulation of more than 20cm (8in.) and an average temperature of 0°C (32°F) or below during the city’s coldest month [41].

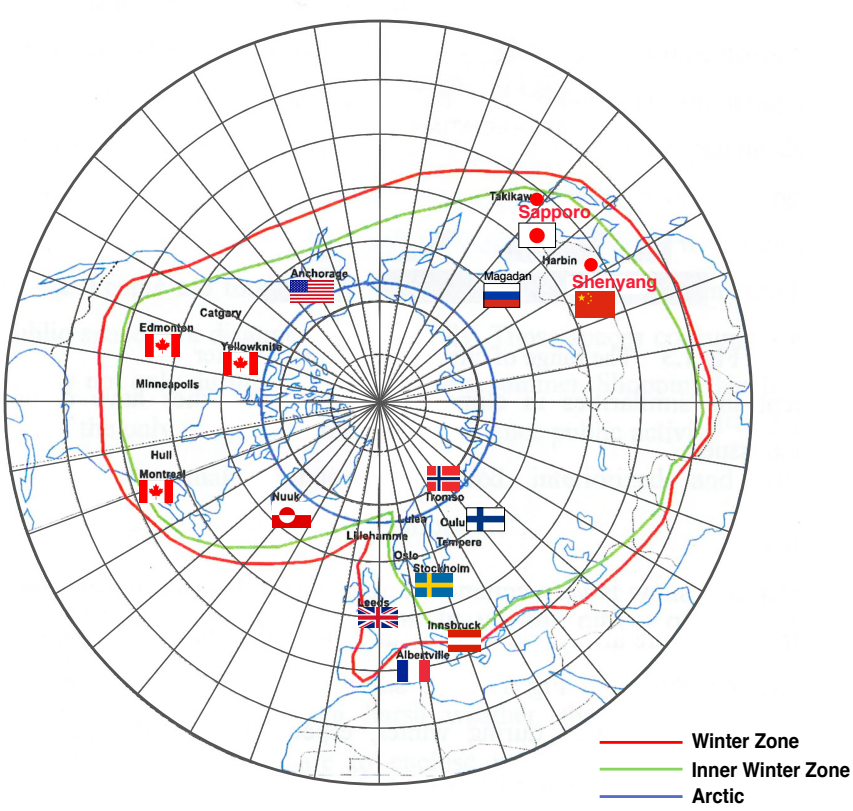


Figure 1-4 World Winter Cities [42 43](revised by author)

Aiming at the development policies and landscape planning based on severe and extreme microclimate, Pressman N (1985, 1988) [44 45] defined winter city as those exposed to prolong period of cold temperature (normally below freezing), precipitation (usually in the form of snow and where water is frozen), restricted hours of sunshine / daylight, and which experience seasonal variation.

Figure 1-5 Building Climate Zoning Map in China [46](revised by author)

In China, seven climate subareas are divided for urban and architecture design (Fig. 1-5). All the winter cities in China are belong to the Area I where suffer a long severe cold winter and relative short summer, the humidity become lower from the east to west in winter [46]. The annual temperature range is relatively lower than other areas, however, there are also several weeks in summer which suffer high temperature [47]. Depends on those differences, there are obvious different usages of open space between summer and winter. Also, for the open space design, there are great relationships between the microclimate and people's reaction including sensation and behavior in an urban open space, especially in the extreme weather situation.

Winter cities often have unique geographical features because of their different climate characteristics. It is obviously not sensible to treat winter cities with different climate characteristics simply by using common design methods. In terms of basic functions, the designs of winter cities often need to consider the long-term winter cold climate and the large temperature difference between winter and summer. Coupled with the winter snow and ice roads, shorter daylight hours, rain and snow weather and other factors, it is determined that winter

cities must be far more complicated in design language than general urban design.

An important part of people's perception of the city comes from the urban space that is felt from outside. Whether a city is safe, comfortable, ideal, or aesthetically pleasing depends to a large extent on people's judgment of various urban space qualities. On the basis of space design, the observable elements of the city that can directly affect people's senses are microclimates, including temperature, humidity, airflow and sunlight. For winter cities, the negative effects of microclimate on people tend to dominate the mainstream under extreme climate conditions (too cold or too hot). For urban design of winter cities, on the basis of satisfying the basic urban space design requirements, under extreme climate conditions, how to improve the negative impact of microclimate on people through design means will be particularly important. A good urban open space aims to attract more users to stay longer. In the open space design of winter cities, we should not have to struggle against climate. Instead, we must form alliances with it.

1.2. Originality of this research

On the basis of spatial types in the urban canyon, the microclimate undergoes complex changes, thus affecting outdoor activities dramatically. In the book "*Life Between Buildings: Using Public Space*'', Gehl (1971) [48] firstly studied the influence of microclimate on outdoor activities by counting people sitting on sunny and shady benches has been conducted. The research shows that the local sunny or shady conditions significantly impact the desire of people to either stay or leave.

Over the past few decades, a burgeoning number of studies have researched the relationship between outdoor comfort and activities influenced by microclimate as a goal in urban planning and design (Carr, et al., 1993 [49]; Marcus & Francis, 1998 [10]; Gehl & Gemzøe, 2004 [50]; Maruani & Amit-Cohen, 2007 [51]).

1.2.1. Macroclimate and people

Most of the relative studies tend to research about the relationship between microclimate and people's sensation. In generally, such studies are often conducted in hot and humid areas, and few studies are conducted in sub-zero temperatures. Even if such research is carried out in a specific urban space, few studies will use spatial design improvement as the ultimate goal of research. They tend to focus on the changing patterns between thermal sensations of people and the measured microclimate data.

Many applications on the topic of urban climatology have yielded in various climates situation around world. Ahmed, K. S. (2003) [52] researched on outdoor comfort based on field investigations conducted in Dhaka, a city in the wet-Tropics. The findings include factors affecting comfort outdoors and a comfort regime based on environmental parameters for urban outdoors is presented.

By conducted the field surveys of microclimatic and human monitoring in 14 different case study sites, across five different countries in Europe. Nikolopoulou & Lykoudis, 2006 [53] studied the environmental and comfort conditions of open spaces in cities. The findings confirm a strong relationship between microclimatic and comfort conditions, with air temperature and solar radiation being important determinants of comfort, although one parameter alone is not sufficient for the assessment of thermal comfort conditions.

By summarizing an extensive literature review on outdoor comfort studies and human test in an open plaza in Hong Kong, Cheng, et al. (2006, 2010) [37 32] developed guidelines for urban Hong Kong based on the outdoor thermal sensation which is presented as functions of air temperature, wind speed, solar radiation intensity and absolute humidity. For a person in Hong Kong where the air temperature is about 28°C and relative humidity about 80%, a wind speed of about 1.6 m/s is needed to achieve neutral thermal sensation.

To understand the relationship between people's declared bioclimatic comfort, their personal characteristics (age, origin, clothing, activity and motivation, etc.) and the atmospheric conditions, Andrade, et al. (2011) [54] conducted questionnaire surveys with weather measurements (air temperature, relative humidity, solar and long-wave radiation and wind speed) in two open leisure areas of Lisbon in Portugal. The preference for a different temperature depends on the season and is strongly associated with wind speed. Furthermore, a general decrease of discomfort with increasing age was also found. Most people declared a preference for lower wind speed in all seasons; the perception of wind shows significant differences depending on gender, with women declaring a lower level of comfort with higher wind speed. It was also found that the tolerance of warmer conditions is higher than of cooler conditions, and that adaptive strategies are undertaken by people to improve their level of comfort outdoors.

Lai, et al. (2014) [55] conducted a field study on the relation between outdoor thermal comfort and space usage through the monitoring of microclimate conditions, interviews with residents, and recording of occupants' activities in an urban residential community in Wuhan, China. The results show that thermal comfort is the most important factor in the quality of outdoor space. Other significant factors include air quality, acoustic environment, functionality, and convenience.

1.2.2. Microclimate and open space

Several studies have proved that the open space layout greatly influence the shade situation in urban canyon, thus affecting comfort sensation.

Ali-Toudert & Mayer (2006) [36] discussed the contribution of street design in hot and dry climate area, i.e. aspect ratio (or height-to-width ratio, H/W) and solar orientation, towards the development of a comfortable microclimate at street level for pedestrians. The study revealed that the time and period of day, as well as the spatial distribution of PETs at street level, depend strongly on aspect ratio and street orientation.

Gulyas, Unger & Matzarakis (2006) [56] examined outdoor thermal comfort conditions through two field-surveys in Szeged. They found that the complex urban environments can result in very different radiation situation which cause changes in the thermal comfort sensation.

By study on the semi-arid climate area, Bourbia (2010) [57] found that the lower H/W ratio, the higher temperature were recorded either air or surface. The temperature can be reduced by controlling the sky view factor and inclusion of vegetation. Shade trees reduce heat gain by directly shading buildings and also by evapotranspiration.

Hwang (2011) [58] discussed the effects of shading on long-term outdoor thermal comfort and seasonal variation on six urban streets at tropical monsoon climate area in Taiwan. By using the PET index and RayMan model for simulation, the study found that the degree of shade which influenced by SVF will affect the thermal comfort significantly. Slightly shaded locations typically have high frequency hot conditions in summer, especially at noon. However, highly shaded locations tend to have a relatively lower PET in winter.

Andreou (2012, 2013, 2014) [59-61] conducted a series of research on shading analysis at the urban canyons in contemporary and traditional sites. Parametric shading analyses were carried out in order to examine the effect of parameters such as street geometry, height/width ratio, orientation and trees, on shading and solar access conditions, which affect urban canyon microclimate.

Shahrestani 2015 [62] presented an experimental study of microclimates for the low and middle rise building complex in London. The study revealed that the microclimatic parameters are significantly influenced by the attributes of urban textures and consequently, buildings within an urban area, are operating against their own individual microclimatic variables rather than the meteorological weather data.

1.2.3. Open space and spatial behaviour

Eliasson, et al. (2007) [63] investigated four urban public space, representing various designs and microclimates in Gothenburg, Sweden during four seasons to estimate how weather and microclimate affect people in urban outdoor environments. Multiple regression analysis of meteorological and behavioral data showed that air temperature, wind speed and clearness index (cloud cover) have a significant influence on people's assessments of the weather, place perceptions and place-related attendance.

Nikolopoulou and Lykoudis (2007) [64] presented that there is a strong relationship between microclimatic conditions and the use of open space, while there is also a difference in people's sensitivity to them. Observations of the use of space revealed that air temperature and solar radiation were found to be the most dominant parameters in relation to the use of space, with wind speed and relative humidity having a weak effect. Overall presence is reduced when air temperature rises significantly. The diurnal pattern of the use of space also reveals a strong dependency on meteorological parameters.

Thorsson, et al. (2007) [65] investigated the relationship between subjective thermal comfort and outdoor activity in a park and a square in a satellite city northeast of Tokyo. This study found that the use of the park was influenced more by the thermal conditions than by the use of the square, which can mainly be attributed to the different functions of the two places.

1.2.4. Winter research

However, almost of all the research were conducted at the area above 0 Celsius degree with hot and humid conditions.

As the concept of "Winter City" had been defined by Pressman in 1985 [44], the relative research began. Manty and Pressman (1988) firstly discussed about the relationship between urban design and climate in winter city at the book "*Cities designed for winter*"[66].

In the book "*Northern cityscape- linking design to climate*" [43], Pressman systematically discussed the uniqueness of winter cities and the corresponding measures and design methods for urban design in winter by providing detailed materials through a large number of examples.

Outdoor environment in winter due to its low temperature, low humidity, snowfall, strong wind and other objective reasons, it is generally not suitable for outdoor activities, resulting in the utilization of outdoor space in winter is significantly lower than other seasons. At the same time, there are few studies on the outdoor environment in winter. However, for the long winter in northern cities, outdoor activities play a vital role in the residents' lives, and the assessment of the environmental quality of outdoor space in winter also directly affects the evaluation of open space.

Therefore, the relationship between microclimate and people's reactions, including comfort sensation and spatial behaviors in urban canyon should be paid more attention, especially in cold weather.

Some open space research based on low temperature in winter shows as following:

Li (1994) [67] researched on small urban space in New York in winter to study the spatial behaviour influenced by climatic conditions.

Baruch (1998) [68] discussed the relationship among building, design, and climate, introducing design principles in different climate regions, broadly including cold regions.

Meng (2010) [69] provided open space design guidelines for downtown areas suffering strong winds and low winter temperatures by simulating various types of downtown, high-rise buildings in a wind tunnel.

Erell et al. (2012) [70] have provided new perspective on interaction between microclimate and urban landscape for architects and urban designers. Although, this research covered almost all the climate

theories using on the urban planning and design, there is only few theories can be used on the regions that suffer wide differences in temperature between summer and winter.

By using microclimate monitoring and interviews, Lai (2014) [71] conducted a field survey at a park in northern China revealed the relationship between human comfort and each parameter of boreal climate. Furthermore, this research estimated northerners' comfort level and cold-resistant level by multimethod.

Using wind and snow tunnel simulation and evaluation, Setoguchi et al. (2004, 2007, 2008, 2009) [72-75] and Watanabe et al. (2016) [76] discussed design procedures for winter cities, especially those suffering heavy snow. They discussed urban structures and building forms which are suitable for outdoor activities in cold season.

An outstanding open space should satisfy different requirements of outdoor comfort in different climate conditions. Other than the indoor space which can be created to satisfy the needs of the occupants, the outdoor space which affected by urban microclimate should be built by understanding the microclimate and should responds to them in appropriate ways [70].

Based on previous studies (Fig. 1-6), this study selected northern cities with significant temperature differences between winter and summer as research cases, and studied the extreme outdoor environments in summer and winter. This study analyzes the use of the same outdoor environment in different seasons. Through the observation and inquiry of spatial behavior, the subjective feedback of the objectively measured microclimate is obtained. Based on results of feedbacks, the wind simulation is performed. This study also attempts to optimize the design of outdoor space where suffered hot weather in summer and cold weather winter.

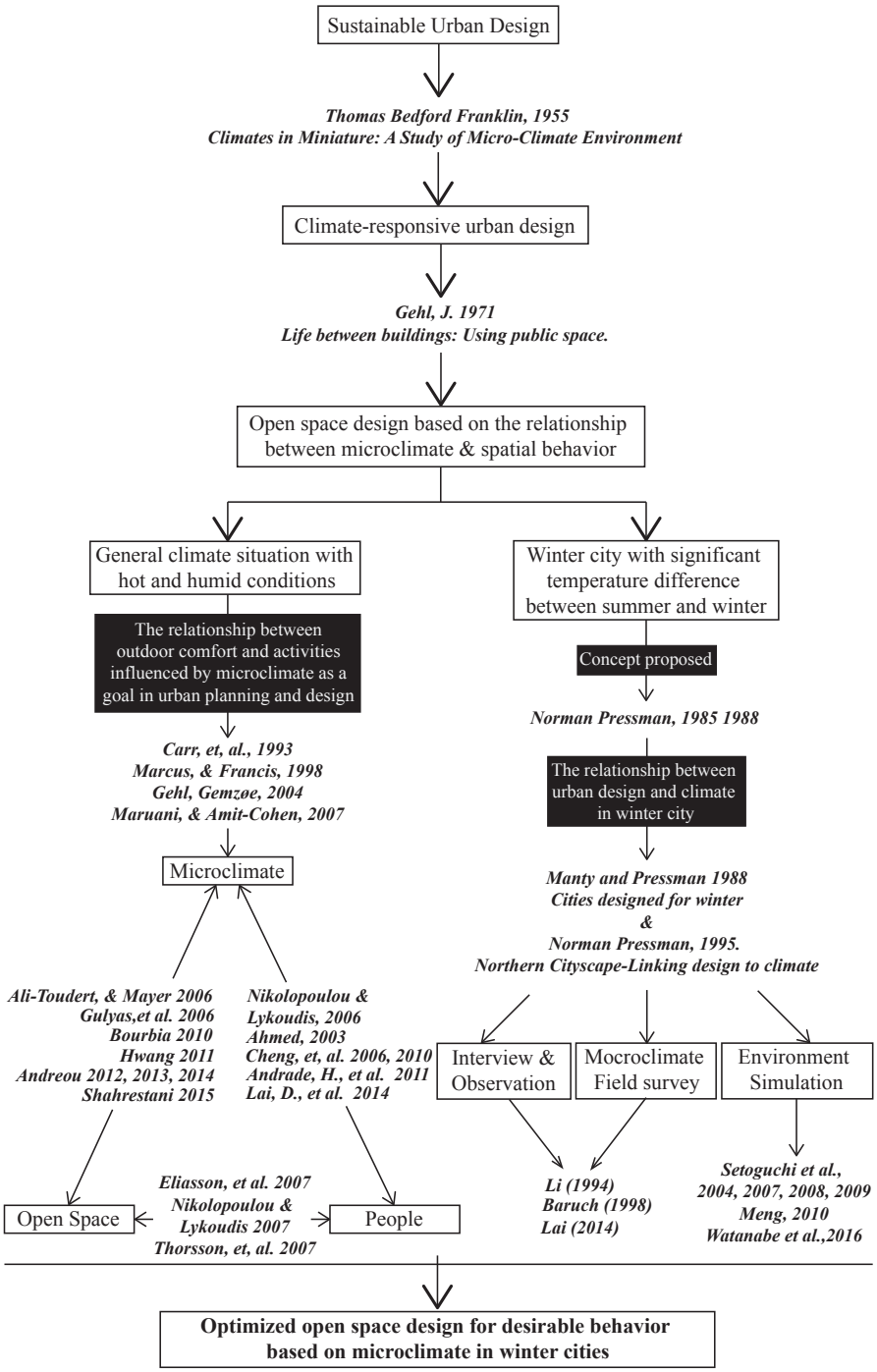


Figure 1-6 The originality of this research

1.3. Research purpose, methodology and research structure

By using people's sensation and spatial behavior as the standards to evaluate the open space, this research discusses about open space design which will affect the people's sensation and behavior significantly and how to prevent the bad situation on hot summer, cool period and cold winter. According to the results, this thesis provides

optimized open space design guidelines for desirable behavior based on microclimate.

This study selects the typical downtown open space in northern China and northern Japan. By using the microclimate measurement, environmental feedback and spatial behavior observation this research evaluate the environmental characteristics and the open space design of the target sites.

On the basis of the prevailing air velocity and directions in both summer and winter in this area, a wind tunnel simulation was conducted on the Chinese case, the results from which informed a proposal for optimum street alignments and building types. By analyzing the results, the reasons for the wind changes in the area were found.

CFD simulation was also used for the wind tunnel simulation to check the wind paths. However, as the reliability and accuracy of CFD simulation have been questioned [77], in this study, the CFD simulation was set with the same conditions as the wind tunnel simulation only to check the wind path as a reference for the wind tunnel simulation. Using the above research design, this paper developed design guidelines and research methods for public spaces in colder climates. Finally, the climate-responsive urban design approaches and optimization open space design guideline were conducted .

The thesis consists 7 chapters shows in Fig. 1-7.

Chapter 1 gives a general introduction about the research background including the definition and the classification of open space, the important role of open space in urban area, the research scale of urban microclimate and spatial characteristics of street canyon. Current research, development direction on such topics and the originality of this research which explain orientation of this thesis are presented in this chapter. Winter city is the main topic introduced in this chapter on dealing with the relationship between open space

design and human behavior to pursue desirable outdoor open space in cold area.

Chapter 2 introduces the urban conditions in Shenyang and Sapporo, including geographical locations, climate characteristics, urban structures, and the reason for selecting these two cities on open space research. Shenyang has long severely cold winter, relatively short summer and huge annual temperature range. Sapporo has long cooling period in the early and late winter. Since many similarities like locations, climate characteristics, living habits and different characteristics like urban layouts, spatial scales can be realized, these two winter cities have representative and typical research value for this thesis.

Chapter 3 figures out how the open space forms affect microclimate, thus affect comfort sensations and spatial behaviors by taking people's comfort and spatial behaviors as criterions in hot summer and cold winter in public open space in Shenyang. Results shows that microclimate obviously affected people's comfort. In hot season, shade and air-flow play crucial roles in outdoor comfort. People tend to stay outside in the shade and the area with higher air velocity. After sunset is popular period for outdoor activities. In cold season, at the same ambient temperature, lower air velocity will raise the comfort level. Shade also has influences on comfort sensation but do not affect spatial behaviors significantly.

Chapter 4 clarifies the relationship between outdoor environmental conditions and the behaviors of people in outdoor public spaces in three public space and analysis of the microclimate and sitting behaviors in these space during the cooling period (8 - 20 degree centigrade) in downtown Sapporo. At air temperature higher than 20 degree centigrade, the outdoor environment do not affect the spatial behaviors. At temperatures below 5 degree centigrade, almost no sitting behaviors are observed. Increasing sunlight and reducing the wind can extend the duration of use of outdoor public space during the cooling period in winter cities.

Chapter 5 conducts the wind tunnel and CFD (computational fluid dynamics) simulations to evaluate the open space in Shenyang and several assumptions about canyon orientation and building types are proposed. Depending on the results, figuring out the prevailing wind directions during hot and cold periods in a monsoon climate city and making the winter wind direction perpendicular to the main street will significantly improve wind comfort. The urban layouts which affect wind situation at pedestrian height are found to cause five types of airflow as followings:

(1). Wind shadow area with native pressure created by high-rise buildings will reduce the wind speed at pedestrian height.

(2). The skyway acted as a wind diverter causes the increased air velocity to under it.

(3). Funnel effect formed by narrow street with buildings running continuously along both sides causes the accelerated air velocity.

(4). Roofs can resist head wind to create lower wind speed at pedestrian height.

(5). The streamlining of the building edges changes the air duct area and causes a higher wind speed at the narrow section.

Chapter 6 indicates the climate-responsive open space approaches. The suitable outdoor microclimate situation and activity time during hot summer, cold winter and cooling period are clarified. Combining with the results of field surveys and wind simulations, this chapter gives comprehensive conclusions on how the open space forms affect microclimate, thus affect comfort sensations and spatial behaviors. In the research area, funnel shape entrance and skyway will bring higher wind speed, thus make people feel comfortable in summer. Building corners, high-rise and low-rise building groups will reduce the wind speed resulting higher comfort sensation in winter. The roof and podiums can also resist the head wind. Shade formed by roof , building structures and landscape facilities will make the open space attractive.

Chapter 7 proposes optimized open space design guidelines from the general perspective to specific design details with examples. First, thinking mode of open space evaluation is put forward. Secondly, the optimization street canyon layout including ideal type, orientations and desirable microclimate situations are introduced. Based on the above proposals, specific design methods are given from 3 aspects as followings:

(1). In the wind and buildings part, the wind situations of isolated high-rise building and building groups, channeling effect, downwash effect, stepping effect are clarified.

(2). In the human and open space part, the paths of outdoor activities and the spatial scale should be noticed during the open space design.

(3). In the human and environment part, design strategies with comfortable microclimate creation, landscape facilities arrangement like roofs, skyways, sun rooms, waterside and vegetation are introduced with several examples to explain the guidelines.

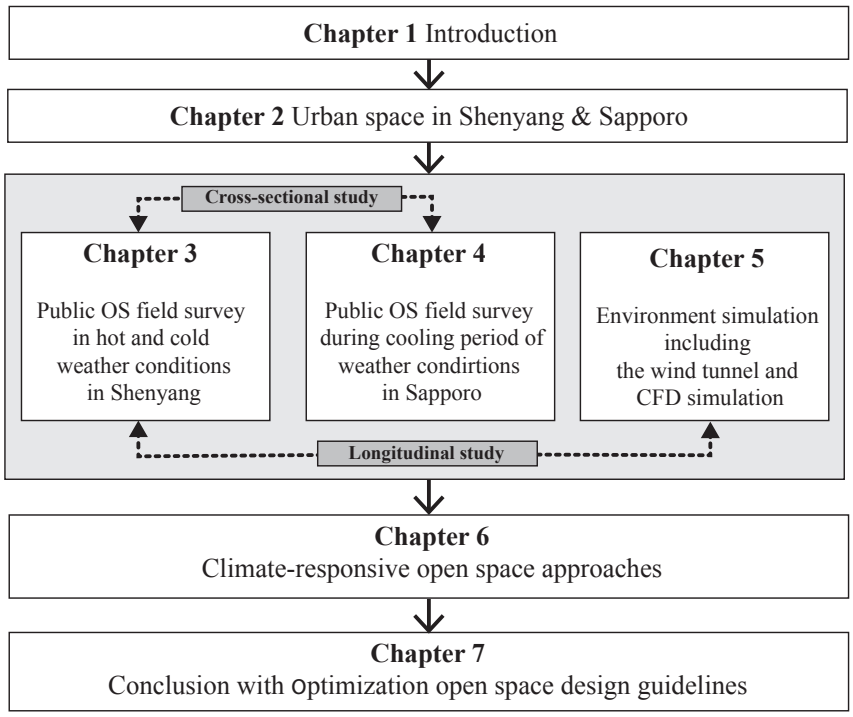


Figure 1-7 Thesis structure

1.4. Reference

[1] Toshinobu Ashihara. (1975). *Exterior Design in Architecture.* Tokyo: Shokokusha Publishing Co., Ltd.

[2] Krier, R., IBELINGS, H., GREENWOOD, F., & KRIER, K. (2003). *Town spaces.* Berlin: Contemporary Interpretations in Traditional Urbanism.

[3] Wikipedia. (2018, March, 17). *Public space.* Retrieved from https://en.wikipedia.org/wiki/Public_space

[4] Carr, S., Francis, M., Rivlin, L. G., & Stone, A. M. (1993). *Public space.* New York: Cambridge University Press.

[5] Marcus, C. C., & Francis, C. (Eds.). (1997). *People places: Design guidelines for urban open space*. New York: John Wiley & Sons.

[6] Gehl, J., & Gemzøe, L. (2004). *Public spaces, public life.* Copenhagen: Danish Architectural Press and the Royal Danish Academy of Fine Arts.

[7] Maruani, T., & Amit-Cohen, I. (2007). Open space planning models: A review of approaches and methods. *Landscape and Urban Planning*, 81(1–2), 1–13. https://doi.org/10.1016/j.landurbplan.2007.01.003

[8] Krier, R., & Vorreiter, G. (1988). *Architectural composition* (Vol. 10). New York: Rizzoli.

[9] Krier, R., & Rowe, C. (1979). *Urban space*. London: Academy editions.

[10] Marcus, C. C., & Francis, C. (1998). *People places – Design guidelines for urban open space*. New York: Wiley & Sons, Inc.

[11] Nicholson, S. E. (1975). A pollution model for street-level air. *Atmospheric Environment (1967)*, 9(1), 19-31. http://dx.doi.org/10.1016/0004-6981(75)90051-7

[12] Nakamura, Y., & Oke, T. R. (1988). Wind, temperature and stability conditions in an east-west oriented urban canyon. *Atmospheric Environment (1967)*, 22(12), 2691-2700. http://dx.doi.org/10.1016/0004-6981(88)90437-4

[13] Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of climatology*, 1(3), 237-254. http://dx.doi.org/10.1002/joc.3370010304

[14] Johnson, G. T., & Watson, I. D. (1984). The determination of view-factors in urban canyons. *Journal of Climate and Applied*

Meteorology, 23(2), 329-335. http://dx.doi.org/10.1175/1520-0450(1984)023<0329:TDOVFI>2.0.CO;2

[15] Terjung, W. H., & LOUIE, S. S. (1973). Solar radiation and urban heat islands. *Annals of the Association of American Geographers*, 63(2), 181-207. http://dx.doi.org/10.1111/j.1467-8306.1973.tb00918.x

[16] Nunez M. and Oke T. R. (1977) The energy balance of an urban canyon. *Journal of Applied Meteorology*, 16, 11-19 https://doi.org/10.1175/1520-0450(1977)016<0011:TEBOAU>2.0.CO;2

[17] Vardoulakis, S., Fisher, B. E., Pericleous, K., & Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons: a review. *Atmospheric environment*, 37(2), 155-182. http://dx.doi.org/10.1016/S1352-2310(02)00857-9

[18] Spagnolo, J., & De Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and environment*, 38(5), 721-738. http://dx.doi.org/10.1016/S0360-1323(02)00209-3

[19] de Assis, E. S., & Frota, A. B. (1999). Urban bioclimatic design strategies for a tropical city. *Atmospheric Environment*, 33(24), 4135-4142. https://doi.org/10.1016/S1352-2310(99)00155-7

[20] Franklin, T. B. (1955). *Climates in miniature. A study of micro-climate and environment.* London: Faber and Faber

[21] The American Heritage® Science Dictionary. (Nov. 14, 2017). *Microclimate. (n.d.).* Retrieved from http://www.dictionary.com/browse/microclimate

[22] Oke, T. R. (1997). *The Surface Climates of Canada*, Montréal: McGill-Queen's University Press.

[23] Fanger, P. O. (1970). Thermal comfort: Analysis and applications in environmental engineering. *Perspectives in Public Health*, 92(3), 164-164.

[24] Höppe, P. (1999). The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *International journal of Biometeorology*, 43(2), 71-75. https://doi.org/10.1007/s004840050118

[25] Yao, Y., Lian, Z., Liu, W., & Shen, Q. (2007). Experimental study on skin temperature and thermal comfort of the human body in a recumbent posture under uniform thermal environments. *Indoor and Built Environment*, 16(6), 505-518.

[26] Monteith, J., & Unsworth, M. (2007). *Principles of environmental physics.* Cambridge: Academic Press.

[27] Pearlmutter, D., Bitan, A., & Berliner, P. (1999). Microclimatic analysis of "compact" urban canyons in an arid zone. *Atmospheric Environment*, 33(24), 4143-4150. https://doi.org/10.1016/S1352-2310(99)00156-9

[28] Pearlmutter, D., Berliner, P., & Shaviv, E. (2006). Physical modeling of pedestrian energy exchange within the urban canopy. *Building and Environment*, 41(6), 783-795. https://doi.org/10.1016/j.buildenv.2005.03.017

[29] Task Committee on Outdoor Human Comfort of the Aerodynamics, Committee of the American Society of Civil Engineers (2004). *Outdoor human comfort and its assessment: State of the art*. Reston, VA: American Society of Civil Engineers.

[30] Fanger, P. O. (1982). *Thermal comfort: Analysis and application in environment engineering*. New York: McGraw Hill Book Company.

[31] ISO (1994). *Moderate thermal environments – Determination of the PMV and PPD indices and the specification of conditions for thermal comfort.* Geneva: International Standard 7730.

[32] Cheng, V., Ng, E., Chan, C., & Givoni, B. (2010). Outdoor thermal comfort study in sub-tropical climate: A longitudinal study based in Hong Kong. I*nternational Journal of Biometeorology*. https:// doi:10.1007/s00484-010-0396-z.

[33] Nikolopoulou, M., Baker, N., & Steemers, K. (2001). Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Solar Energy*, 70, 227–235. https://doi.org/10.1016/S0038-092X(00)00093-1

[34] Thorsson, S., Lindqvist, M., & Lindqvist, S. (2004). Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg. *International Journal of Biometeorology*, 48, 149–156.

[35] Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38, 43–49.

[36] Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, 41, 94–108. https://doi.org/10.1016/j.buildenv.2005.01.013

[37] Cheng, V., & Ng, E. (2006). Thermal comfort in urban open spaces for Hong Kong. *Architectural Science Review*, 49(3), 236–242.

[38] Lin, T.-P. (2009). Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, 44, 2017–2026.

[39] Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology*, 43, 76–84.

[40] Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., & Lim, E.-M. (2007). Thermal comfort and outdoor activity in Japanese urban public places. *Environment and Behavior*, 39, 660–684. https://doi.org/10.1007/s004840050119

[41] City of Sapporo. (2016 Feb 22). *World Winter Cities Association for Mayors - What is a "Winter city"*. Retrieved from https://www.city.sapporo.jp/somu/kokusai/wwcam/definition.html

[42] City of Sapporo. (2017, Feb., 28). *World Winter Cities Association for Mayors – Member cities.* Retrieved from https://www.city.sapporo.jp/somu/kokusai/wwcam/membercities_e.html

[43] Pressman, N. (1995). *Northern cityscape: Linking design to climate*. Ann Arbor: Winter Cities Association.

[44] Pressman, N. (1985). *Reshaping winter cities: Concepts, strategies and trends*. Waterloo: University of Waterloo Press.

[45] Pressman N. (1988). Developing climate-responsive winter cities. *Energy and Buildings*, 11(1): 11-22. https://doi.org/10.1016/0378-7788(88)90019-9

[46] Chinese State Bureau of Technology Supervision (CSBTS), Chinese Ministry of Construction. (1994). *GB50178 Standard of Climate Regionalization for Architecture*. Beijing: Standard Press of China. (in Chinese)

[47] China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. (1971-2000). *The database of climate standard daily value in Chinese international ground switching center [database online]. [cited 1990-2000 Jul., Aug.]*. Retrieved from http://data.cma.cn/data/detail/dataCode/A.0029.0001.html)

[48] Gehl, J. (1971). *Life between buildings: Using public space*. Copenhagen: Danish Architecture Press.

[49] Carr, S., Francis, M., Rivlin, L. G., & Stone, A. M. (1993). *Public space. Cambridge*. New York: Cambridge University Press.

[50] Gehl, J., & Gemzøe, L. (2004). *Public spaces, public life.* Copenhagen: Danish Architectural Press and the Royal Danish Academy of Fine Arts, School of Architecture Publishers.

[51] Maruani, T., & Amit-Cohen, I. (2007). Open space planning models: A review of approaches and methods. *Landscape and Urban Planning*, 81(1–2), 1–13. https://doi.org/10.1016/j.landurbplan.2007.01.003

[52] Ahmed, K. S. (2003). Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environments. *Energy and Buildings*, 35, 103–110. https://doi.org/10.1016/S0378-7788(02)00085-3

[53] Nikolopoulou, M., & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41(11), 1455–1470. https://doi.org/10.1016/j.buildenv.2005.05.031

[54] Andrade, H., et al. (2011). Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics. *Int J Biometeorol*, 55(5): 665-680. https://doi.org/10.1007/s00484-010-0379-0

[55] Lai, D., et al. (2014). Outdoor space quality: A field study in an urban residential community in central China. *Energy and Buildings,* 68, 713-720. https://doi.org/10.1016/j.enbuild.2013.02.051

[56] Gulyas, A., Unger, J., & Matzarakis, A. (2006). Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements. *Building and Environment*, 41, 1713–1722. https://doi.org/10.1016/j.buildenv.2005.07.001

[57] Bourbia, F., & Boucheriba, F. (2010). Impact of street design on urban microclimate for semi-arid climate (Constantine). *Renewable Energy, 35*(2), 343-347. https://doi.org/10.1016/j.renene.2009.07.017

[58] Hwang, R. L., Lin, T. P., & Matzarakis, A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Building and Environment, 46*(4), 863-870. https://doi.org/10.1016/j.buildenv.2010.10.017

[59] Andreou, E., & Axarli, K. (2012). Investigation of urban canyon microclimate in traditional and contemporary environment. Experimental investigation and parametric analysis. *Renewable Energy, 43,* 354-363. https://doi.org/10.1016/j.renene.2011.11.038

[60] Andreou, E. (2013). Thermal comfort in outdoor spaces and urban canyon microclimate. *Renewable Energy, 55,* 182-188. https://doi.org/10.1016/j.renene.2012.12.040

[61] Andreou, E. (2014). The effect of urban layout, street geometry and orientation on shading conditions in urban canyons in the Mediterranean. *Renewable Energy, 63,* 587-596. https://doi.org/10.1016/j.renene.2013.09.051

[62] Shahrestani, M., Yao, R., Luo, Z., Turkbeyler, E., & Davies, H. (2015). A field study of urban microclimates in London. *Renewable Energy, 73,* 3-9. https://doi.org/10.1016/j.renene.2014.05.061

[63] Eliasson, I., et al. (2007). Climate and behaviour in a Nordic city. *Landscape and Urban Planning,* 82(1-2): 72-84. https://doi.org/10.1016/j.landurbplan.2007.01.020

[64] Nikolopoulou, M. and S. Lykoudis (2007). Use of outdoor spaces and microclimate in a Mediterranean urban area. *Building and Environment,* 42(10): 3691-3707. https://doi.org/10.1016/j.buildenv.2006.09.008

[65] Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., & Lim, E. M. (2007). Thermal Comfort and Outdoor Activity in Japanese Urban Public Places. *Environment and Behavior*, 39(5), 660-684. https://doi.org/10.1177/0013916506294937

[66] Mänty, J., & Pressman, N. (Eds.). (1988). *Cities designed for winter (Vol. 12).* Ann Arbor: Building Book Limited.

[67] Li, S. (1994). User's behaviour of small urban spaces in winter and marginal seasons. *Architecture and Behaviour*, 10, 95-109.

[68] Givoni, B. (1998). *Climate considerations in building and urban design.* New York: John Wiley & Sons.

[69] Meng, X. W., & Setoguchi, T. (2010). Development of Urban Design Guidelines with Wind Tunnel Simulations for Downtown Districts in Winter Cities. *Journal of Asian Architecture and Building Engineering,* 9(2), 355-362. https://doi.org/10.3130/jaabe.9.355

[70] Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate: designing the spaces between buildings*. New York: Routledge.

[71] Lai, D., Guo, D., Hou, Y., Lin, C., & Chen, Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment*, 77, 110-118. https://doi.org/10.1016/j.buildenv.2014.03.026

[72] Setoguchi, T. (2004). Efficiencies of infill developments against snow problem in winter cities-the snow simulations for desirable block designs using wind tunnel. *Journal of Asian Architecture and Building Engineering*, 3(2), 335-340. https://doi.org/10.3130/jaabe.3.335

[73] Setoguchi, T., & Tsutsumi, T. (2007). Snow and wind environmental assessment on the public space comparing high-rise and medium-rise building blocks using the wind tunnel simulation. *Journal of Architecture and Planning (Transactions of AIJ)*, (614), 167-174.

[74] Setoguchi, T. (2008). New urban design approaches with snow simulations for cold and snowy cities. *Journal of Asian Architecture and Building Engineering*, 7(1), 93-99. https://doi.org/10.3130/jaabe.7.93

[75] Setoguchi, T. (2009) The development of urban design planning process linking with snow and wind environmental assessments on the urban complex redevelopment project in snowy and cold cities, *J. Archit. plan., AIJ*, 74(642), 1777-1786.

[76] Watanabe, N., Setoguchi, T., Sato, K., & Tsutsumi, T. (2016). New city block design approaches incorporating environmental assessment for downtown districts in cities with severe winter climates. *Journal of Asian Architecture and Building Engineering*, 15(3), 455-462. https://doi.org/10.3130/jaabe.15.455

[77] Blocken, B. J. E., Stathopoulos, T., & van Beeck, J. P. A. J. (2016). Pedestrian-level wind conditions around buildings. *Building and Environment*, 100(1), 50-81.

2. Urban space in Shenyang and Sapporo

2.1. General introduction Of Shenyang

2.1.1. Location of Shenyang

Shenyang is the provincial capital and the largest city of Liaoning Province in China with 12,980 km^2 city total area (3,495 km^2) as well as the largest city in Northeast China by urban population (Fig. 2-1). According to the 2010 census, the city's urban area has 6.7 million inhabitants, while the total population of the Shenyang municipality, which holds the administrative status of a sub-provincial city, is up to 8.2 million [78].

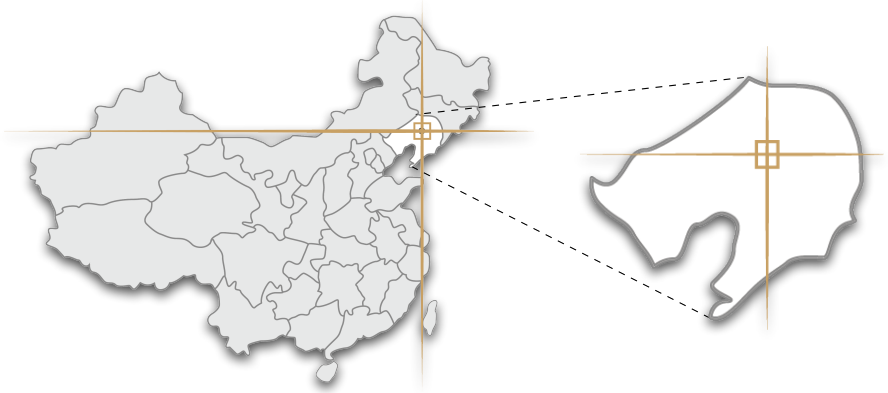


Figure 2-1 Shenyang, Liaoning Province, China 41.8°N 123.4°E

2.1.2. Climate introduction of Shenyang

Shenyang has a monsoon-influenced humid continental climate characterized by hot, humid summers due to the monsoon, and dry, cold winters due to the Siberian anticyclone.

The four seasons here are distinctive. Nearly half of the annual rainfall occurs in July and August. As the Fig. 2-2 shows, monthly mean temperatures range from −11.4 °C in January to 24.6 °C in July, for an annual average of 8.5 °C. The frost-free period is 183 days, which is long considering the severity of the winters [79].

The city receives 2,406.4 hours of bright sunshine annually; monthly percent of possible ranges from 45 percent in July to 62 percent in October. Extreme temperatures range from −32.9 °C to 38.3 °C [80 81].

Climate data for Shenyang (normals 1986—2015, extremes 1951—2017)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C	8.6	17.2	20.6	30.0	34.3	37.5	38.3	35.7	32.9	29.2	21.7	13.4	38.3
Average high °C (°F)	-4.9	-0.1	7.1	16.7	23.6	27.4	29.1	28.7	24.1	16.3	5.7	-2.4	14.3
Daily mean °C (°F)	-11.4	-6.4	1.4	10.5	17.6	22.1	24.6	23.7	17.7	9.9	0.2	-8.2	8.5
Average low °C (°F)	-16.9	-11.9	-3.9	4.3	11.5	17.0	20.5	19.3	12.1	4.3	-4.5	-13.2	3.2
Record low °C (°F)	-32.9	-30.1	-25.0	-12.5	0.2	3.6	12.0	5.7	-2.6	-8.3	-22.9	-30.5	-32.9
Average precipitation mm	6.7	9.1	19.3	40.5	55.9	93.0	168.3	153.8	60.8	43.6	21.2	11.6	683.8
Average precipitation days (≥0.1 mm)	3.8	3.5	4.9	7	8.9	12.1	12.8	10.4	6.7	6.8	5.7	4.9	87.5
Average relative humidity (%)	63	57	53	51	54	68	78	79	71	65	63	64	63.8
Mean monthly sunshine hours	165.8	185.8	222	225.5	247.6	219.7	193.4	211.4	223.3	207.4	156.8	147.7	2,406.4

Source : China Meteorological Administration.

Figure 2-2 Climate data for Shenyang [81](revised by author)

Shenyang is a monsoon climate; the annual average air velocity is about 2.87 m/s. The air velocity from March to May and from October to November presented peak. Fig. 2-3 shows the distribution of wind frequency throughout one year. The prevailing wind direction during the whole year are NE (2.4%) and SW (2.7%).

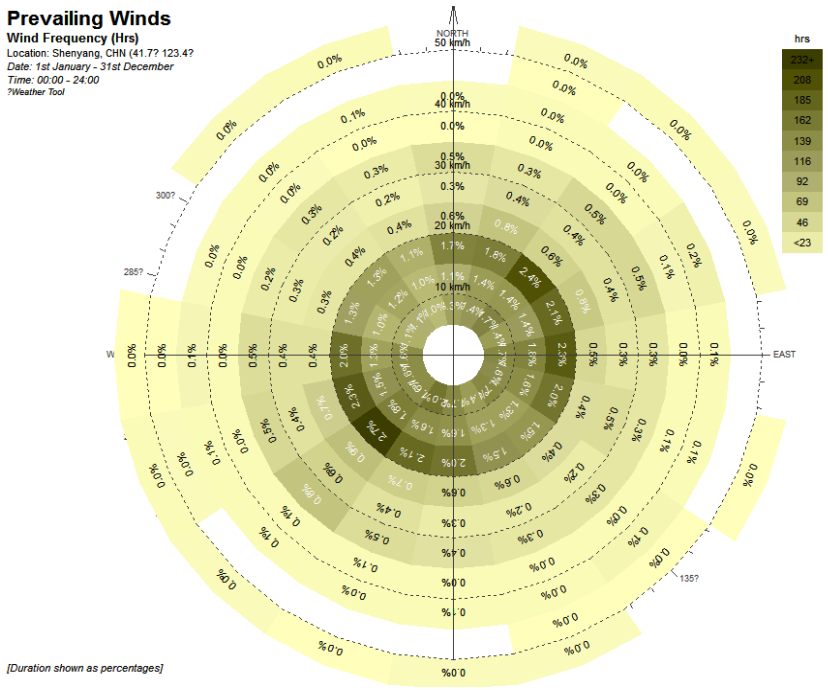
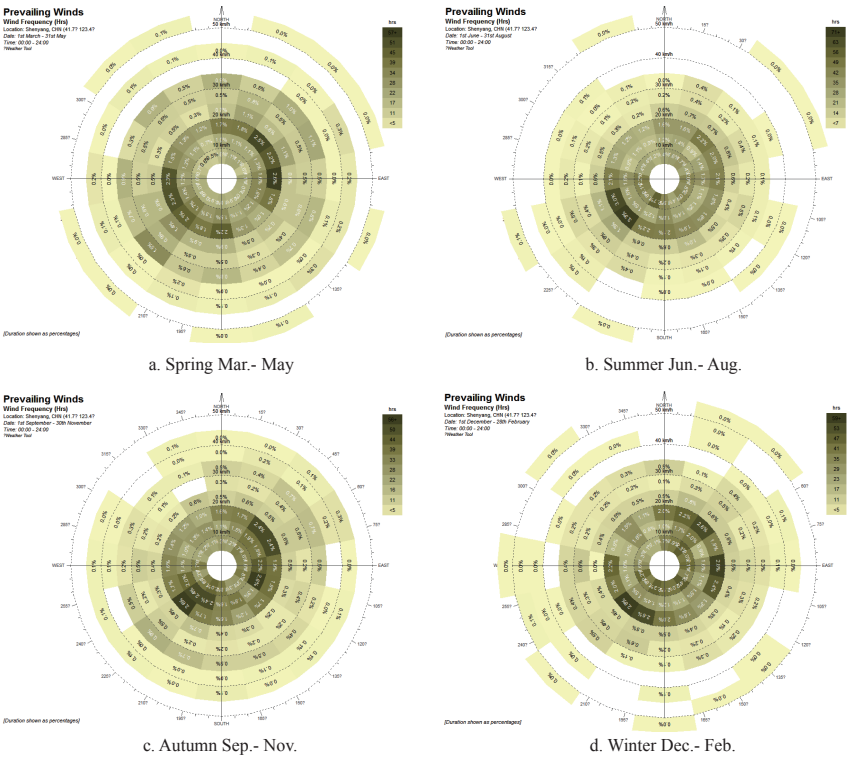


Figure 2-3 Distribution of wind frequency throughout one year in Shenyang [82]



a. Spring Mar.- May　　b. Summer Jun.- Aug.

c. Autumn Sep.- Nov.　　d. Winter Dec.- Feb.

Figure 2-4 Distribution of wind frequency throughout four seasons in Shenyang [82]

From Fig. 2-4, The seasonal direction and frequency of the wind in Shenyang is obvious. In spring, autumn and winter, the wind directions are mainly northeastern and southwestern. Among them, the wind frequency of high air velocity in spring and autumn are higher than in winter. In summer, the wind direction is southwestern.

The Table 2-1 below provides an overview of the annual wind conditions from 1981 to 2010, The frequency of SSW is highest throughout the whole year. The maximum average wind speed appears in April, in spring. According to the "Climate data for Shenyang" (Fig. 2-2), the average wind speed at the coldest January is 2.0 m/s, wind direction is ENE. The average wind speed at the hottest July is 2.5 m/s, wind direction is SSW.

Table 2-1a Overview of the annual wind conditions from 1981 to 2010 [82, 83]

Month	Jan	Feb	Mar	Apr	May	Jun
Avg. Wing speed	2.0	2.7	3.3	3.8	3.5	2.9
Max. WS	16.9	22.5	26	20.3	19.7	19.5
The Most wind direction (including the clam wind)	ENE	C	SSW	SSW	SSW	SSW
frequency of wind direction (including the clam wind) %	12	11	12	16	18	19

Table 2-2b Overview of the annual wind conditions from 1981 to 2010 [82, 83]

Month	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Wing speed	2.5	2.4	2.5	2.8	3	2.6
Max. WS	22.6	25.5	18.1	21.2	18.6	18
The Most wind direction (including the clam wind)	SSW	SSW	SSW	SSW	NNE	SSW
frequency of wind direction (including the clam wind) %	18	13	11	12	11	10

2.1.3. City structure of Shenyang

The overall urban layout of Shenyang is based on the cross axis formed by the major rivers travelled from east to west and the major urban economic corridor from north to south. The circular urban main road and radial secondary main road network formed the city transportation systems. (Fig. 2-5)

As the urbanization goes deeply into in Shenyang, the city gradually expands outward. Industrial and agricultural land gradually moved away from the downtown area, the proportion of residential, administrative, commercial, education and traffic areas will gradually increase. Area centers were built in each district and became necessary places for citizens' leisure and entertainment activities. In recent years, Shenyang has gradually relocated industrial areas to the west of the city and expanded its city center gravity to the south to ease the population pressures in central urban areas and balance the proportion of population and land use in the center of each district. Citizens have also gradually adapted to the distances between their homes and commercial centers and have begun to relocate their entertainment place from the green areas near their homes to large parks, plazas or commercial blocks in urban or regional centers. (Fig. 2-6)

Figure 2-5 The image of urban structure in Shenyang

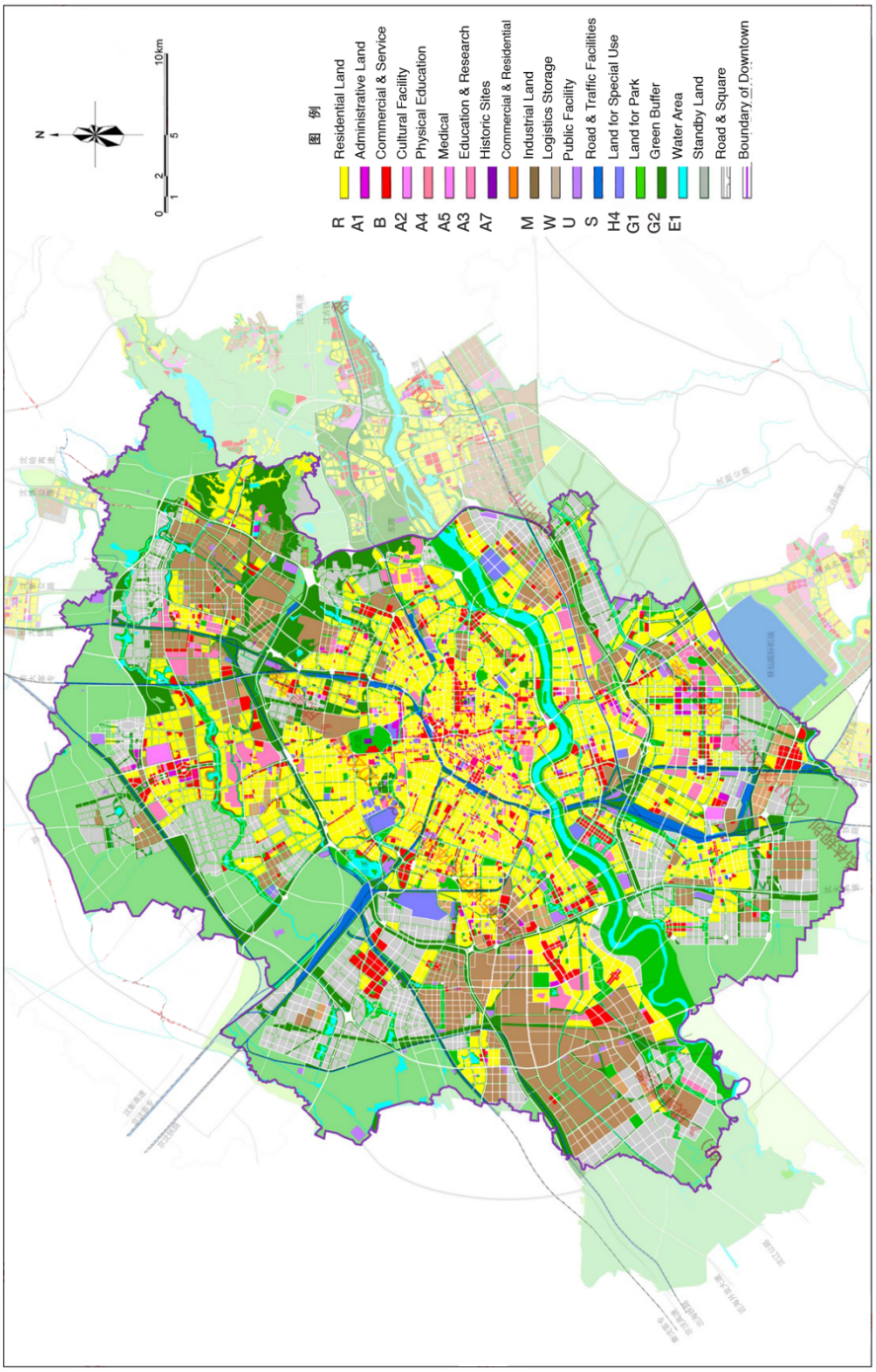


Figure 2-6 Master plan of Shenyang 2011-2020 [84](revised by author)

2.1.4 Typical open space in Shenyang

With the continuous development of the Shenyang city, the population density of the downtown area gradually increases, the original urban green space, plazas, markets, small parks and other recreational places have been unable to meet the basic needs of citizens. In the central part of the city, a concentrated area of commerce,

entertainment, transportation hubs and urban greening has emerged. Its radiation radius is often up to several kilometers and connected with residential area by the city roads and subway lines. These areas have become indispensable parts of urban life in Shenyang.

There are three main basic open space types in Shenyang, most of all the open space comes from these three types, they are as the following:

Type 1: Square, plaza or park in whole piece of land with single function

Type 2: Open space around or next to the public building

Type 3: Street canyon with buildings running continuously along both sides

Combination of type 1 & 2: Wanda square in Tiexi

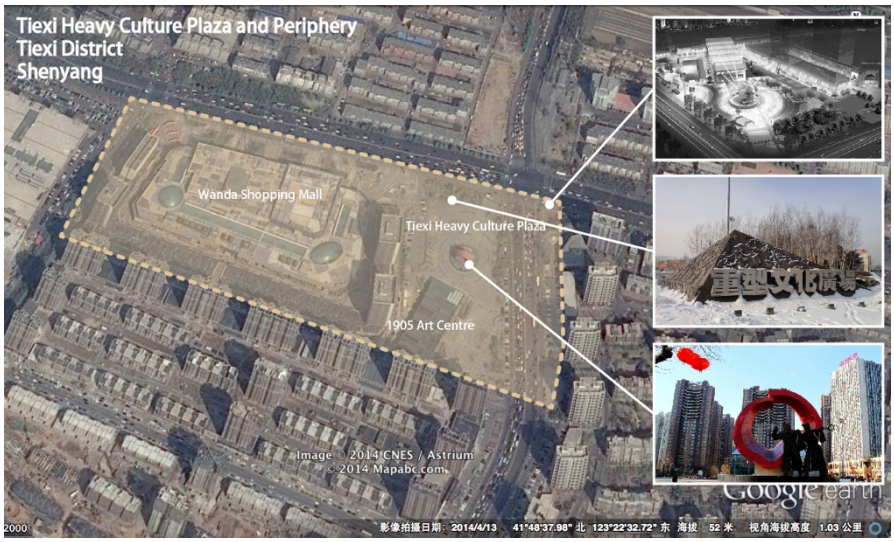


Figure 2-7 Tiexi industural culture plaza and periphery

Fig. 2-7 shows combination form of types 1 and 2. Such open space are based on large commercial buildings. There are both a single square and a circular plaza surrounding the building. It adjacent to the city's major roads and subway stations, it provides a place for shopping and entertainment for the citizens living within several kilometers far from here. The development of such piece of land tends to focus on

the reservation of open space area and seek a suitable proportion between commercial buildings and the open space.

Such open space is mostly ring shape and circling around large-shape commercial building. At the same time, it not only forms an echo relationship with the indoor public space, but also provide large-scale activities space for the public.

The open space shows in Fig. 2-7 is a commercial center located at Tiexi district in Shenyang. A large-scale commercial building is surrounded by circle shape of open space which is next to a city square at street corner. Outdoor open space area and scope of activities have increased by this layout. It belongs to the typical existing form of open space in the central business district of Shenyang City.

Combination of type 1 & 3: Xinghua street

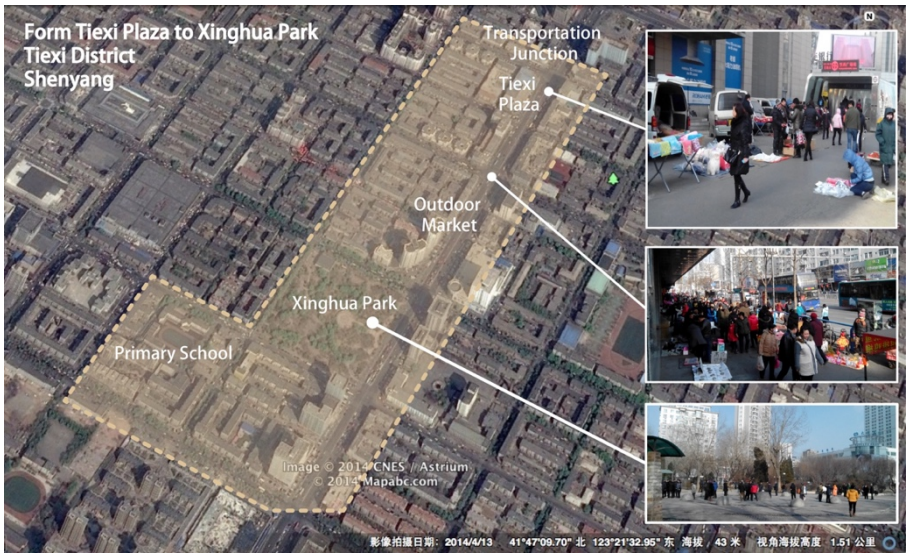


Figure 2-8 Xinghua street from Tiexi plaza to Xinghua park

Fig. 2-8 shows combination form of types 1 and 3. Such open space is a combination of two pieces of land with single function connected by the street canyon. It is generally based on the main road of intensive living areas connecting the transport hub and regional activity center. It is the important way for people passing by after work every day. Commercial-oriented open space behavior gradually formed along the line. It is also one of the typical existing forms of open space in Shenyang.

Type 3: Joy-city in the Mid-street

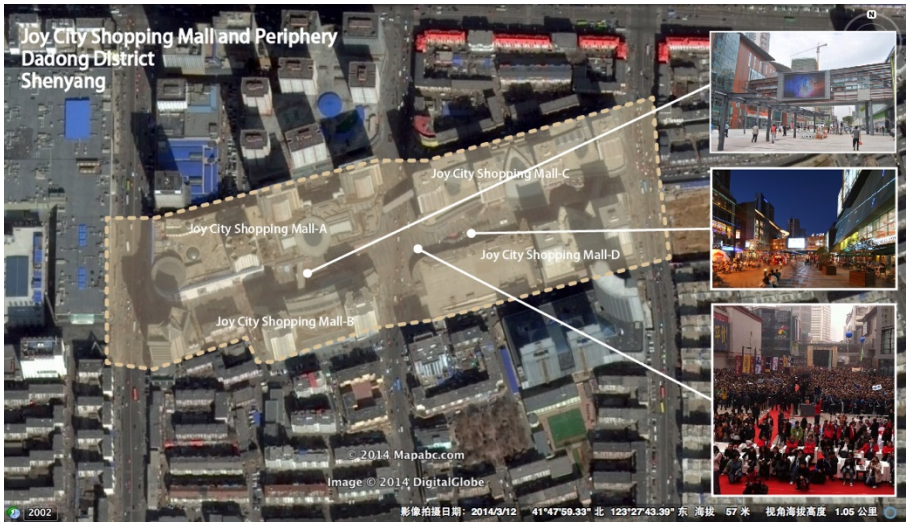


Figure 2-9 Joy-city in the Mid-street

Fig. 2-9 shows street canyon with large-scale commercial buildings running continuously along both sides. Such type of open space is common in commercial pedestrian way in central area. As an independent place without any vehicles, it can provide better domain sense and spatial experience than the other two types.

Since it is surrounded by public buildings with multi-functions, there are rich types of spatial behaviors occur and easier to be observed and research than other types. The place shows in figure 9 can be realized as a pedestrian street canyon between mixed-used buildings with shopping malls, subway station, super market, hotels and high rise apartments.

The place is chosen by this study as the field survey target area for the further research.

2.2. General introduction Of Sapporo

2.2.1. Location of Sapporo

Sapporo is the central city of Hokkaido with a population of about 2 million (35% of the total population in Hokkaido). Sapporo is the fifth-largest city in Japan with 1121.25 km^2 city area. As the Fig. 2-10 Shows, Although Sapporo is located in the southwestern part of Hokkaido, it the an integrated center of economy, politics, culture and

transportation throughout Hokkaido and northern Japan. In 1972, Sapporo and Shenyang built sister cities with many similarities like location and seasonal environment [85].

Figure 2-10 Geographic location of Sapporo

2.2.2. Climate introduction Of Sapporo

Sapporo belongs to the humid continental climate [86], the temperature difference between summer and winter is relatively large, and annual precipitation is relatively average. In Japan's climate zone, Sapporo belongs to the Japan Sea-side Climate[a] [87, 88] which is characterized by a large amount of snowfall in winter and warmer summer with exceptionally high temperatures [89].

Sapporo is affected by the high pressure of the Sea of Okhotsk in summer. The weather is cool in the morning and evening, though the daytime temperatures are higher. Sapporo in winter is colder and snowier, with a maximum snowfall of up to 1 meter and total snowfall throughout the year of 6 meters [90].

a Japan Seaside Climate: 日本海側気候 (In Japanese), is one of the climate classification in Japanese climate zones. It is a kind of winter-type climate characteristic in seaside from Hokkaido to Saninchiho. Japan Sea-side Climate is characterized by a large amount of snowfall in winter and warmer summer with exceptionally high temperatures.

As shows in Fig. 2-11, the annual average temperature in Sapporo is 8.9 ° C. The average maximum temperature in summer is 26.4 ° C. The lowest average temperature in winter is -7 ° C. It is one of the few winter cities with heavy snow in the world with a population of nearly 2 million [91].

Climate data for Sapporo, Japan (1981–2010) (normals 1981-2010, extremes 1951-2017)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C	11.2	10.8	16.8	28	31.1	31.9	36	36.2	32.7	26.4	22.4	14.8	36.2
Average high °C	-0.6	0.1	4	11.5	17.3	21.5	24.9	26.4	22.4	16.2	8.5	2.1	12.9
Daily mean °C	-3.6	-3.1	0.6	7.1	12.4	16.7	20.5	22.3	18.1	11.8	4.9	-0.9	8.9
Average low °C	-7	-6.6	-2.9	3.2	8.3	12.9	17.3	19.1	14.2	7.5	1.3	-4.1	5.3
Record low °C	-27	-28.5	-22.6	-14.6	-4.2	0	5.2	5.3	0.2	-5.8	-15.5	-23.9	-28.5
Average precipitation mm	113.6	94	77.8	56.8	53.1	46.8	81	123.8	135.2	108.7	104.1	111.7	1,106.5
Average snowfall cm	173	147	98	11	0	0	0	0	0	2	32	132	597
Avg. precipitation days (≥ 0.5 mm)	21.8	19	18.5	11.7	10.2	8.3	9.7	9.5	11.1	13.9	17.5	19.2	170.4
Avg. snowy days	28.8	25.4	23.5	6.4	0.1	0	0	0	0	1.2	13.9	26.5	125.8
Average relative humidity (%)	70	69	66	62	66	72	76	75	71	67	67	69	68
Mean monthly sunshine	92.5	104	146.6	176.5	198.4	187.8	164.9	171	160.5	152.3	100	85.9	1,740.4

Source: Japan Meteorological Agency

Figure 2-11 Climate data for Sapporo (1981-2010) [92]

2.2.3. City structure of Sapporo

As the Fig. 2-12 Shows, Sapporo is located in the southwestern part of the Ishikawa Plain, with mountains in the southwestern part, platform in the southeast, alluvial fan in the middle and lowland in the north. The whole city is developed on the basis of the southwestern mountainous areas and the northwestern sea area. The urban center is arranged as a grid relied on Odori Park and Soseigawa river.

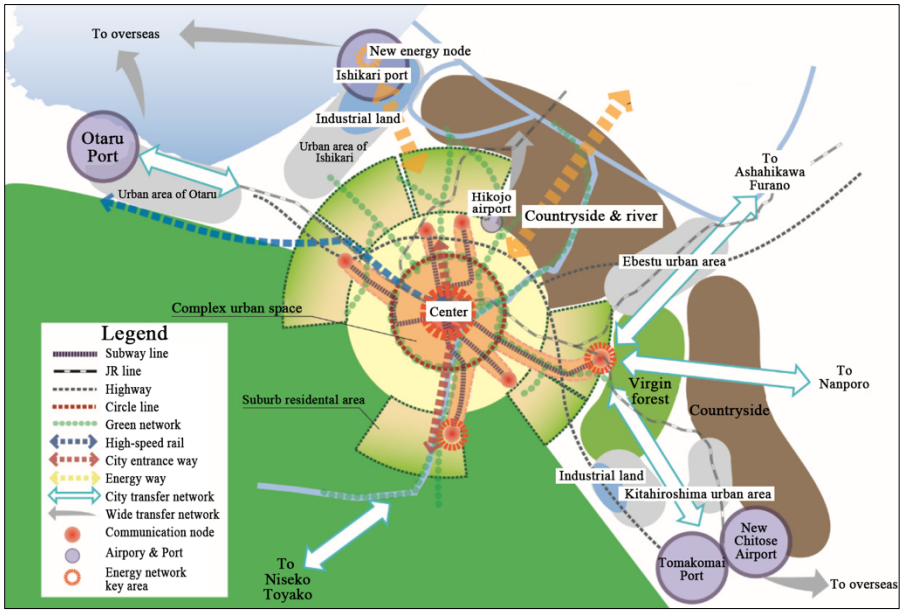


Figure 2-12 The master plan of Sapporo (decided in Mar. 2016) [93](revised by author)

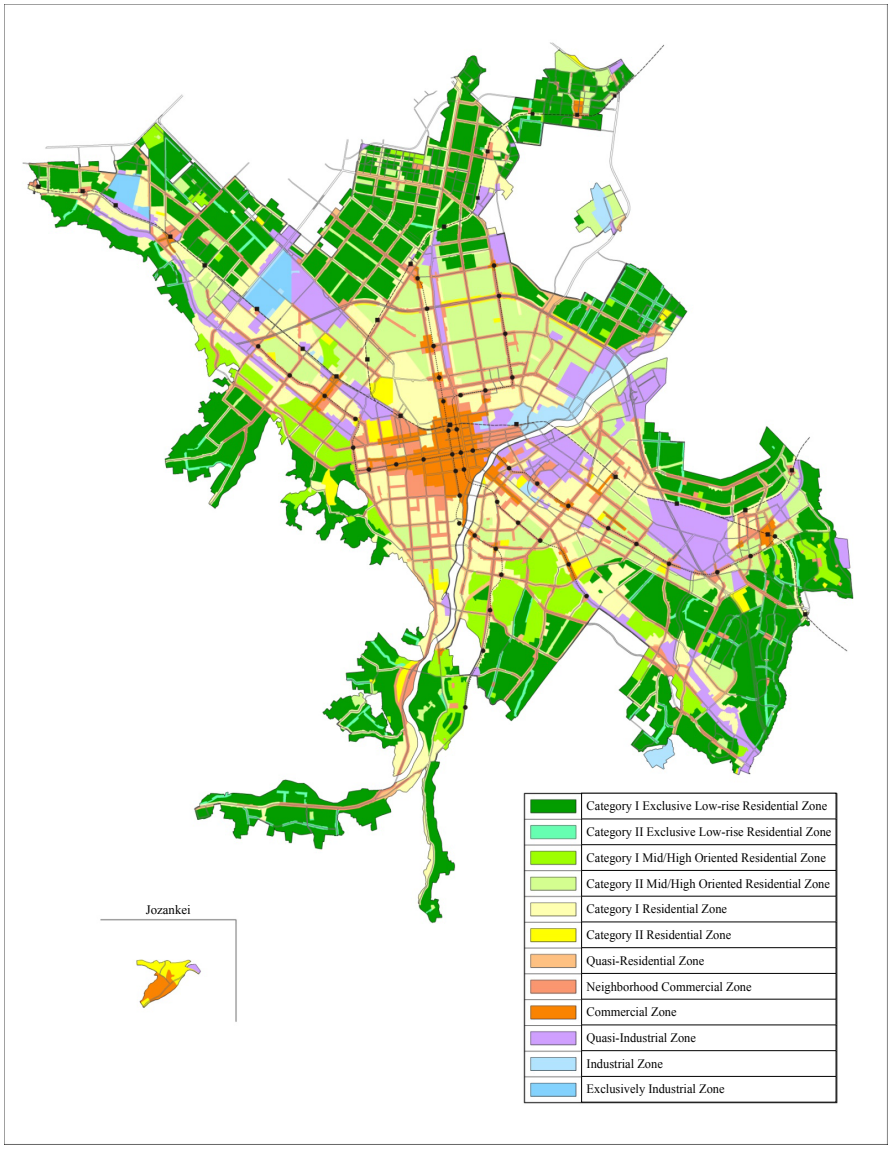


Figure 2-13 Land usage of Sapporo [94](revised by author)

2.3 References

[78] National Bureau of Statistics of the PRC. (2011, Apr., 28). *The Sixth National Population Census of the People's Republic of China in 2010.* Retrieved from http://www.stats.gov.cn/tjsj/tjgb/rkpcgb/qgrkpcgb/201104/t20110428_30327.html

[79] People's Government of Shenyang. (2011, Jul, 07). *A city full of vitality – Shenyang, China.* Retrieved from https://web.archive.org/web/20110707041552/http:/www.shenyang.gov.cn/web/resource/hlzd-yw/hlzd-yw-01.htm.

[80] The Maximiliano Herrera's Site. (2014, Aug., 06). *Extreme Temperatures around the World*. Retrieved from http://www.mherrera.org/temp.htm

[81] China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. (2008. Apr. 4). *The database of climate standard monthly value in Chinese international ground switching center (1951-2017)*. Retrieved from http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_MON.html

[82] China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. (2005). *China Standard Weather Data for Analyzing Building Thermal Conditions.* Beijing: China Building Publishing House.

[83] China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. (2012. Aug. 28). *The database of climate standard daily value in Chinese international ground switching center (1981-2010)*. Retrieved from http://data.cma.cn/data/detail/dataCode/A.0029.0001.html

[84] People′s Government of Shenyang. (2017, Oct,. 27). *City Master Plan of Shenyang(2011-2020).* Retrieved from http://syup1960.com/sy2035/index.php?p=news_show&id=65&lanmu=1

[85] City of Sapporo. (2016, Apr, 14). *Sister City Communication*. Retrieved from http://www.city.sapporo.jp/kokusai/sistercity/shenyang_2.html

[86] Institute for Veterinary Public Health. (2010, Sep. 6). *World Maps of the Köppen-Geiger climate classification*. Retrieved from https://web.archive.org/web/20100906034159/http://koeppen-geiger.vu-wien.ac.at/

[87] 関口武. (1959). 日本の気候区分. *東京教育大学地理学研究報告*, 3, 66-78

[88] 鈴木秀夫. (1962). 日本の気候区分. *地理学評論*, 35(5), 205-211.

[89] City of Sapporo. (2017. Feb. 1). *General information of Sapporo.* Retrieved from: http://www.city.sapporo.jp/city/aramashi/

[90] City of Sapporo. (2018. Mar. 27). *The general information of Sapporo (regional characteristics)*. Retrieved from

https://www.city.sapporo.jp/kikaku/kyoujinka/documents/sankou01_gaikyou.pdf

[91] Sapporo Tourist Association. (2018. Apr. 02). *Sapporo Introduction.* Retrieved from http://www.sapporo.travel/learn/basicinfo/?lang=cn

[92] Japan Meteorological Agency. (2016. Dec. 23). *Climate data for Sapporo (1981-2010).* Retrieved from http://www.data.jma.go.jp/obd/stats/etrn/view/nml_sfc_ym.php?prec_no=14&prec_ch=%90%CE%8E%EB%8Ex%92%A1&block_no=47412&block_ch=%8ED%96y&year=&month=&day=&elm=normal&view=

[93] City of Sapporo. (2016. Dec. 8). *The second master plan of Sapporo city urban planning (decided in Mar., 2018)*. Retrieved from http://www.city.sapporo.jp/keikaku/master/index.html

[94] City of Sapporo. (2012. Aug. 10). *About the change of the land use based on the master plan of Sapporo city urban planning*. Retrieved from http://www.city.sapporo.jp/keikaku/toshikei/youtochiiki/documents/h24minaoshi_h28renew.pdf

3. Public open space field survey on the basis of microclimate and spatial behaviour in hot and cold weather conditions in Shenyang

3.1. Introduction

The study case is a canyon type open space located in the central area of Shenyang, the northern China (41°48′01.11″N, 123°27′49.33″E 55 m). (Fig. 3-1)

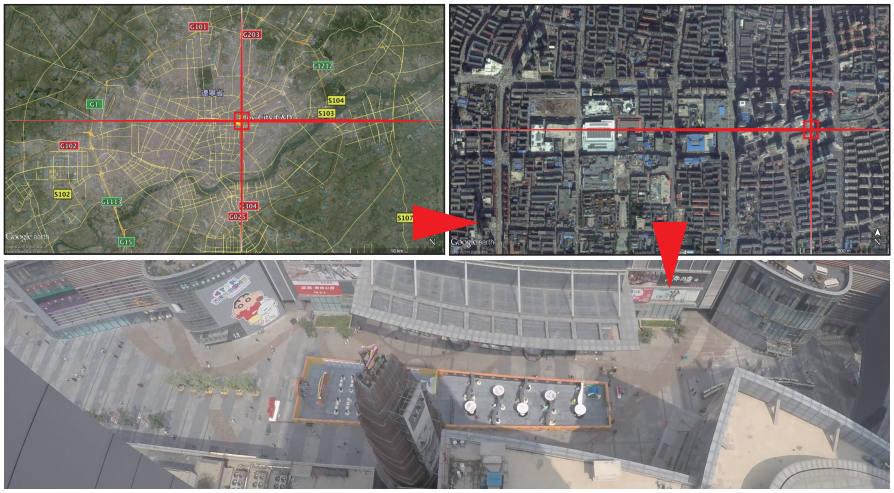


Figure 3-1 Research area in Shenyang

The place can be realized as one of the most popular public space in the center city with resourceful public facilities like shopping malls, supermarket, residence, hotel and apartments (Fig. 3-2). The subway line station is arranged at the underground 2nd floor of the shopping malls.

The main reasons for choosing this location for research is as follows:

(1) The target area is located in the city center.

(2) Surrounding buildings are currently the representative form of urban complex type of buildings. At the same time, many kinds of building shapes can be found. It is beneficial to research the impact of different building forms.

(3) This street canyon can also avoid the microclimate interference from other buildings outside the study area and make sure the research results are relatively accurate.

(4) As an integrated public area, many kinds of visitors can be found as the research samples and references.

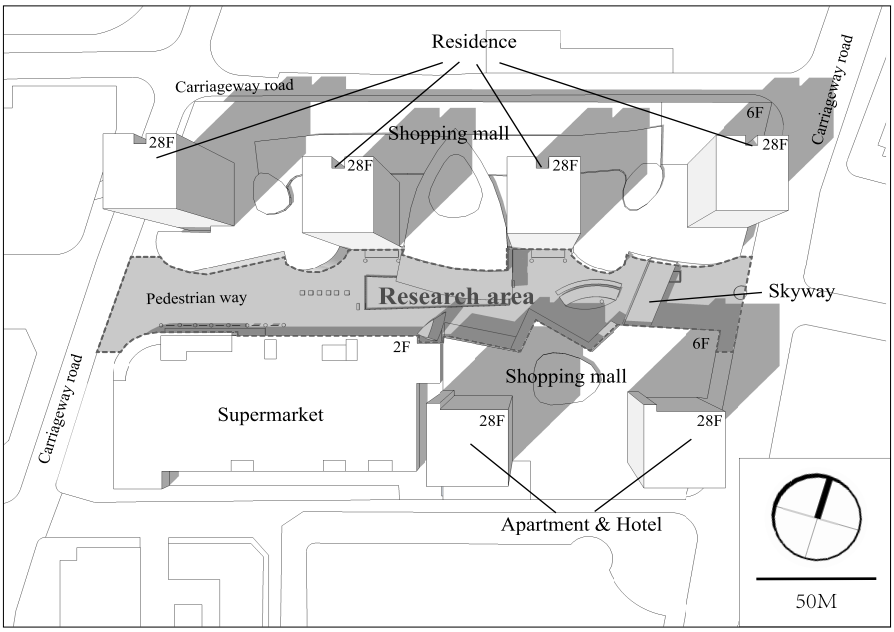


Figure 3-2 Research area introduction

3.2. Methodology

3.2.1. Survey areas & measurement points

Depending on space characteristic, for the later description and analysis, 4 areas named west center line, east center line, north edge side and south edge side, including 15 measurement points were chosen (Fig. 3-3).

These 15 points were separated in 3 groups with 5 points in each group. The data acquisition of each group is performed at the same time. Microclimate data of each point were collected in every 15 minutes during the daytime. (Fig. 3-4)

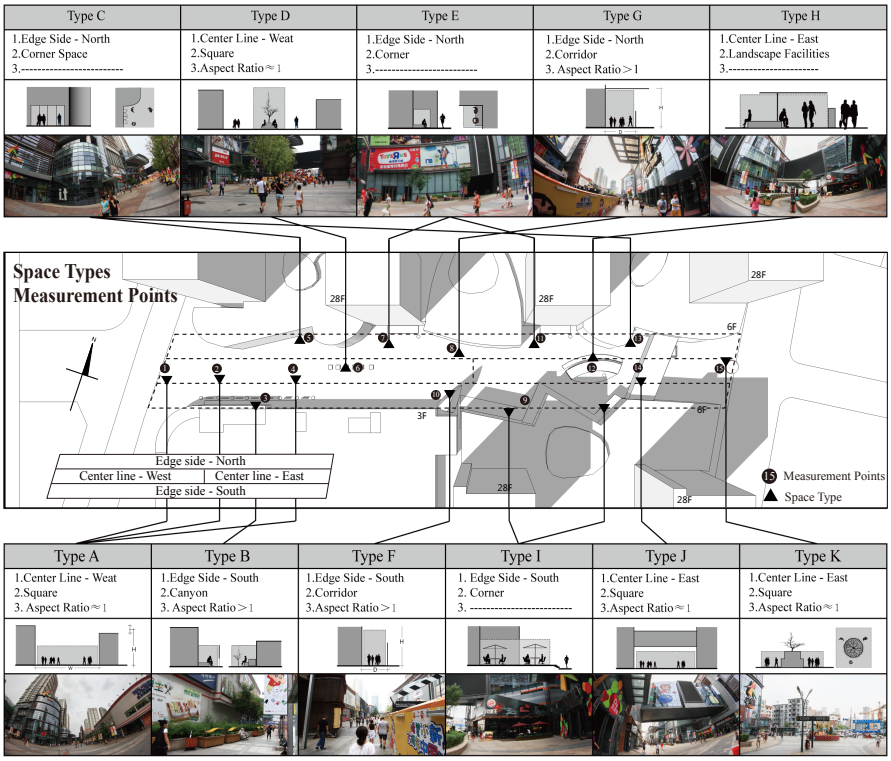


Figure 3-3 Spatial characteristics of each measurement point

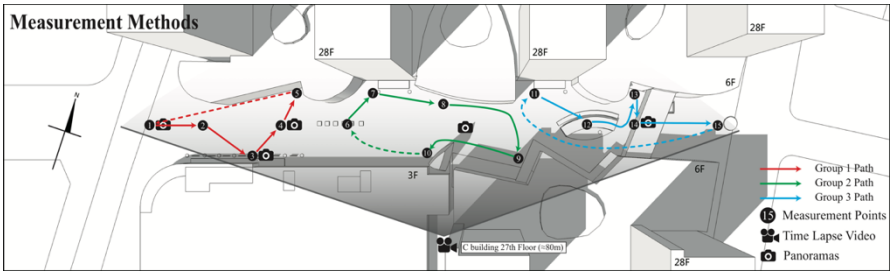


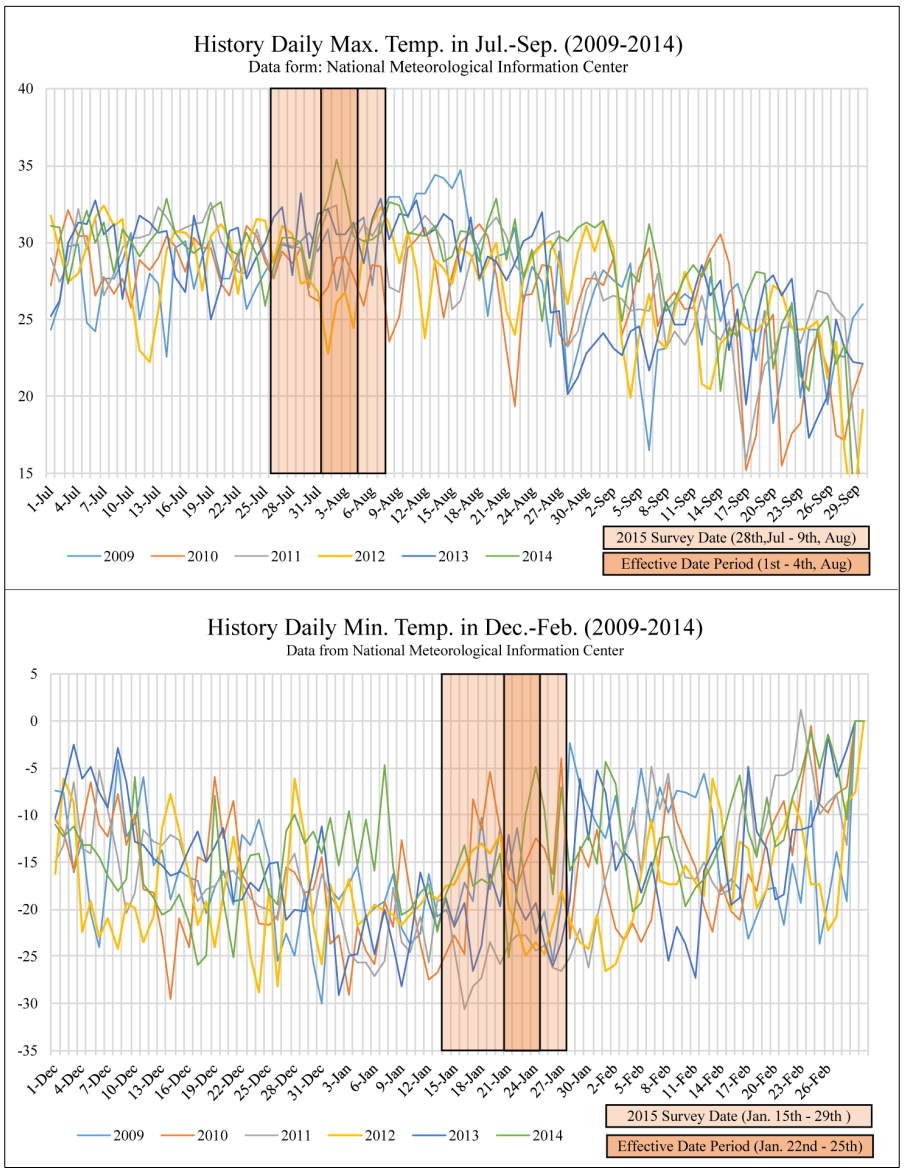
Figure 3-4 Measurement methods

3.2.2. Survey period

The main purpose of this study is to explore the impact of urban layout on the outdoor comfort and spatial behavior under harsh climate conditions to improve the comfort and utilization efficiency of open space through method of urban design. The research also provides urban design guidelines for the urban space under such complex and changing climate conditions.

Based on the 5-years (2009-2014) daily maximum and minimum temperature from Jul. to Sep. (summer) and Dec. to Feb. (winter), this study worked out the temperature graph of the hottest and coldest period in Shenyang during five year (Fig. 3-5). Depending on this five-

years data, Jul. 28–Aug.9, 2015 (12 days in summer) and Jan. 15–29 (15 days in winter), 2016 were chosen as the survey periods. Depending on the survey results, Aug. 1st-4th, 2015 (4 days), and Jan. 22nd-25th ,2016 (4 days) were selected as the summer and winter effective survey period.



Note: Weather station No.:54342 coordinates: 41°44 N, 123°31 E ASL=49m

Figure 3-5 History daily max. and min. temp. from Jul. to Sep. and Dec. to Feb., (2009-2014) [81]

3.2.3. Microclimate measurement

15 measurement points were chosen based on their positions and space types. In every 15 minutes during the survey days from 9:30 to

20:00, the microclimate data, including air temperature (T_a), air velocity (V), relative humidity (RH) globe temperature (T_g) and shade situations and environment comfortable sensation votes were collected.

Table 3-1 Measurement factors of micrometeorological parameters

Sensor	Parameter	Accuracy	Resolution	Range	Setting place
Kestrel 4500	V	3%	0.1 m/s	0.6 to 40.0 m/s	From point No. 1 to No. 15, 1.5m as the average height of the head.
	T_a	0.5 °C	0.1 °C	−29.0 to 70.0 °C	
	RH	3.0 %	0.1 %	5 to 95% non-condensing	
	WC (winter)	0.9°C	0.1°C	Refer to Ranges for the V and T_a Sensors	
TR-71Ui	T_g	0.3°C	0.1 °C	-40 to 110 °C	

Note: *Wind chill temperature (WC) result from combining the effect of wind speed and temperature. Calculated based on the NWS Wind Chill Temperature(WCT) Index* [95].

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 actual non-uniform enclosure" [96]. It is put forward based on the exchange of radiant energy between two objects by emitting and adsorbing heat. In this study, the T_{mrt} is estimated by the globe temperature method. Depending on the previous study, there are relatively small differences between the globe temperature methods and other complicated methods [97]. T_{mrt} is calculated based on the following formula [96]:

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10\times10^8 V^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273 \qquad (3)$$

where T_{mrt} is mean radiant temperature (°C), T_g is globe temperature (°C), T_a is air temperature, V is air velocity (m/s), D is globe diameter (m) (in this study D=0.075m), ε is emissivity (0.95 for black-colored globe).

Depending on the solar incident angle based on the Chinese Standard Weather Data (CSWD) [82] and the Chinese standard for

assessment parameters of sunlight on building (GB/T50947- 2014) [98], this study used software to simulate the shade situation in clear day as a reference of the general shade situation in Aug. 1st and Jan.22nd which can be realized as the hottest and coldest period.

3.2.4. CSV and TSV

Combined with the real-time microclimate data, a 7-points comfort sensation vote (CSV) [99] and thermal sensation vote (TSV) [100] for the subjective responses of preferred change was used by the subjects to record their comfort levels. According to this scale (see Table.3-2), -3 is very uncomfortable or very cold, 0 is neutral and 3 is very comfortable or very hot; any recording in CSV higher than -1 is defined as acceptable.

Table 3-2 Scale for subjective responses in comfort sensation used by subjects during the field surveys.

Value	*Thermal sensation vote (TSV)*	*Comfort sensation vote (CSV)*
-3	Very cold	Very uncomfortable
-2	Cold	Uncomfortable and unacceptable
-1	Cool	Uncomfortable but acceptable
0	Normal	Neutral
1	Warm	Slightly comfortable
2	Hot	Comfortable
3	Very hot	Very comfortable

Fig. 3-6 is the form used in the survey process, staffs need to collect the microclimate while fill this form at the same time. Each team member will record their own TSVs and CSVs into the table during the work period (usually not less than 1.5 hours). At the same time, the machine number, working hours, their own clothing index, work energy consumption, the measured points, the time displayed on the meteorological instrument, the shade situation of the current location and other information were also recorded.

In the analysis process, the data recorded in the form and the data measured by the meteorological instrument will be matched one by one according to the time and sorted into a unified data set for analysis.

Staff Comfort Situation Form V1.4

No.(Name Initial+Serial Number):_____

A.Basic Info.

1.Name No.:_____ 2.Machine No.:_____ 3.Work Period: _____ ~ _____ 4.Clo:_____

5.EC: A.Sit (Relaxed104 / Work126) B.Stand(Relaxed126 / Work167.4) C.Walk (2km/h-198 / 5km/h-360 / 15km/h-900)

B.Feel about the environment (Check in the blank when you move the weather meter.)

No.	Time	MP	S	ASV	-3	-2	-1	0	1	2	3
1				TSV							
				CSV							
2				TSV							
				CSV							
3				TSV							
				CSV							
4				TSV							
				CSV							
5				TSV							
				CSV							
6				TSV							
				CSV							
7				TSV							
				CSV							
8				TSV							
				CSV							
9				TSV							
				CSV							
10				TSV							
				CSV							
11				TSV							
				CSV							
12				TSV							
				CSV							
13				TSV							
				CSV							
14				TSV							
				CSV							
15				TSV							
				CSV							
16				TSV							
				CSV							
17				TSV							
				CSV							
18				TSV							
				CSV							
19				TSV							
				CSV							
20				TSV							
				CSV							

No.	Time	MP	S	ASV	-3	-2	-1	0	1	2	3
21				TSV							
				CSV							
22				TSV							
				CSV							
23				TSV							
				CSV							
24				TSV							
				CSV							
25				TSV							
				CSV							
26				TSV							
				CSV							
27				TSV							
				CSV							
28				TSV							
				CSV							
29				TSV							
				CSV							
30				TSV							
				CSV							
31				TSV							
				CSV							
32				TSV							
				CSV							
33				TSV							
				CSV							
34				TSV							
				CSV							
35				TSV							
				CSV							
36				TSV							
				CSV							
37				TSV							
				CSV							
38				TSV							
				CSV							
39				TSV							
				CSV							
40				TSV							
				CSV							

Note:

NAME No.: Initial+Date TIME: HH:MM EC:Energy Consumption (Unit-W) MP:Measurement Points S: √ In the Shadow × Not in Shadow √/× Half & Half

TSV (Thermal Sensation Vote): -3: Very Cold -2: Cold -1: Cool 0: Normal 1: Warm 2: Hot 3: Very Hot / CSV(Comfort Sensation Vote): -3~3 Uncomfortable-Comfortable

Figure 3-6 Comfort sensation form during field survey

3.2.5. Behaviour observation and behaviour analysis method

Through the spatial behavior record, the differences of spatial behavior caused by different spatial characteristics and microclimate factors in open space are analyzed and compared, and the spatial environment quality is evaluated by the spatial behavior as the feedback condition.

In the high position (27th floor in a high-rise building, approximately 80m tall), a Hi-Q video camera was used to record the

people's behaviour during the survey (Fig. 3-7). Panorama images were taken every 30 minutes at camera points to record the positions of people.

Fig. 3-7 shows the methods of behavior observation by using the video recording equipment during the investigation. Fig. 3-7 a is a screenshot of the image taken at seat No. 1, from which almost all the behavior that takes place in the field can be observed. Figs. 3-7 b c shows the placement situation of seat No.2 which are used to assist the observation in summer and winter. Figs. 3-7 d e shows the placement situation at point No.1. According to the video material, both overall analysis and fine analysis can be done.

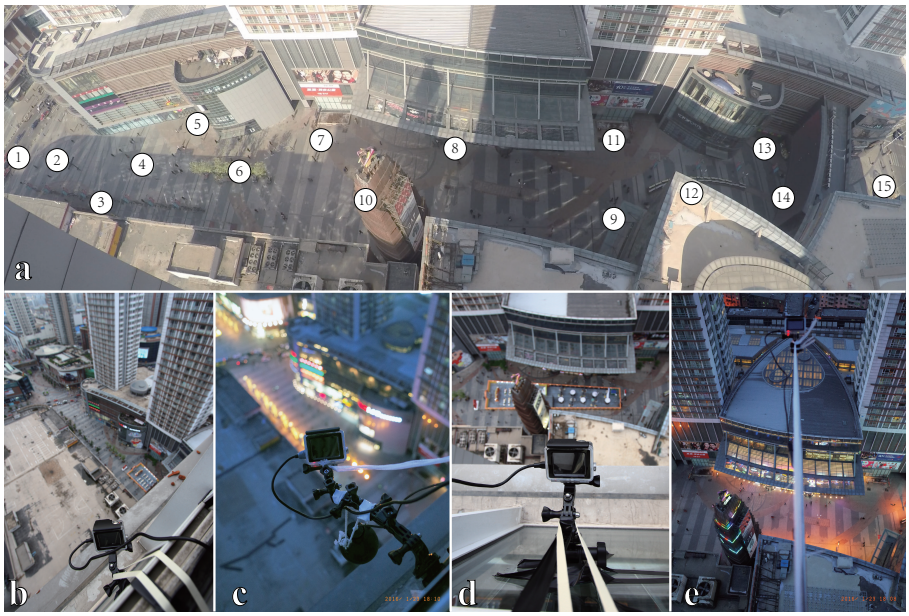


Figure 3-7 Methods of behavior observation by using the video recording equipment

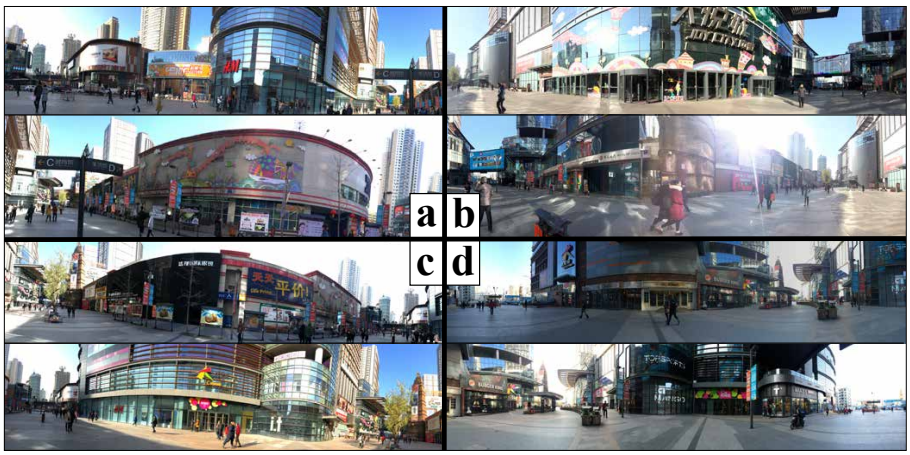


Figure 3-8 Panoramic photos took in 14:00 p.m. Jan. 23rd, 2016

The person present were counted as a comparison of sunny days in summer and winter by analyzing the panorama images and the time lapse videos in every 30 mins from 9:30 to 20:00.

Fig. 3-8 is panoramic photos from four camera points at 14 p.m. on January 23, 2016. Panoramic photos can make up the blind spots by high-altitude video data while providing clearer records of behavior and providing material for population statistics and behavioral analysis.

In the pedestrian routes, the study used the time lapse video to draw down the moving path of the pedestrians with the same quantity (150 pedestrians) during the lunch time (12:00-12:30) which can be realized as the busiest period during one day to analyze the different behaviors between different microclimate situations.

As shown in Fig. 3-9, The time lapse video was imported into the software of Adobe After Effect for moving object path analysis. In this study, the image data within half an hour was intercepted into three segments of 10 minutes each. Draw motion paths of 50 people in 10 minutes and finally add these three segments into one figure to get the behavior path analysis graph. According to the horizontal comparison of the action path, the use of space and the rules of the distribution of people flow can be found out.

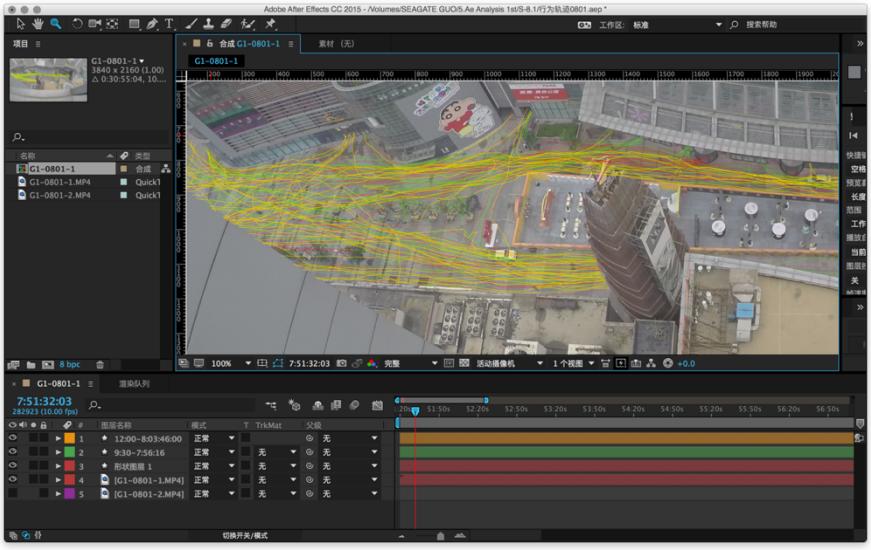


Figure 3-9 Path analysis in the software of Adobe After Effect

In the position maps, the study drew down the people's position for every 30 mins from 9:30 to 20:00, including the pedestrians and stationaries and integrate them into one picture and counted the quantity of users, including the pedestrians and stationary people. (Fig. 3-10)

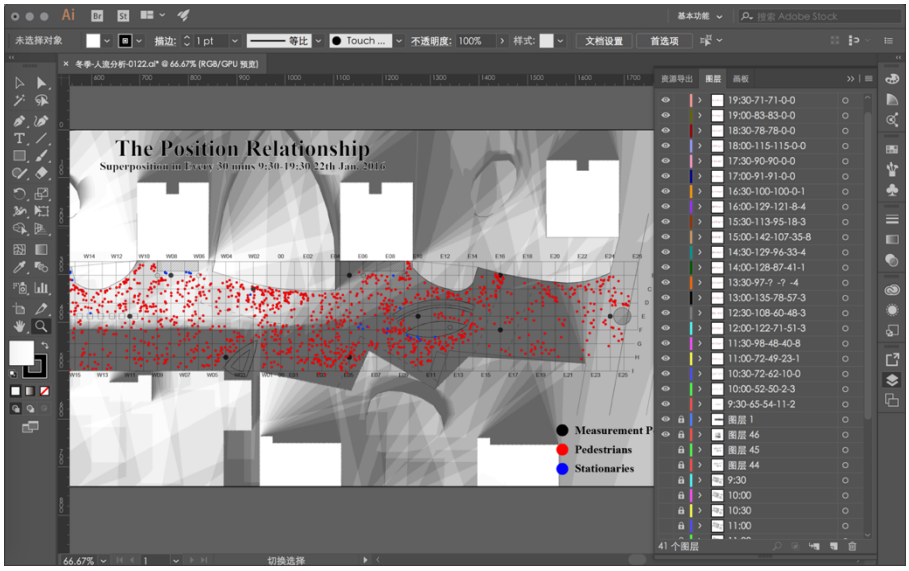


Figure 3-10 Position relationship analysis in the software of Adobe Illustrator

3.3. Results of field survey

During the survey, 2489 groups of microclimate data and the corresponding CSV in summer and 2501 groups in winter were collected. The measured T_a range were 24.4–35.9℃ in summer,

−21.6–2.2℃ in winter. The maximum temperature range between summer and winter was 57.5℃. The measured air velocity range were 0–7.1 m/s in summer and 0–4.8 m/s in winter. The mean air velocity in summer was 1.2m/s higher than in winter (1m/s). The RH range were 36–100% in summer (mean RH was 38.8%) and 20–56.2% in winter (mean RH was 20%).

3.3.1. Comfort sensation and microclimate

Tables 3-3 & 3-4 displays the correlations [101] between CSV and shade situation, T_a, V, RH, T_{mrt} and WC by using the software IBM SPSS Statistics (Version 20.0.0) (N_{summer}=2489, N_{winter}=2501). It can be used to evaluate the microclimate elements which will affect the comfort level greater. The higher the correlation coefficient, the greater influence on comfortable level. A measure of linear correlation between the two variables X and Y, a value is given between +1 and −1, inclusively, with 1 indicating total positive correlation, 0 indicating no correlation, and −1 indicating total negative correlation.

The results indicated that in summer, all measured factors affected CSV significantly. Among them, shade had the highest correlation (r=−0.464) with CSV, followed by RH (r=0.449). T_a was third, with a coefficient of −0.421, follow by the Tmrt (r=−0.234). The weakest correlation with CSV was air velocity, with a coefficient of 0.222. More shade, lower T_a, higher air velocity, and higher RH improved sensations of comfort.

In winter, the RH cannot be measured precisely, it also cannot be used as evaluation part for comfort level. Instead, wind chill is employed as an important part for comfort evaluation. There are significant correlations between CSV and all measured factors. Tmrt affected CSV most with a coefficient of 0.336, followed by wind chill (r=0.310). Correlation coefficients decreased gradually from T_a (r=0.298) and shade (r=0.236) to air velocity (-0.074). Higher wind chill, less shade, higher T_a, and lower air velocity improve sensations of comfort.

Consequently, all the parameters mentioned in this part will affect the CSV more or less. However, there is no correlation coefficients above 0.5, that is, no single parameter will affect the CSV as a leading role. All the factors have come together on the comfort level.

Table 3-3 Correlations between comfort sensation votes (CSV) and microclimates in summer

		CSV	Shade	T_a	T_{mrt}	V	RH
summer	CSV	1					
	Shade	-.464**	1				
	T_a	-.421**	.288**	1			
	T_{mrt}	-.234**	.250**	.215**	1		
	V	.222**	-.080**	-.157**	.216**	1	
	RH	.449**	-.287**	-.685**	-.283**	.165**	1

** *Correlation is significant at the 0.01 level (2-tailed).*

CSV-comfort sensation votes, T_a- air temperature, T_{mrt} – mean temperature radiant, V-air velocity, RH-relative humidity.

Table 3-4 Correlations between comfort sensation votes (CSV) and microclimates in winter

		CSV	Shade	T_a	T_{mrt}	V	WC
winter	CSV	1					
	Shade	.236**	1				
	T_a	.298**	.036**	1			
	T_{mrt}	.336**	.157**	.461**	1		
	V	-.074**	-0.008	.124**	.260**	1	
	WC	.310**	.038*	.894**	.321**	-.290**	1

** *Correlation is significant at the 0.01 level (2-tailed).*

CSV-comfort sensation votes, Ta- air temperature, Tmrt – mean temperature radiant, V-air velocity, RH-relative humidity.

Previous studies had demonstrated that shade affect the solar radiation, thus affect the thermal sensation greatly [102 103]. Among the microclimate parameters, shade situation is easy to be distinguished and calculated. Therefore, separating the shade situation to analyze the relationship among mean CSV, microclimate factors and time may provide some distinct insights on the outdoor environment research.

Figs. 3-11 a & b shows the relations among microclimate factors and CSV as a function of time in different shade situations, the following results were obtained:

In summer, CSV curves in and out of shade are obviously separate. In the morning (before 10:00 a.m.) the CSV was higher than other periods. In the evening (after 5:00 p.m.), most people feel comfortable. T_a and RH change with time gradually. From morning, T_a increase gradually until 14:30 p.m. After 14:30 p.m., the T_a started to decrease gradually. The RH was opposite to the T_a with higher rate of change. Air velocity was not about time but significantly affects instantaneous CSV.

In winter, all the measured CSV was below 0 Celsius temperature. From morning, CSV curving in and out of shade separated gradually. From 13:00 p.m. to 15:00 p.m., higher CSV can be measured especially out of the shade. T_a and RH changed gradually with time, however, wind chill changed with air velocity, significantly affected instantaneous CSV.

Consequently, the RH and T_a will change with time. It can be suggesting that according to the solar radiation and spatial characteristics, some of the microclimate factors will change gradually with time. Meanwhile, the air velocity which is not related to time will also affect the CSV significantly. By according to the ruler guide in Figs. 3-11 a & b, almost all the instantaneous change was due with the air-flow.

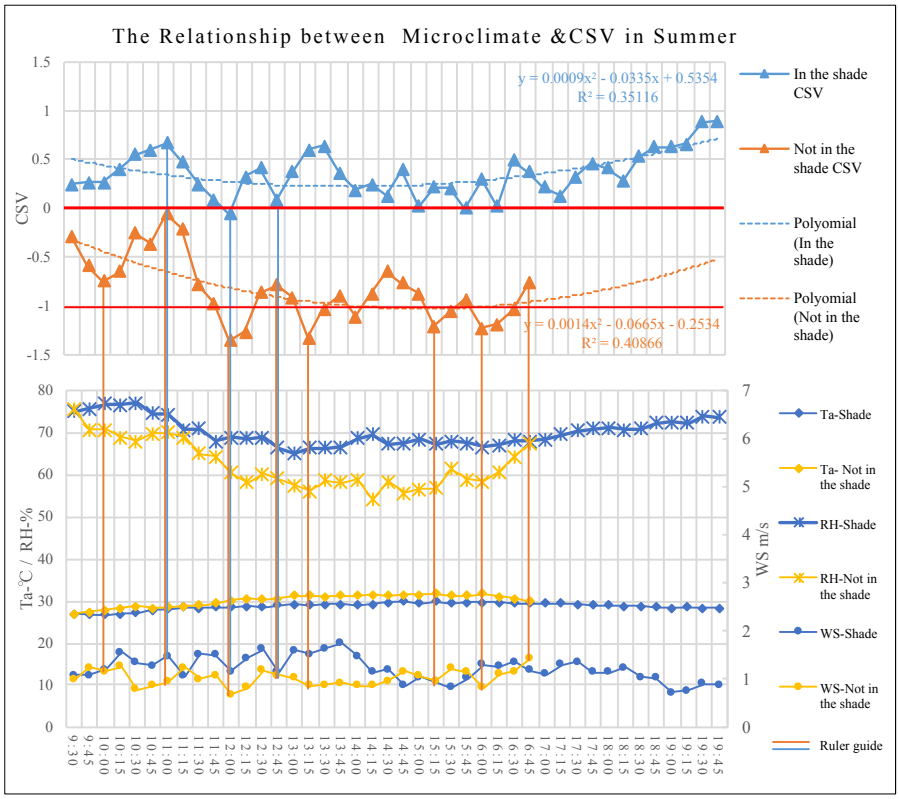


Figure 3-11a Relationships among mean CSV, microclimate factors with time in different shade situations in Summer

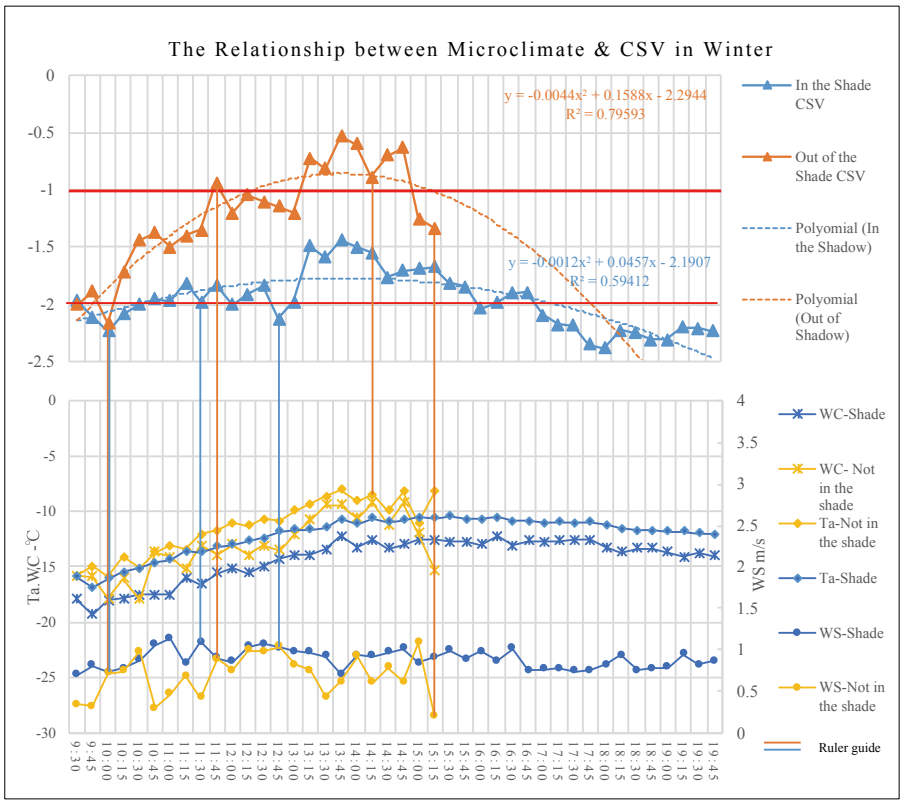


Figure 3-11b Relationships among mean CSV, microclimate factors with time in different shade situations in Winter

By analyzing mean CSV at the same ambient temperature, air velocity, and relative humidity in summer, ambient temperature, air velocity, and wind chill in winter, the following change trends were found: In summer, as Figs. 3-12 a, b & c show, CSV decreased with increasing ambient temperature, decreasing air velocity, and rose in relative humidity. Among these meteorological parameters, 29.6°C of T_a, 1.1 m/s of air velocity, and 67% of RH were threshold values for whether the environment was comfortable or not. When the T_a is higher than 31.9°C and the RH is lower than 52%, it can be seen to be uncomfortable situation. To sum up, in summer, lower ambient temperature, higher air velocity and relative humidity are more comfortable.

In winter, all the CSV was below 0°C, that is, all the measured microclimate cannot satisfy people's comfort level. CSV decreased with increasing air velocity and decreasing ambient temperature and wind chill (Figs. 3-13 a, b & c). Among them, −14.4°C of T_a, −16.5°C of WC, and 1.6 m/s of air velocity were environmental threshold values that can be accepted or not. Consequently, in winter, lower air velocity, higher ambient temperature and wind chill will make the outdoor environment more comfortable.

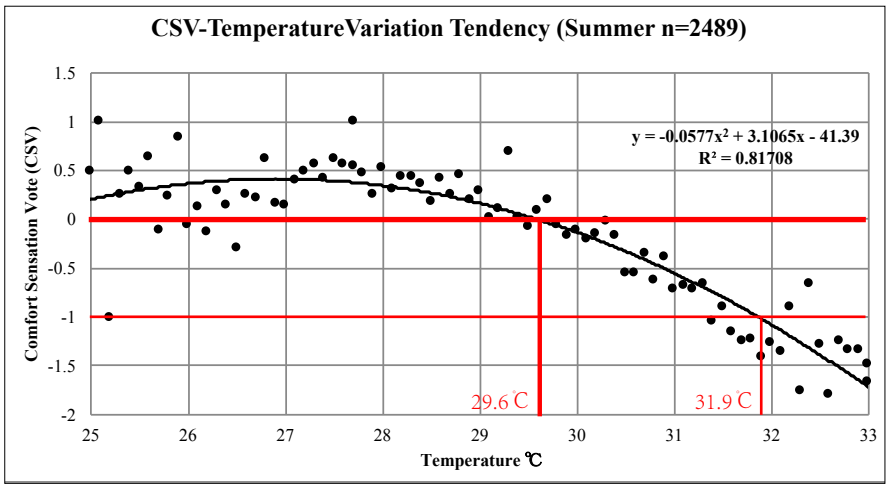


Figure 3-12a CSV- ambient temperature variation tendency (Summer)

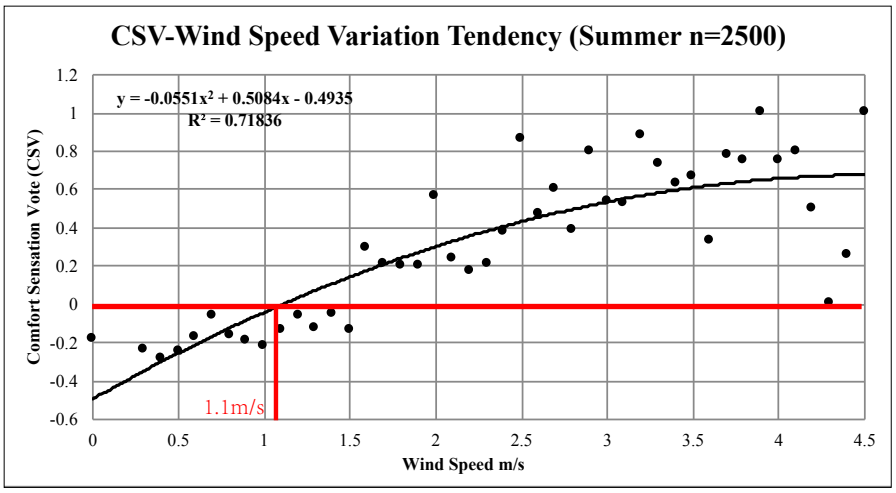


Figure 3-12b CSV- air velocity variation tendency (Summer)

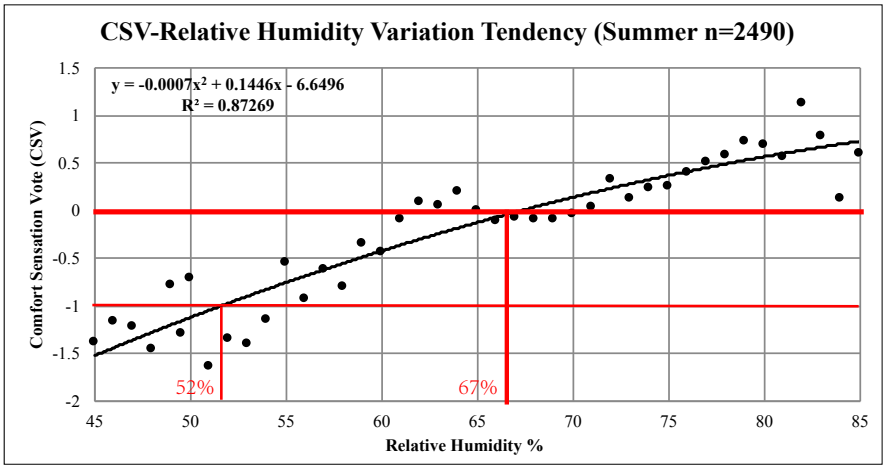


Figure 3-12c CSV- relative humidity variation tendency (Summer)

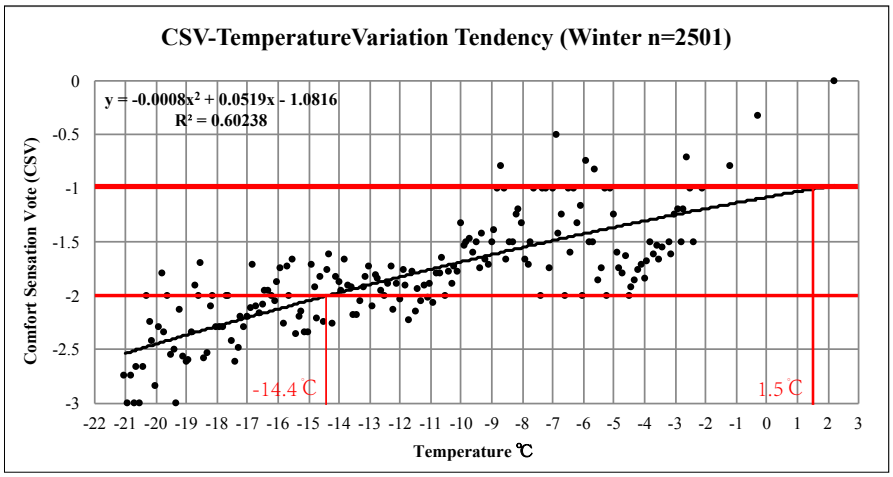


Figure 3-13a CSV- ambient temperature variation tendency (Winter)

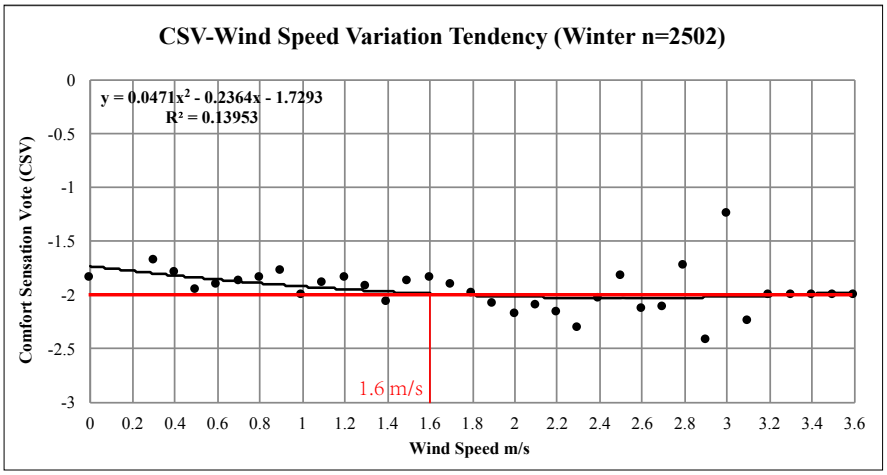


Figure 3-13b CSV- air velocity variation tendency (Winter)

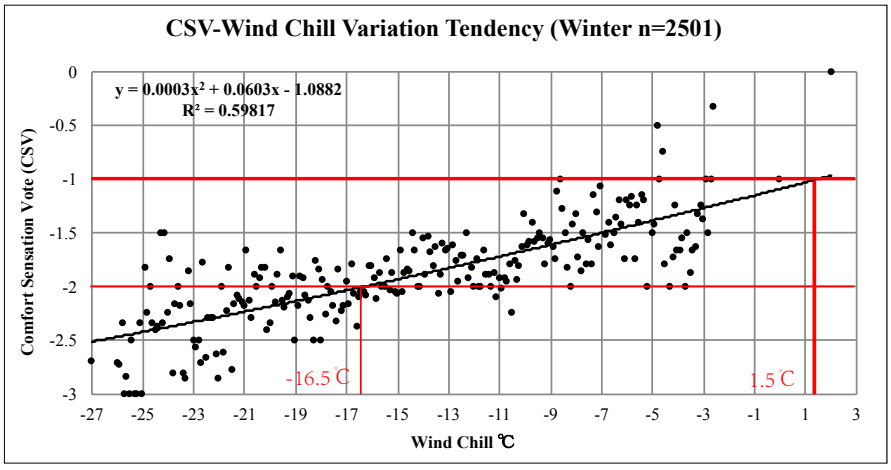


Figure 3-13c CSV- wind chill variation tendency (Winter)

In Fig. 3-14, for every 0.5K of PET interval, the mean CSV was calculated in both summer and winter as suggested by Ref. (Lin, 2008) [104]. The PET ranges were −31.7 to 3.1℃ (cold season) and 21 to 40.9℃ (hot season). Linear regression was conducted as follows:

Cold season:

$$y = 0.0497x - 1.1394 \quad (R^2 = 0.86436) \qquad (4)$$

Hot season:

$$y = -0.1043x + 3.1178 \quad (R^2=0.71803) \qquad (5)$$

The correlation between mean CSV and PET in both summer and winter were higher than 0.7 (R^2=0.86 in winter, R^2=0.72 in summer). The regression coefficients were 0.0497 in winter and −0.1043 in

summer. The results indicate that comparing with the cold season, the residents in Shenyang were more sensitive to hot season. With the scale for subjective responses about comfort sensation in Table 2, the unacceptable PET range is lower than −17.32℃ in winter. The neutral PET is 29.89℃ in summer.

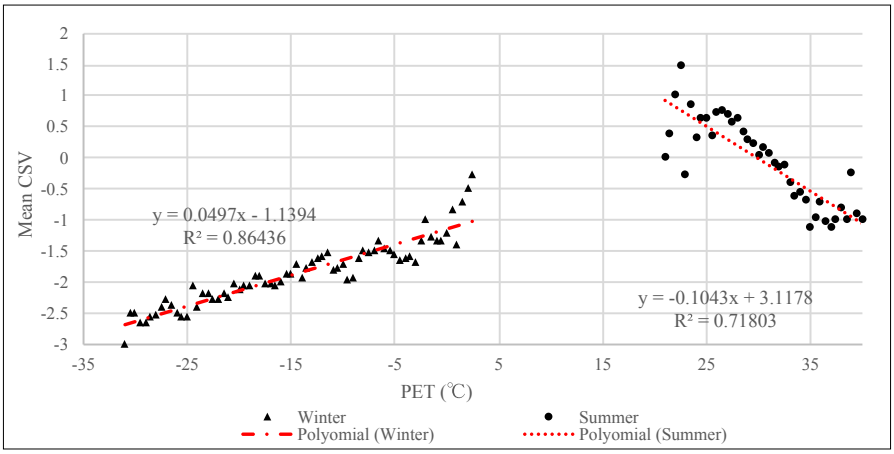


Figure 3-14 Relationship between mean CSV and PET

3.3.2. Tmrt and Ta

In summer, measured mean air temperature and calculated mean radiant temperature (T_{mrt}) on clear and overcast days were shown in Figs.3-15 a & b. The measurement point for this comparison was set on point No.11 where can get sunlight before afternoon on clear day and change slightly on air velocity during whole day.

The different of air temperature and mean radiant temperature between clear day and overcast day was shown. The difference of mean air temperature between two days was 6.13℃. During the clear day, higher temperature was recorded. The effect of shade on the magnitude of T_{mrt} was also clearly shown. Depending on the Figs. 3-15 a & b, on the clear day, when the measurement point was exposed in sunlight before 13:00 a.m., the T_{mrt} is significantly higher than the air temperature. When the building shade fell over the measurement point, slightly higher T_{mrt} than air temperature was recorded. The same result was also found in overcast day.

During the winter survey, two measurement points of T_g were chosen since the solar incident angle is too low to provide enough

sunlight for the whole area, neither to guarantee one measurement point can get long time sunlight during the survey. As shown in Figs. 3-16 a & b, the source data of $T_{mrt}1$ was from the measurement point located at a high position where can receive sunlight all the time during the clear day. It can be used to calculate the mean T_{mrt} at the survey area suffered sunlight. the source data of $T_{mrt}2$ was from point No.11 where cannot get sunlight during whole day in winter. It can be used to calculate the mean T_{mrt} at the survey area without suffering sunlight.

By comparing the data in two-days, significant difference between the Tmrt exposed to the outdoor space in sunlight and in shade. The T_{mrt} value in the shadow is almost indistinguishable from the outdoor air temperature.

By comparing the data in summer and winter, the influence of solar radiation on air temperature in winter and summer is not obvious, but the impact on T_{mrt} and the change is very significant. T_{mrt} is also an important index that affects the thermal comfort of the human body. It can be learned that the presence or absence of sunlight and the amount of existence directly and significantly affect the comfort level of the human outdoor space.

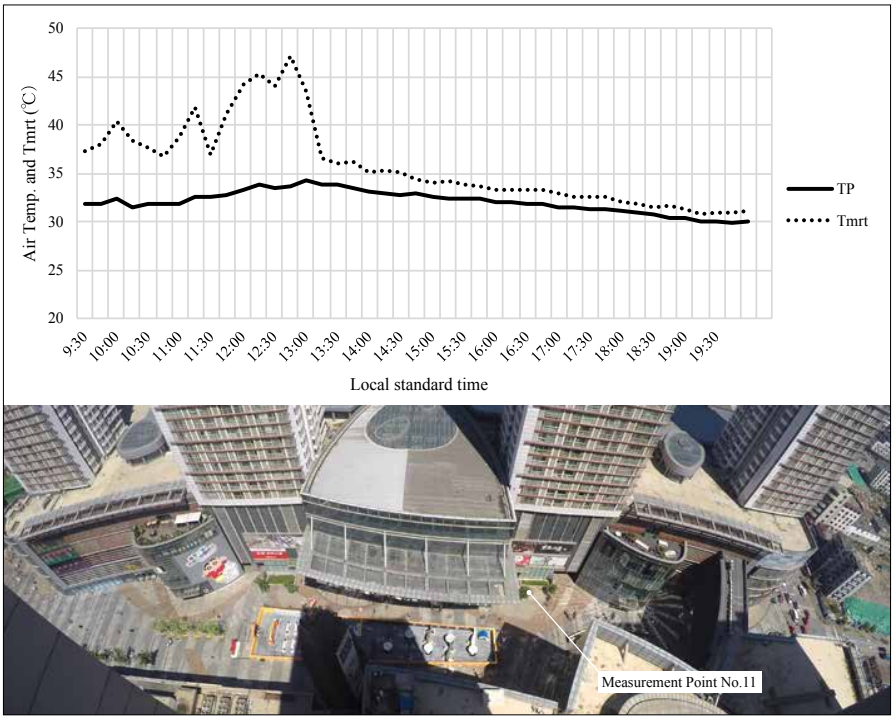


Figure 3-15a Measured mean T_a and calculated T_{mrt} on a clear day (5th Aug. 2015) and the photograph at 10:30 a.m.

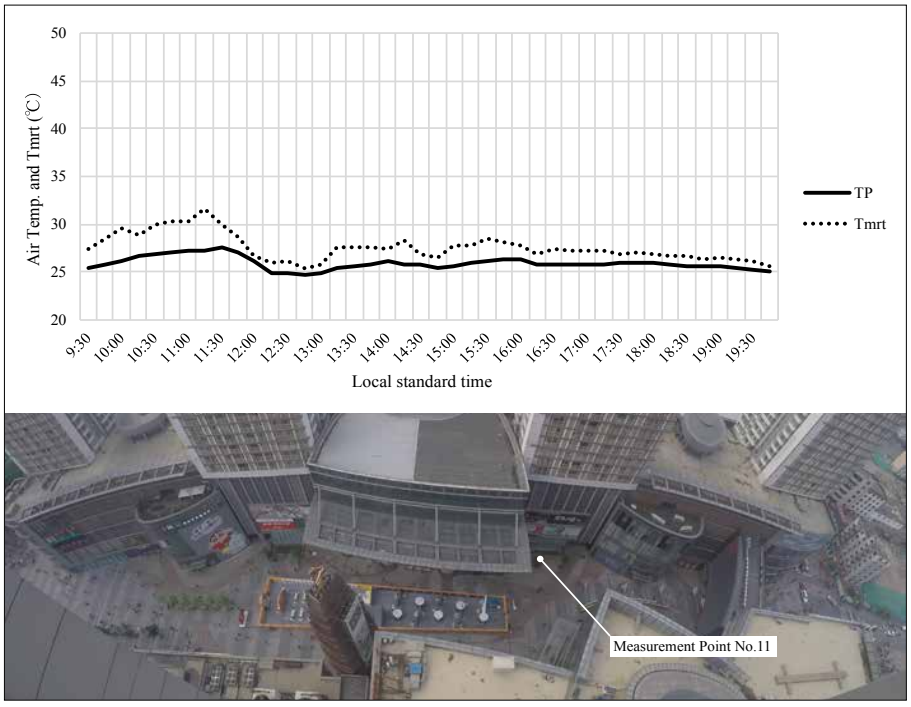


Figure 3-15b Measured mean T_a and calculated T_{mrt} on an overcast day (6th Aug. 2015) and the photograph at 10:30 a.m.

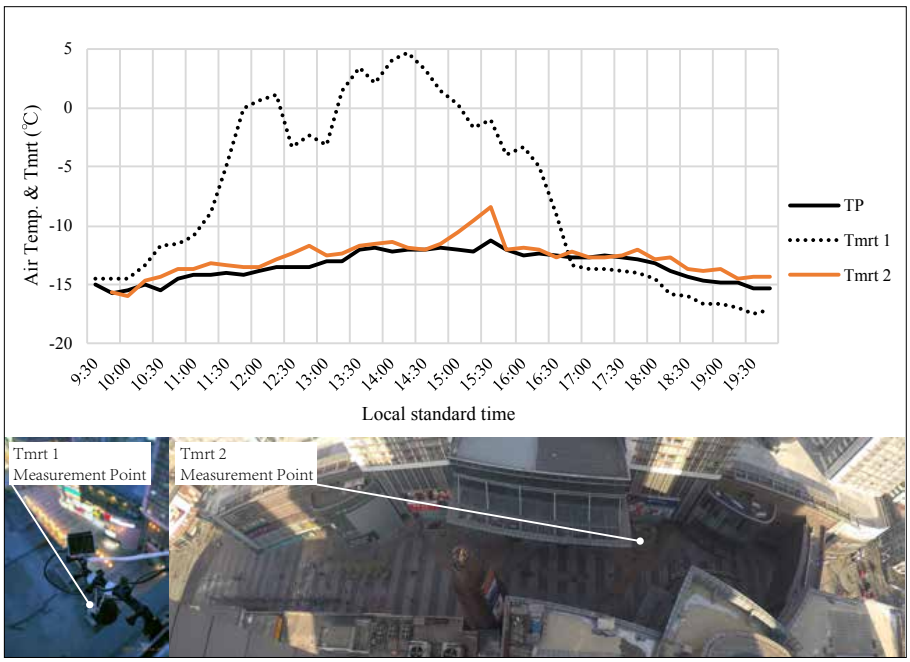


Figure 3-16a Measured mean T_a and calculated T_{mrt} on a clear day (22nd Jan. 2016) and the photograph at 10:30 a.m.

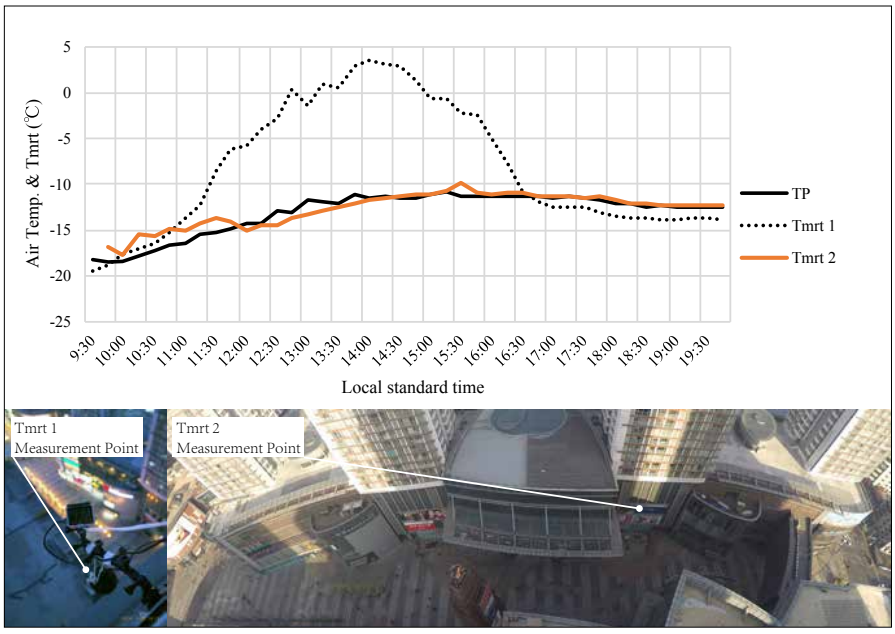


Figure 3-16b Measured mean T_a and calculated T_{mrt} on a clear day (24th Jan. 2016) and the photograph at 10:30 a.m.

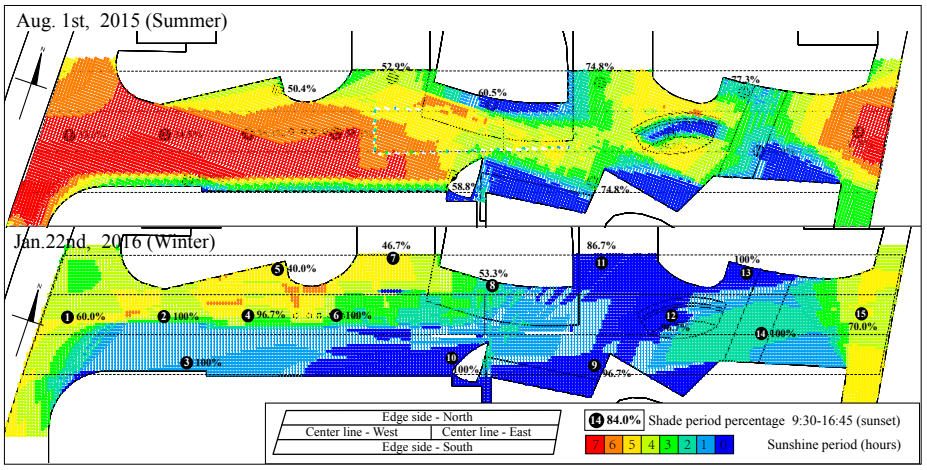


Figure 3-17 Simulation analysis of the strongest and weakest sunshine periods in winter and summer

According to the correlation analysis in 3.3.1, however, a comfortable environment need longer time of sunlight in cold season and shorter time of sunlight in hot season. According to the results of simulation analysis of the strongest and weakest sunshine periods in winter and summer in the research area (Fig. 3-17), the above demand is just the opposite of the actual situation, in other words, if the existing conditions are adjusted to comfort ones, manual intervention should be done on adjusting the lighting time by design techniques.

It should note that, however, the results in specific days may be subject to several errors. Nevertheless, combining with the above correlation results, and several previous studies, shade will play an important role on people's comfort [105-108]. It can be considered as higher priority to separate the other factors on analyzing the outdoor situation.

3.3.3. Microclimate analysis at each measurement point

Microclimate comparison among different areas and points were conducted. Based on different spatial characteristics, the results of microclimate are as the Figs. 3-18 a & b. In summer and winter, the ambient temperature and humidity did not show large differences among each point. Relative humidity at north side where can get more sunlight was lower. Air-flow affected by the spatial forms at center line was higher than edge sides. The highest mean air velocity in both

summer and winter were found at the point No.14, where located at the narrowest place in canyon. The lowest mean air velocity was in No.5 located at building corner which can be realized as shelter from the wind.

Furthermore, the mean CSV show regularity as different microclimate. In summer and winter, the mean CSV distributions are just opposite to each other. In summer, the highest mean CSV was found at the east center line where located at the long shade and relatively narrow space with high air-flow. The lowest mean CSV was located at west center line named as unshaded and wide area where suffered relatively low air velocity. In winter, the north edge space with relatively lower air velocity and short shade got the highest mean CSV. The east center line with higher air velocity and longer shade got the lowest mean CSV. Consequently, different spatial forms will cause different microclimate conditions, thus affect the comfort level. The air velocity and shade situation are the two factors that easy to be affected by spatial form.

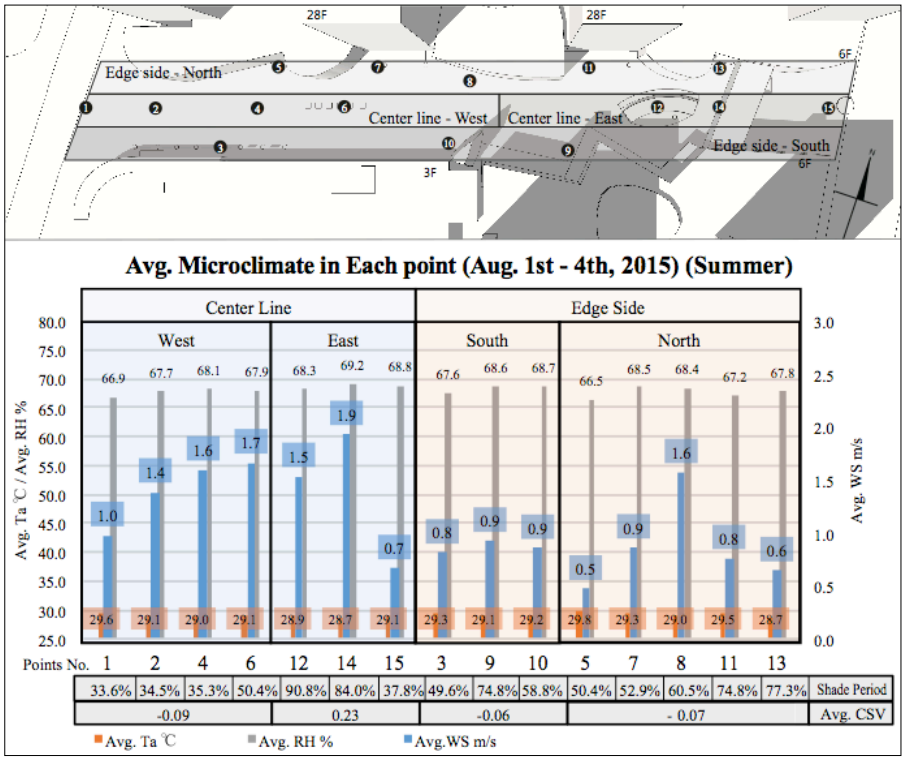


Figure 3-18a Mean microclimate data at each point with mean CSV (summer)

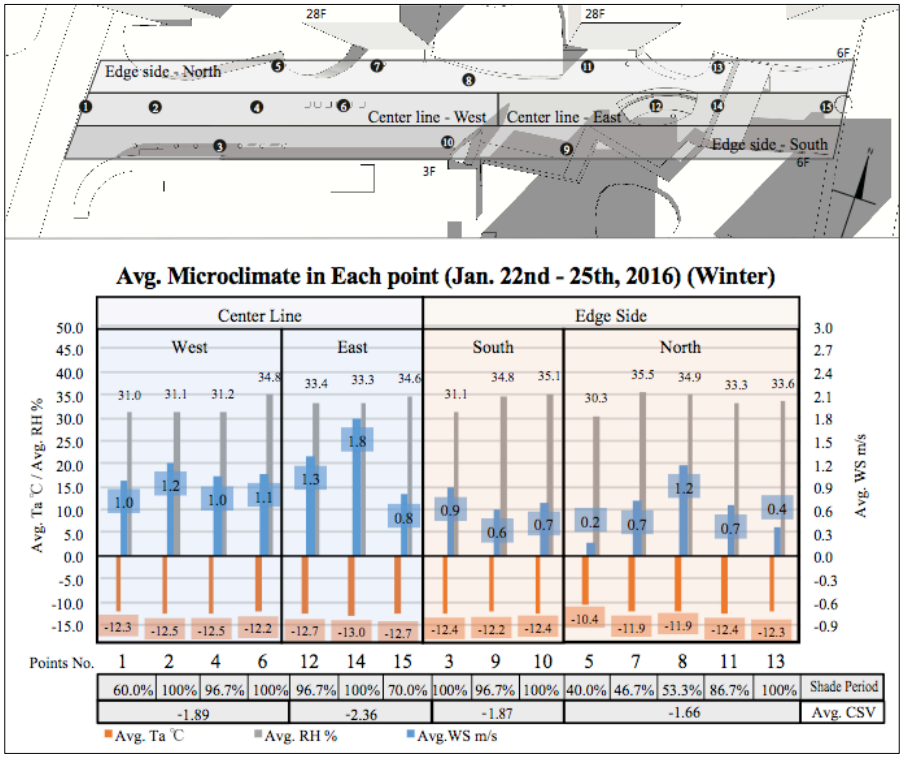


Figure 3-18b Mean microclimate data at each point with mean CSV (winter)

Two special points (Nos.5 & 14) with extreme microclimate were chosen to evaluate the microclimate factors difference during a continuous period (Aug. 1st-4th, 2015 in summer, Jan. 22nd-25th, 2016 in winter). These two points also had relatively exceptional T_a and RH. In Fig. 3-19, there are huge difference in air velocity and temperature between No.5 and No.14. Air velocity at No. 14 which is located at canyon "entrances" was higher than at Nos. 5 located at building corner. According to the previous study by H. Wu (1994) [109], the skyway above the point No.14 can be seen as a diverter of air-flow. The wind pass through the skyway was separated into two parts. The area of air duct was decreased by the skyway. The air volume per unit area was increased. That caused the air velocity under the skyway to increase. The building corner at No.5 can resist the air-flow from the vertical direction. At the same time, it can also lead the air-flow from parallel direction to skim over the corner.

Differences in T_a between the highest point (No. 5) and lowest point (No. 14) vary with shade situations. The difference in temperature between these two points can reach 6.4℃ in summer and 9.5℃ in winter. In terms of their spatial characteristics, No. 5 is located at the north edge of the building and is exposed to sunlight and solar reflection from the glass building. On the contrary, No. 14 is under the skyway with almost no sunlight all day long; it is also far from the building's reflection. Therefore, people can feel higher CSV at No. 14 in summer, with lower ambient temperature, and lower CSV at No. 5 in winter.

Consequently, because of the different spatial forms, there are huge differences on microclimate in the same place to affect comfort sensation.

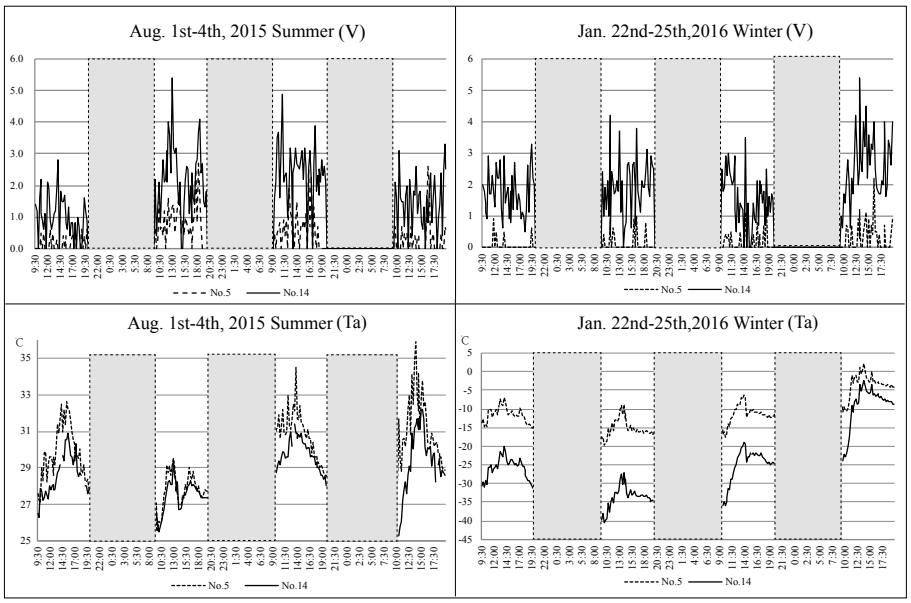


Figure 3-19 Air velocity and ambient temperature distributions at measurement points Nos. 5 and 14 in summer and winter

3.3.4. People present study with time

People present study is another way to evaluate the environmental quality. Two days (Aug. 4, 2015 in summer and Jan. 22, 2016 in winter) were chosen to compare the differences between summer and winter by the following reasons: First, two days were all clear days. There were no influences by cloud. Secondly, these two days were all workdays and there were no commercial events during the survey periods. The pedestrian volume can be seen as normal levels. As Fig. 3-20 shows, both in summer and winter, total numbers relate to the time of day. The average total number in summer (212.10) was twice than that in winter (99.76). The least number of people were recorded during the morning (9:30−10:30) in both summer and winter. Since all the shopping malls open at 10:00, it can be speculated that the number of people affected by the function of open space.

In summer, during the afternoon, the total number was least at 14:30, but after sunset (no direct sunlight in the study area) at about 16:45, numbers of people increased substantially. In the outdoor space, approximately 30% of people were stationary. Before sunset, the number of stationary people remained stable, and approximately 60% of them stayed in the shade. Hence, afternoon before sunset was the

most unpopular time in summer, but after sunset, more people came outside.

In winter, the biggest number of people were recorded around 3 o'clock p.m. People not in the shade related significantly to time change, and there were almost no stationary people outside. Consequently, from lunchtime (12:00−13:00) to sunset at about 16:30 was the most attractive period for people in winter.

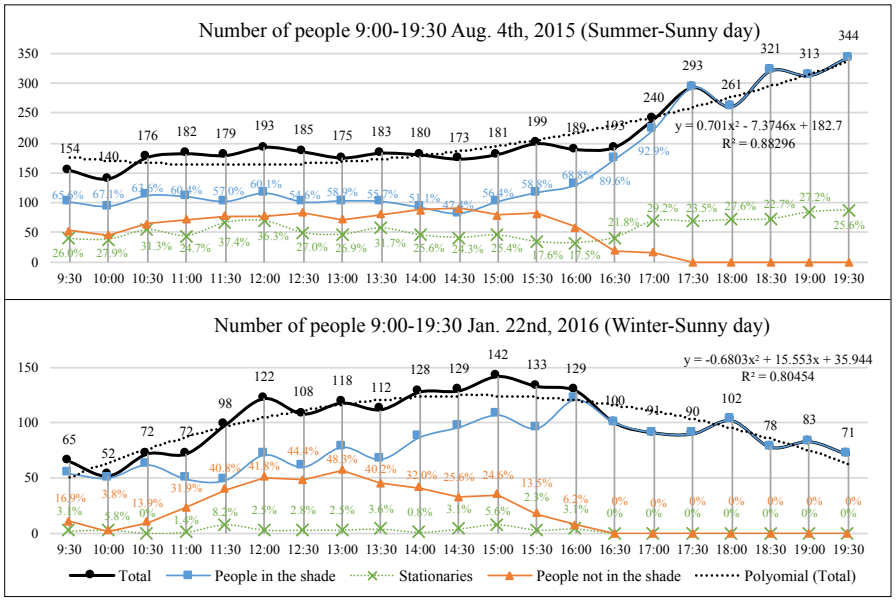


Figure 3-20 Number of people present in sunny day at research site (Aug. 4, 2015 and Jan. 22, 2016)

3.3.5. Spatial behaviour

Spatial behaviors study was conducted in two clear days (Aug. 4, 2015 and Jan. 22, 2016) between summer and winter. On the basis of solar simulation and high-resolution photographs, the position of people was recorded every 30 minutes. Figs. 3-21 a & b shows the analyses of position relationships with shade simulation results. The uneven shade distributions which cause the different outdoor activities.

In summer, according to the results at 3.3.3, the south side suffer higher CSV than north. The area in west center line is not popular by pedestrians. Instead, as Fig. 3-21a shows, the east side with long periods of shade, abundant seats and other facilities can gather more people than the west side. There are sufficient seats inside the shade at

the Nos. 3, 9, 11 and 12, and there are also seats under vegetation which can provide shade at No. 6. Most of the stationaries will choose these places to stay. From the above, the necessary factors for the people who stay outside in summer are shade and rest facilities.

In winter, as shown in Fig. 3-21b, people distribute evenly. Shade and rest facilities do not affect the position distribution seriously. Meanwhile, a few of people who stay outside will choose sunlight place or the place related to their behavior, for example: the entrance of the supermarket or the shopping mall or the subway station. The rest facilities and shade are not the necessary factors of attracting people to stay or sit outside in winter.

Consequently, the practical action of people is not only affected by microclimate, but also affected by the arrangement of rest facilities.

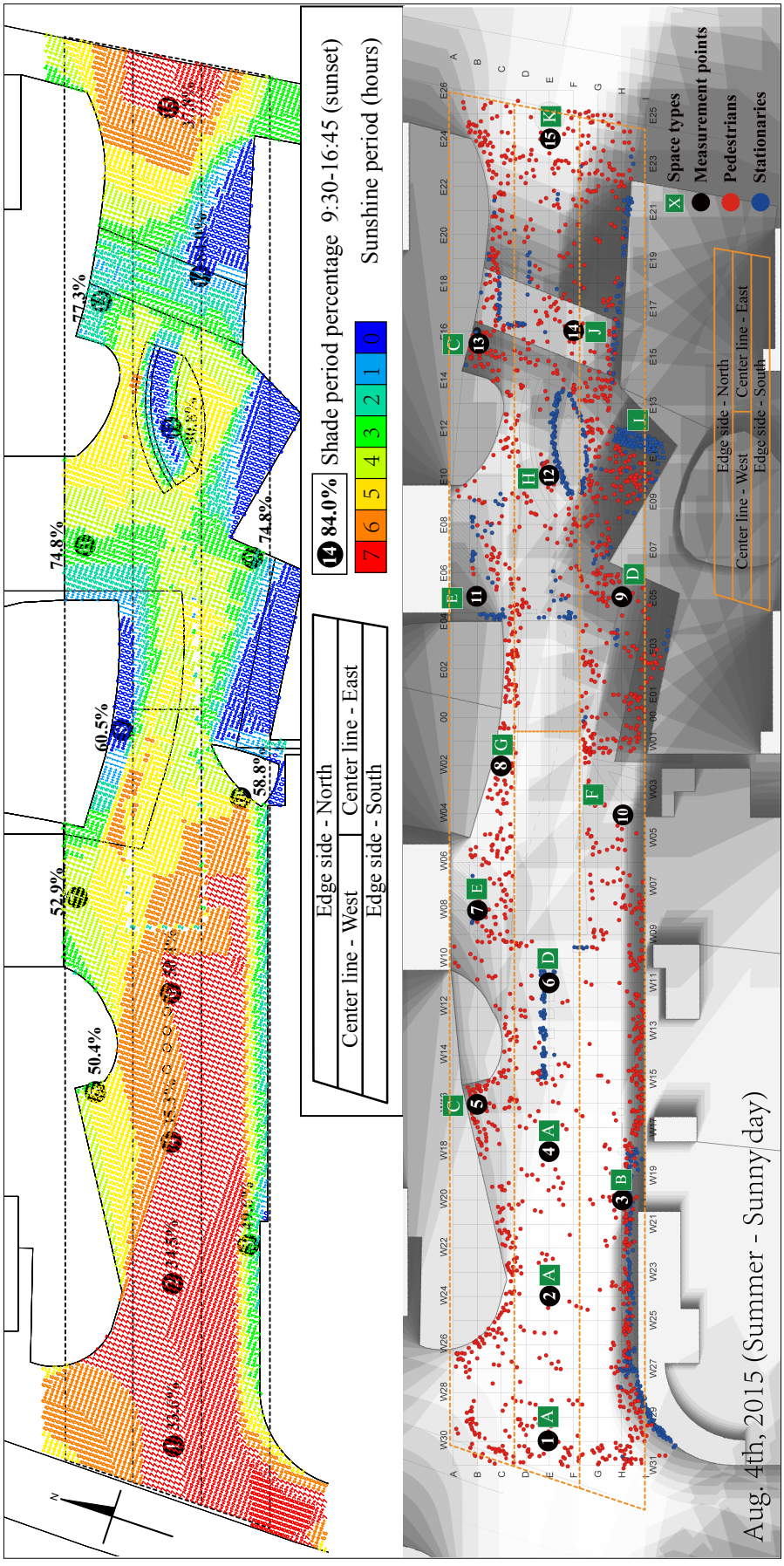


Figure 3-21a The position relationship with shade situation in summer

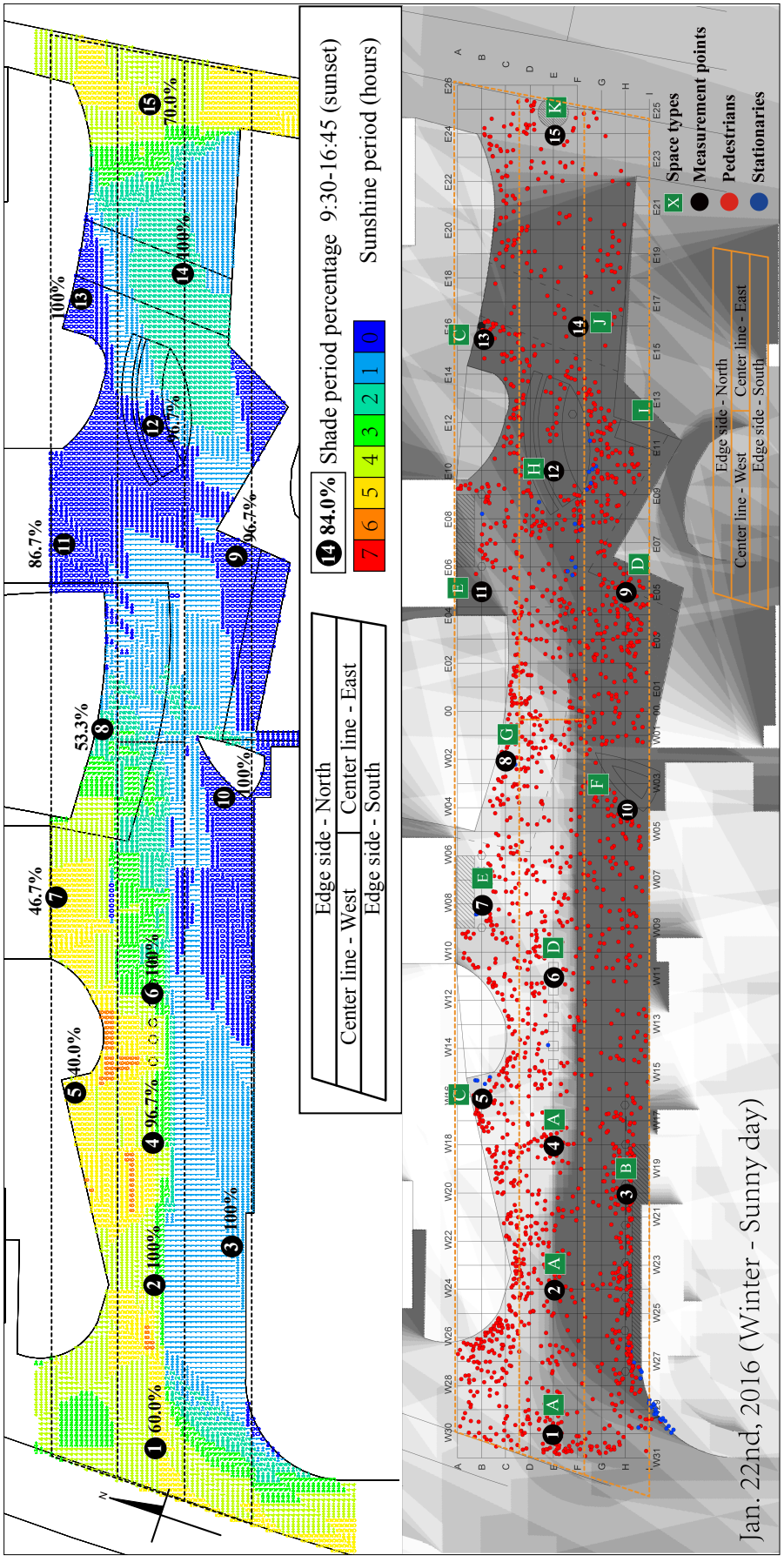


Figure 3-21b The position relationship with shade situation in winter

The study also picked up the lunch time during these 2 days to draw down the pedestrian routes. The characteristics of pedestrians were analyzed with the same quantity between different microclimate situations. As shown in Fig. 3-22, when the number of analyzed people is equal, the general routes are in the east-west direction (left-right direction). All the pedestrian routes are curved with almost no straight lines. In both cases, the pedestrian routes tend to be thicker at the edge of the buildings and the narrow space (space type F and G). When the space becomes wider, the routes tend to be laxer. Narrow canyon type space and the cross-flow are the space disadvantages for pedestrians. Pedestrians can choose any path in this case. It will create interferences between the pedestrians and stationary people, such as space types D (No. 6) and E (No. 7), because there are almost no boundaries or separations between the static space and dynamic space. However, a static place that has sufficient space in front does not cause as much interference with pedestrians, such as space types I and E (No.11). Also, some triangular blank areas are formed by angular space edges and curved pedestrian routes. Both pedestrians and stationary people do not tend to choose this type of space that has the potential for interference.

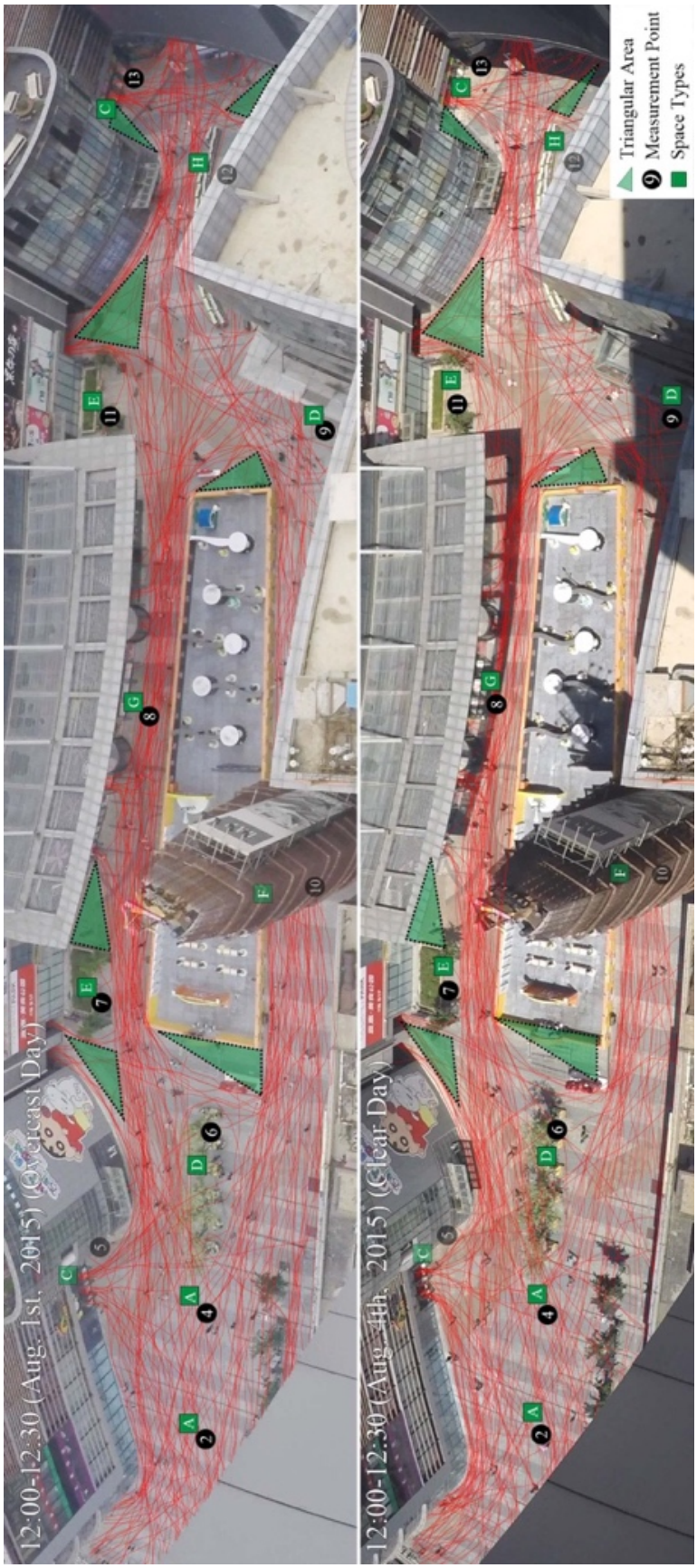


Figure 3-22 Pedestrian routes comparison between clear day (1st, Aug) and overcast day (4th, Aug)

3.4. Conclusion

By using microclimate and human comfort as standards for environmental evaluation, this research conducted a field survey at a downtown pedestrian street both in hot summer and cold winter which have not been studied in the past. By analyzing how extreme weather situations influenced human behaviour and comfort, the study aimed to discover the microclimate associated with open space use, to support further open space design. The survey has demonstrated the following:

• Microclimate obviously affected people's comfort. In addition, the influence effect in summer and winter were distinct. No single parameter will affect the spatial comfort as a leading role. All the factors have come together on the comfort sensation.

• In summer, lower T_a, higher air velocity, RH and more shade brought higher CSV. 29.6°C of T_a, 1.1 m/s of air velocity, and 67% of RH were threshold values for whether the environment was comfortable or not. In winter, higher T_a, lower air velocity and less shade, caused higher CSV. −14.4°C of T_a, −16.5°C of WC, and 1.6 m/s of air velocity were environmental threshold values that can be accepted or not.

• The residents in Shenyang were more sensitive to hot season than cold season.

• Among all meteorological factors, change of T_a, RH, and shade situation were closely related to time and changed evenly. However, air velocity changed unevenly and significantly affected instantaneous comfort.

• Spatial form affected the shade situation and air velocity, and further affected comfort sensation.

• The human present is related to microclimate that change along with time, that is, in summer, afternoon before sunset (at about 16:30) was the most unpopular time, but after sunset, more people came

outside. From lunchtime (12:00−13:00) to sunset at about 16:30 was the most attractive period for people in winter.

• Different spatial forms cause the differences of microclimate, thus affect comfort sensation. In summer, shade influences the overall distributions of people obviously. Rest facilities with sufficient shade also attract people. In winter, no strong relations were found between shade situation and distributions of people.

3.5. Reference

[95] The NWS Wind Chill Temperature (WCT) index [database on the Internet]. *MD (US): The National Weather Service.* Retrieved from http://www.nws.noaa.gov/om/winter/windchill.shtml

[96] ASHRAE. (2001). *ASHRAE Handbook of Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[97] S. Thorsson, F. Lindberg, I. Eliasson, B. Holmer. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology*, 27 1983–1993.

[98] Ministry of Housing and Urban-Rural Development of the PRC(MOHURD). *Chinese standard for assessment parameters of sunlight on building (GB/T50947- 2014)*. Beijing: Standard Press of China; 1994. (in Chinese)

[99] S.I. Tanabe. (1988). *Thermal Comfort Requirements in Japan* (Doctoral dissertation). Waseda University, Tokyo, Japan.

[100] Fanger P (1972) *Thermal comfort*. New York : McGraw-Hill.

[101] Blalock, H. M. (1972). *JR. Social statistics*. New York: McGraw-Hill

[102] Lin, T. P., Matzarakis, A., & Hwang, R. L. (2010). Shading effect on long-term outdoor thermal comfort. *Building and Environment*, 45(1), 213-221.

[103] Hwang, R. L., Lin, T. P., & Matzarakis, A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Building and Environment*, 46(4), 863-870.

[104] Lin, T. P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, 52(4), 281-290.

[105] Johansson, E., & Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. *International journal of biometeorology*, 51(2), 119-133.

[106] Cheng, V., Ng, E., Chan, C., & Givoni, B. (2012). Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong. *International journal of biometeorology*, 56(1), 43-56.

[107] Hwang, R. L., Lin, T. P., & Matzarakis, A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Building and Environment*, 46(4), 863-870.

[108] Shimazaki, Y., Yoshida, A., Suzuki, R., Kawabata, T., Imai, D., & Kinoshita, S. (2011). Application of human thermal load into unsteady condition for improvement of outdoor thermal comfort. *Building and Environment*, 46(8), 1716-1724.

[109] Wu, H. (1994). *Pedestrian-level wind environment around buildings* (Doctoral dissertation). Concordia University, Montreal, Canada.

4. Public open space field survey on the basis of microclimate and spatial behaviour during cooling period weather conditions in Sapporo

4.1. Introduction

In the field survey, this study selected three open space which can be realised as important places for city live of citizens in Sapporo. These three open space are built next to public buildings and providing outdoor activity places to the public as well as connecting various of urban space.

4.2. Methodology

4.2.1. Survey area and measurement points

As shows in Fig. 4-1, target area A is attached to an office building and a shopping mall. The open space is canyon type and divided into a ground part and a underground part at the corner. Entrances of the adjacent buildings are opening towards the open space. The total area of target area A is 1496 m^2 (A1=784 m^2, A2=368 m^2 A3=344 m^2).

Target area B is zonal space, next to an apartment building, an office building and a public service building. It serves not only as a connecting space for the three buildings, but also as a traffic space for the passing the block. The open space is mainly hard paved with small trees and shrubs. The total area of B is 756 m^2.

Target area C is a square space, on both sides of the north and south are large-scale comprehensive buildings, on the west side is the old government office which is known as an iconic city landscape. The total area of C is 3228 m^2 (C1=501 m^2, C2=2727 m^2).

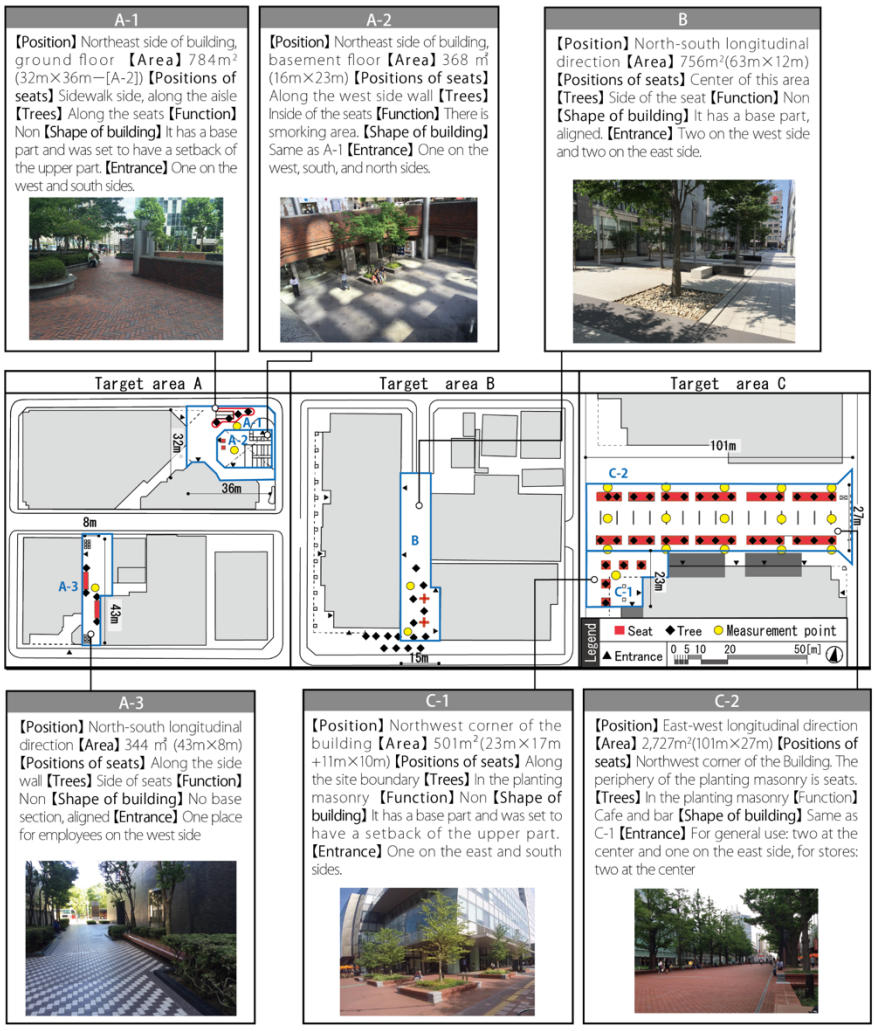


Figure 4-1 Spatial composition of each target area in Sapporo

4.2.1. Survey period

Eight days were selected between September 2016 and May 2017 with one day in a month without snow cover (Table 4-1). In each time of survey day, the field survey was conducted in lunchtime from 12:00 p.m. to 1:00 p.m., when the most sitting behaviors were expected. All the survey conducted on workdays in order to eliminate restrictions between office workers' lunchbreaks and other people's breaks as much as possible.

Table 4-1 Survey periods

2015	2016
3rd, Sep.	18th, Mar.
22th, Sep.	23rd, Apr.
29th, Oct.	29th, Apr.
12th, Nov.	21st, May

4.2.3. Measurement factors

The microclimate factors including temperature, wind speed, and sunlight were measured. Temperature and wind speed were measured by Kestrel 4500 in every 15 minutes at the measuring points. Sunlight measurement conducted by drawing the shade position depending on the video and photos taken in every 15 minutes during the survey periods.

4.2. Result of field survey in Sapporo

Firstly, the macroclimate conditions of the central area of Sapporo on each survey day were obtained from Japan Meteorological Agency (JMA).(Table 4-2)

Table 4-2 General meteorological data for Sapporo

	3rd, Sep.	22th, Sep.	29th, Oct.	12th, Nov.	18th, Mar.	23rd, Apr.	29th, Apr.	21st, May
Temperature [°C]	25.1	18.6	5.5	7.8	5.3	8.4	15.1	22.4
Wind Speed [m/s]	6.5	5.4	10.4	0.9	5.2	3.3	4.9	2.9
Weather	Cloudy	Cloudy	Sunny	Sunny	Sunny	Sunny	Sunny	Cloudy

Next, the measured data were plotted in Fig. 4-2. Of all the survey days, the highest temperature was 25.1°C on September 3rd, 2016 and the lowest temperature was 5.3°C on March 18th, 2017. There were no significant differences among the target areas.

Since the different shapes of the surrounding building volumes can be known, the three target areas are not far away from each other. The building shapes can be realized as the main influence on wind speed. As shown in Table 4-3, depending on the measured wind speed the public space B, and C-2 can be considered as high wind speed areas and A-3 can be considered as low wind speed area. The different aspect ratio of the public open space was considered to be an important factor for different wind speed.

In the public space A-2 which is surrounded by walls, the wind speed was low and steady. Compared with the other public space, there were variations in the wind speed in the space with buildings on two adjacent sides (A-1, C-1). The wind direction was also considered to be an influencing factor.

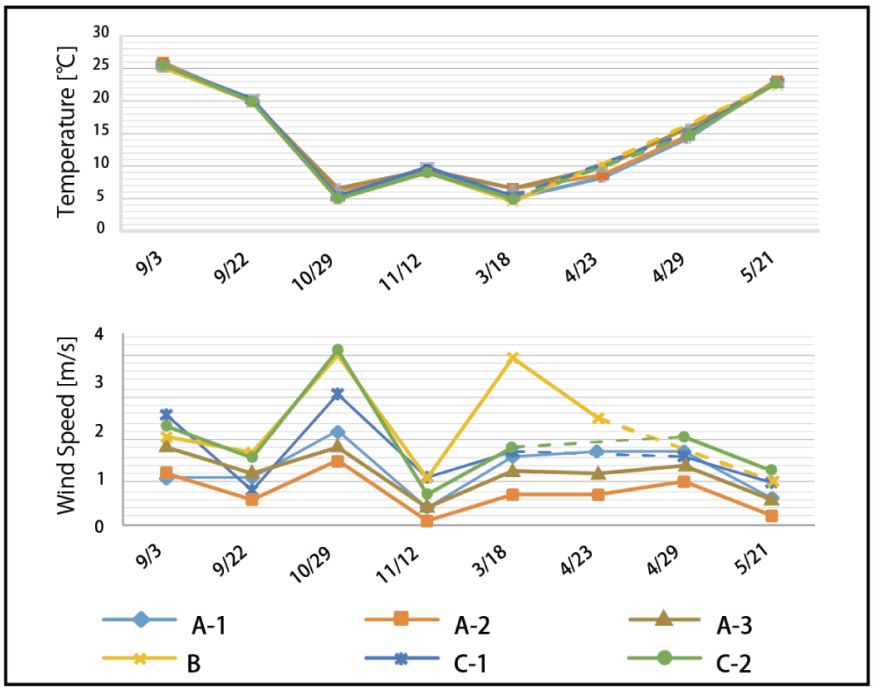


Figure 4-2 Microclimate data for each public space

The proportions of the sunlight distributions of each public space were compared. More than half of the public space area covered by sunlight was defined as “a public space with a large sunny area.” A public space with a sunny area less than half of its sitting surface was defined as “a public space with a small sunny area” (see Fig. 4-3).

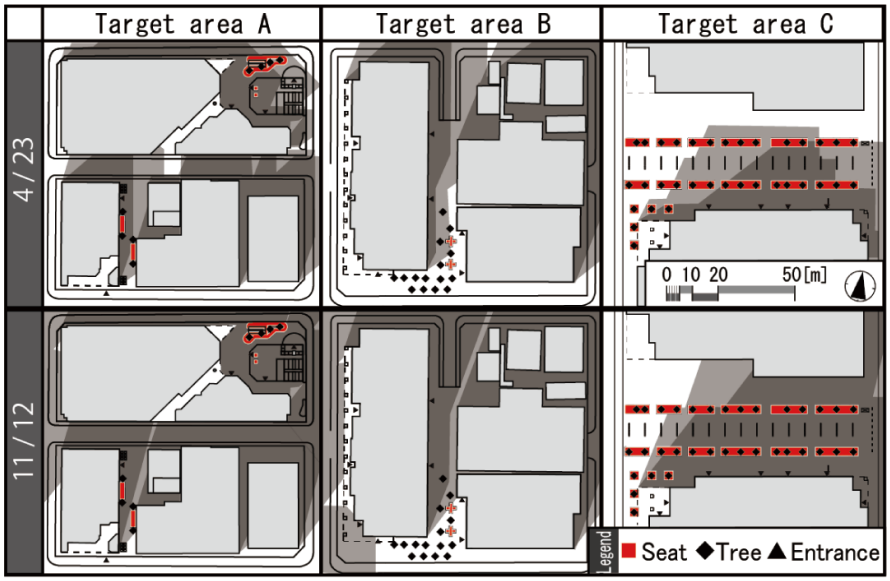


Figure 4-3 Sunlight distributions in each public space

From the above, six kinds of public space were classified based on the environmental conditions depending on the sunlight and wind speed. From the Table 4-3, significant differences among each public space can be distinguished.

Table 4-3 Classification of public spaces

		Wind Speed		
		Low	High	Changing
Sunny area	Large	-	B	C-1
	Small	A-2, A-3	C-2	A-1

Next, the sitting position and the distributions were analyzed as shown in Fig. 4-4.. It was found that places around the building entrances are the most used in all kinds of the public space.

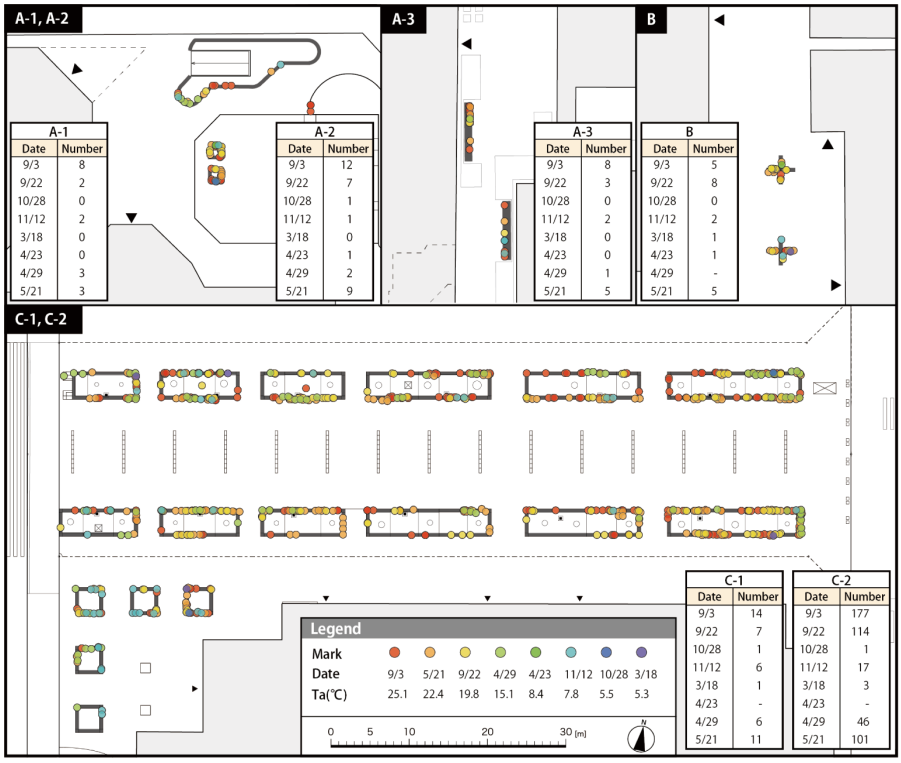


Figure 4-4 Plot of people sitting on each survey day

4.3. Analysis of field survey in Sapporo

4.3.1. Impact of temperature on sitting behaviours

The changes in the number of sitting groups and the average sitting time caused by the lowering of the temperature in each public space were analyzed. At around 20°C or higher air temperature, the influence of the environment was barely observed for both the number of sitting groups and the average sitting time. This was considered to be a comfortable temperature for sitting, and the space was used freely. Also, at around 8°C or lower, the sitting behaviors in each public space were very few, almost not seen. That was assumed to be a result of the influence of low temperature (see Fig. 4-5).

In the temperature zone (cooling period) from 8°C to 20°C, there were variations in how the sitting behavior changed depending on the public space. It was inferred that environmental factors such as sunlight and wind speed, which varied depending on the public space, influenced the increase and decrease of sitting behaviors.

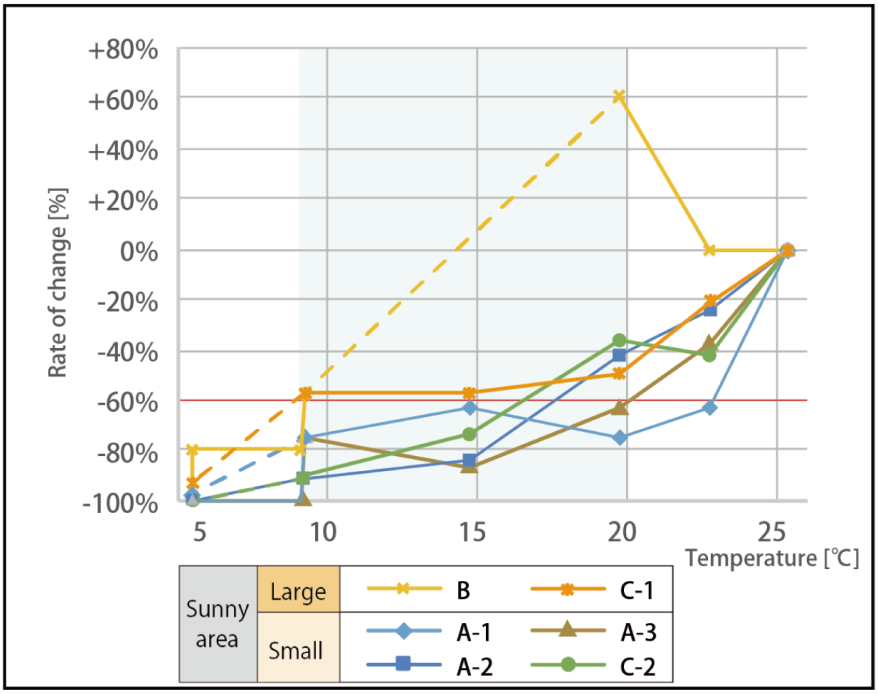


Figure 4-5 Analysis of the relationship between human activity and temperature

4.3.2. Impact of sunlight on sitting behaviours

Fig. 4-6 shows the shade lines at 12:30 p.m. and the sitting positions during one hour from 12:00 p.m. to 1:00 p.m. on each investigation day at the target site C. The sitting places in the plaza are evenly used on investigation days with temperatures of 15°C or more. However, on investigation day with a temperature of 7.8°C, the number of people sitting in the shade is fewer than the number of people sitting in the sun. It can be said that the areas that are more exposed to sun are preferred for sitting behaviors during the cooling period. On the investigation day with a temperature around 8°C, sitting behavior is rarely seen regardless of sunlight. Regarding the number of sitting groups, the public space with a large sunny areas (B, C-1) have a higher rate of sitting groups at 7.8°C (approximately 40%), compared with the rate for the public space with a small sunny area (see Fig. 4-5, rate of change). According to the results, we can assume that a sunny place is preferred for sitting during the cooling period. Additionally, a decrease in the number of sitting groups is observed for the public space that have a large sunny area. Therefore, sunlight is the critical factor that induces sitting behaviors. Moreover, the average sitting

time does not show a difference relative to the sunny area. It is believed that sunlight has no effect on the time of remaining in a sitting place.

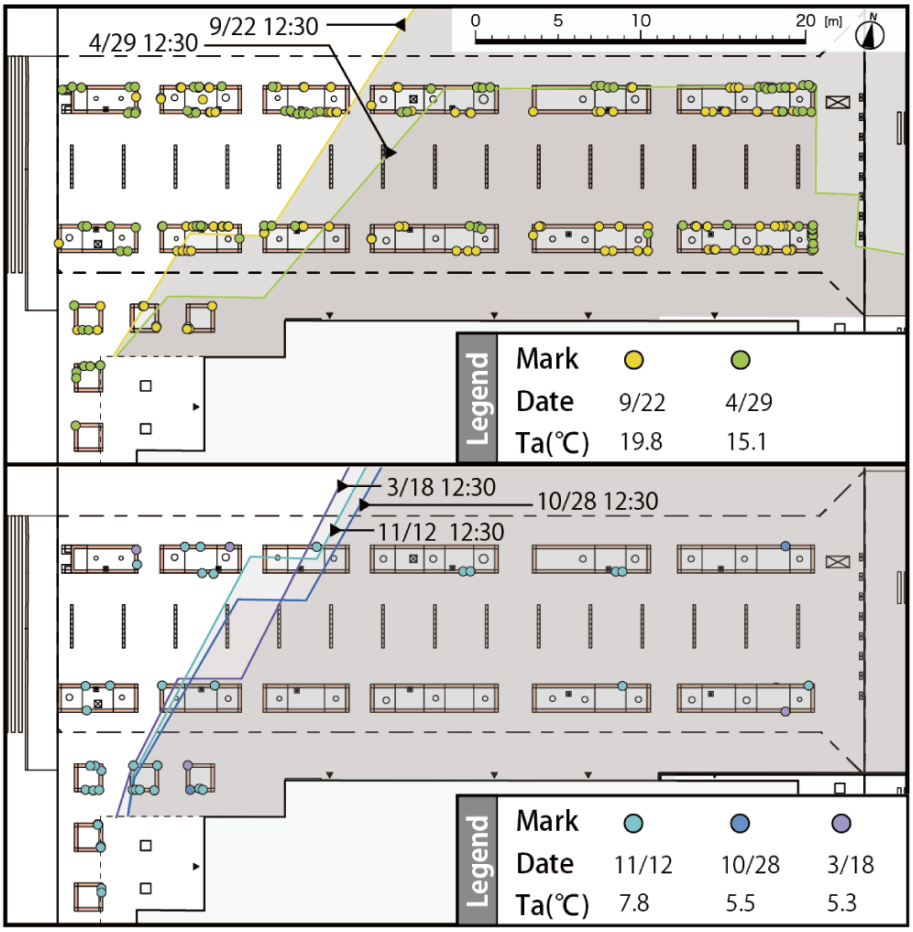


Figure 4-6 Plot of people's sitting locations in sunny places in the Target area C

4.3.3. Impact of wind speed on sitting behaviours

There is no difference in the decrease in the number of sitting groups relative to the trend of the wind speed. Fig. 4-7 shows the relationship between the average sitting time and wind speed. When the wind speed is lower, the average sitting time is longer, however, when the wind speed is higher, the average sitting time is shorter during the cooling period. In public space with low wind speed (A-2, A-3), the average sitting time during the cooling period is similar to that at 20°C or more. The maximum value of the average sitting time decreased as the wind speed increased. It turned out that the public space with low wind speed was used regardless of the temperature. However, when the temperature decreases to under approximately 8°C, the sitting

behavior tends to disappear. Moreover, the average sitting time for public space with low wind speed is longer than that for public space with high wind speed. Therefore, it is assumed that people keep sitting longer in public space with lower wind speed versus those with higher wind speed, even if the temperature drops.

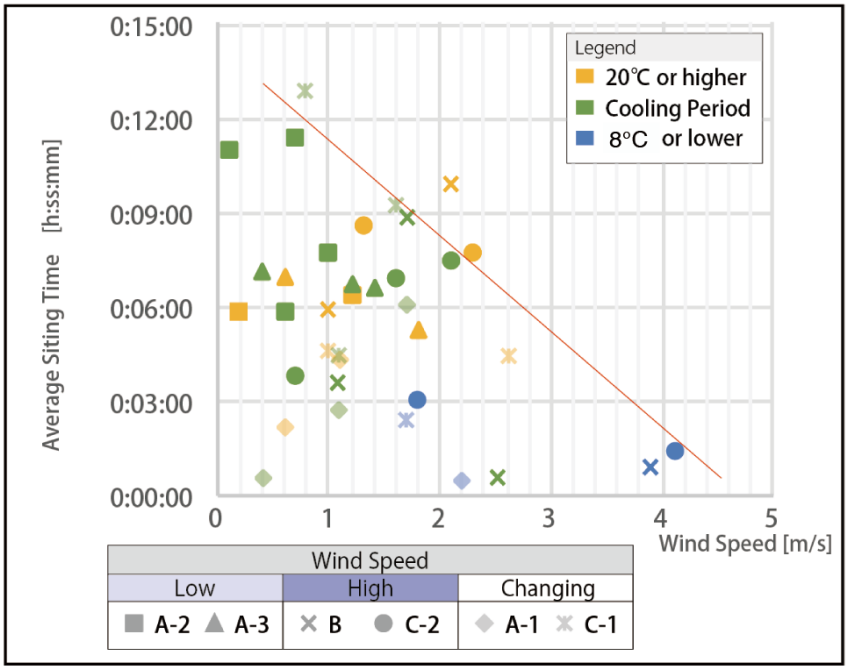


Figure 4-7 Analysis of the relationship between average sitting time and wind speed

4.4. Conclusion

This study conducted a field survey and analyzed the relationship between the outdoor environment and sitting behaviors in outdoor public space in downtown Sapporo.

At around 20°C or higher, the outdoor environment did not affect the number, time or location of sitting behaviors, and many sitting behaviors were observed in the public space. In addition, almost no sitting behaviors were observed in public space at temperatures below 8°C. During the cooling period (around 20°C to 8°C), the sitting behaviors decreased with lowering temperatures. However, microclimates influenced by sunlight and wind speed affected the reduction in the number of sitting groups, sitting time, and sitting

behaviors. Therefore, it is important to control the microclimates of the outdoor public space and to create desirable outdoor environments in order to promote sitting behaviors during the cooling period.

The reduction in the number of sitting groups was suppressed in public space with large sunny areas until the temperature dropped to approximately 8°C. It appeared that a situation with sunlight was a trigger for sitting behaviors. In the public space with low wind speeds, the average sitting time was maintained even as the temperature decreased. As the wind speed increased, the average sitting time decreased. Furthermore, the sitting time could be lengthened by reducing the wind speed.

Based on the above results, a public space design that secures plenty of sunny area and reduces wind speed can suppress the reduction in sitting behaviors during the cooling period and extend the duration of use of outdoor public space in winter cities.

This study has clarified the environmental conditions in outdoor public space to promote sitting behaviors in the cooling period. In future research, it will be necessary to study the relationship between outdoor environmental conditions and outdoor public spatial compositions, including the surrounding building designs. This will allow for the development of urban design guidelines that create desirable environments to promote human activity in outdoor public space in winter cities.

5. Wind tunnel simulation and CFD simulation

5.1. Introduction of environment simulation

The different shades and layouts of buildings gathered in the city, geographical differences in the urban environment and other reasons increase the air-flow resistance and reduce the air velocity. However, due to the city's surface is generally rough as a mountainous terrain, at the same time, the area in the street and between two buildings can form the effect of collecting wind as a tuyere in the mountains. It is possible to create strong air-flow in some areas at low wind speed area.

Environmental simulation is the physical simulation of the meteorological changes by using the model of large-scale urban space and the analysis of the results to detect the existing meteorological problems.

The meteorological factors in the city are complex and it is neither realistic nor feasible to simulate all the variables because of the complexity of the variables. In all kinds of urban meteorological variables, the wind environment is an important index which is the

most easily affected by the city layouts and architectural forms, and can significantly affect the pedestrian comfort.

In practice, the wind environment simulation is mainly divided into computer simulation and wind tunnel simulation. In this study, wind-tunnel simulation is used to simulate the wind environment in the study area, and CFD simulation analysis is used to analyze the distribution of airflow. The purpose of this study is to find out the distribution of wind environment measured in the survey area and its relationship with the building environment, and to provide theoretical support for the optimization design.

5.2. Methodology of environment simulation

5.2.1. Wind tunnel simulation

Introduction of wind tunnel

Wind tunnel experiment was first applied to the field of aviation for aircraft research. By setting the drive power unit in the air flow pipe, the airflow is controlled to simulate the real situation on meeting the airflow conditions and boundary layer conditions. By measuring the relevant values from the small-scale experimental model, the wind tunnel simulation can provide guidance advices to the actual case.

With the continuous improvement of science and technology, the simulation of wind tunnel is no longer confined to the use of aircraft research, and to develop a large number of types to correspond to different fields of experiment. According to the direction of air-flow, the wind tunnel can be divided into vertical wind tunnel and horizontal wind tunnel; According to the flowing types, the wind tunnel can be divided into direct current type system and circulating type system; According to the use of wind tunnel, it can be divided into aeronautical wind tunnel, construction wind tunnel, weather wind tunnel, industrial wind tunnel; According to the air velocity, it can be divided into high-speed wind tunnel and low-speed wind tunnel; Aeronautical wind tunnels and industrial wind tunnels generally belong to high-speed wind tunnels and generally adopt direct current type. Both

construction wind tunnel and weather wind tunnel are low-speed wind tunnels. They are usually circulating types. Compared with the aeronautical wind tunnel, most of the boundary conditions for building wind tunnel simulation are near-surface wind field with high turbulence and wind changes is complex. At the same time, because of the large scale of the building wind tunnel, the "scale effect" of Reynolds factor of building wind tunnel experimental model is more prominent. As Fig. 5-1 shows, the wind tunnel needs to adjust the shape and size of the wind blade according to the boundary conditions, at the same time, turbulence is simulated by the roughness elements in the tunnel.

Wind tunnel simulations were conducted several times for the original case and the redesigned cases for both summer and winter. The research area model and its surrounding buildings were built of Styrofoam at a scale of 1 to 500. The research area comprised a circle with a diameter of 900m. An atmospheric boundary layer wind tunnel with a 1.8m by 1.8m cross section and a 20m/s maximum air velocity was used for this research (Fig. 5-2).

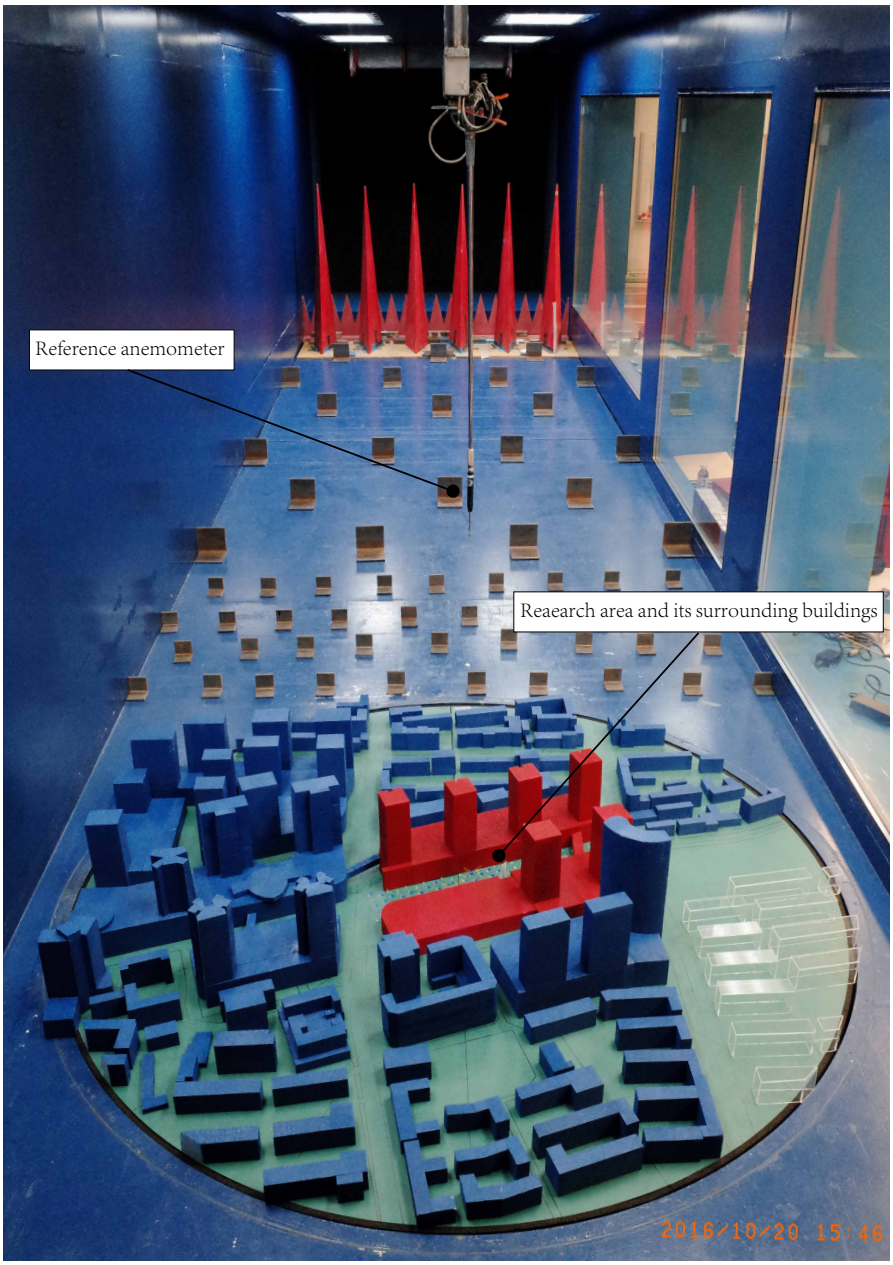


Figure 5-1 Research model in the wind tunnel

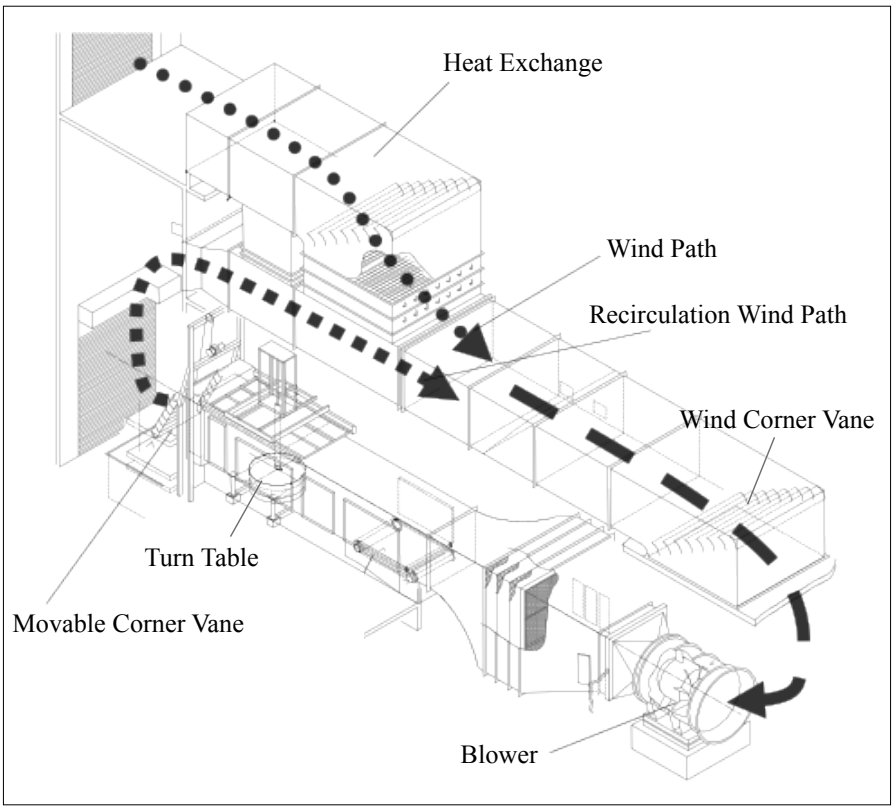


Figure 5-2 Environmental wind tunnel used in this research (adapted from Takuya 2009 [110])

Model making

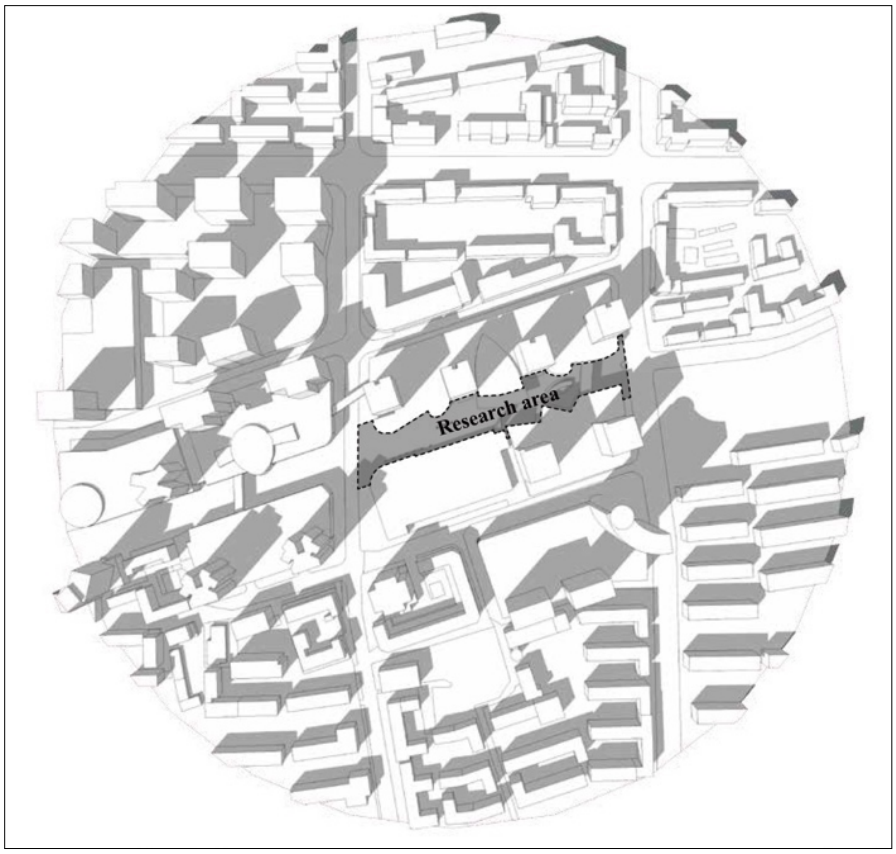


Figure 5-3 Computer model diagram

The models of research area and its surrounding buildings were built of Styrofoam at a scale of 1 to 500. The research area comprised a circle with a diameter of 900m (Fig. 5-3).

The model pedestal is made up of two semicircular planks, and the layout of the research area is drawn on this planks according to the scale of 1: 500 (Fig. 5-4). The building volumes made of foamed plastic and plexiglass plate will be glued on the base by strong double-sided tape. Building monomers can be changed according to the experiment. The strong double-sided tape can not only ensure the bonding strength against the strong wind but also to ensure the replacement flexibility.

Figure 5-4 Model making process

In the study area, 103 holes with a diameter of 2.5 mm were reserved for the temperature and wind speed probes (Kanomax Climomaster model 0965-03) and numbered one by one (Fig. 5-5). During the experiment, the vacant holes will be filled with the same material as the base to ensure that the physical parameters of the base will not change significantly.

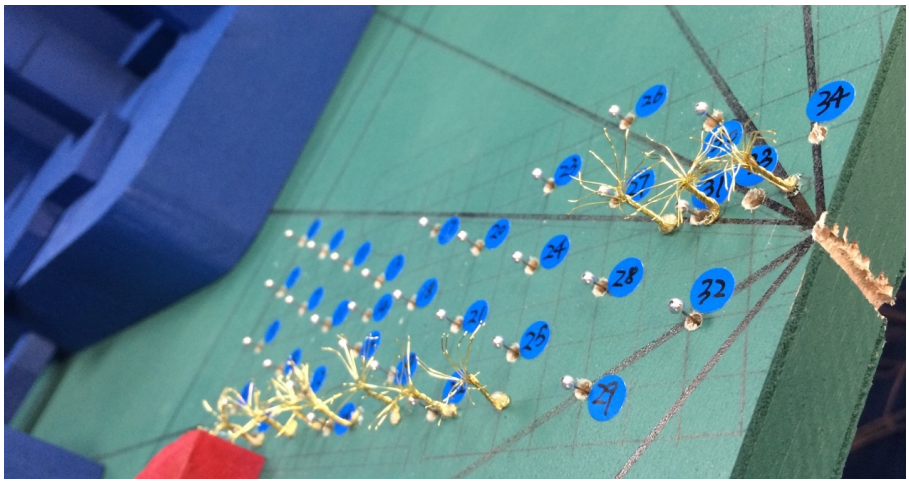


Figure 5-5 Probes layout

Calculation methods

Depending on the relations between the positions, 93 measurement points were determined, as shown in Fig. 5-5, at which 93 thermistor anemometers (Kanomax Climomaster model 0965-03) were set at the height of 3mm on the model to measure the air velocity every second, which was calculated at 1.5m, which was determined as the average head height of Chinese in a real situation (General Administration of Sport of China 2014[111]). A reference anemometer (Kanomax Climomaster model 0965-21) (Fig. 5-1) was set in front of the model

at the height of 0.4m, which was equal to 200m, so as not to affect the surrounding buildings, to calculate the real air velocity from the vertical air velocity profiles, which could be calculated using the power-law at an exponent of 0.27 (Kaltschmitt 2007 [112]) (Fig. 5-6). Depending on the annual mean air velocity, the air velocity at each measurement points was calculated, as follows (Heier 2005 [113]):

$$\frac{V_w}{V_r} = (\frac{H_w}{H_R})^{\alpha} \qquad (4)$$

where:

V_w = air velocity in wind tunnel at the height of the weather station

V_R = air velocity at the height of the reference anemometer

H_w= height of the weather station (No.54342 41°44′N, 123°27′E H_w=44.7m (China Meteorological Bureau et al., 2005 [114]))

H_R = height of the reference anemometer (200m)

α = exponential coefficient (0.27)

$$\frac{V_{1.5}}{V_w} = \frac{V_{r1.5}}{V_{rw}} \qquad (5)$$

where:

$V_{1.5}$ = air velocity at a height of 1.5m in the wind tunnel

V_w = air velocity at the height of the weather station in the wind tunnel

$V_{r1.5}$ = air velocity at a height of 1.5m in the real situation

V_{rw} = annual average air velocity from the weather station (summer 2.5m/s SSW, winter 2.0 m/s ENE) (China Meteorological Bureau et al., 2005 [115])

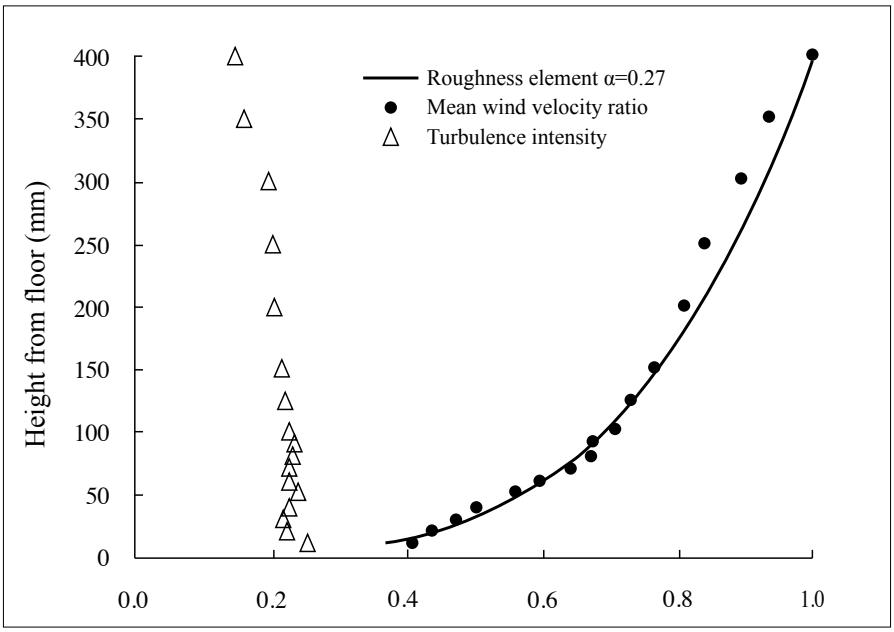


Figure 5-6 Vertical air velocity profiles (adapted from Meng 2010 [114])

Experience methods

Since the model base of the wind tunnel is a disc design, the model can be freely rotated according to the centre of the circle, and the wind tunnel simulation has done on 16 different wind directions.

Data collection and analysis

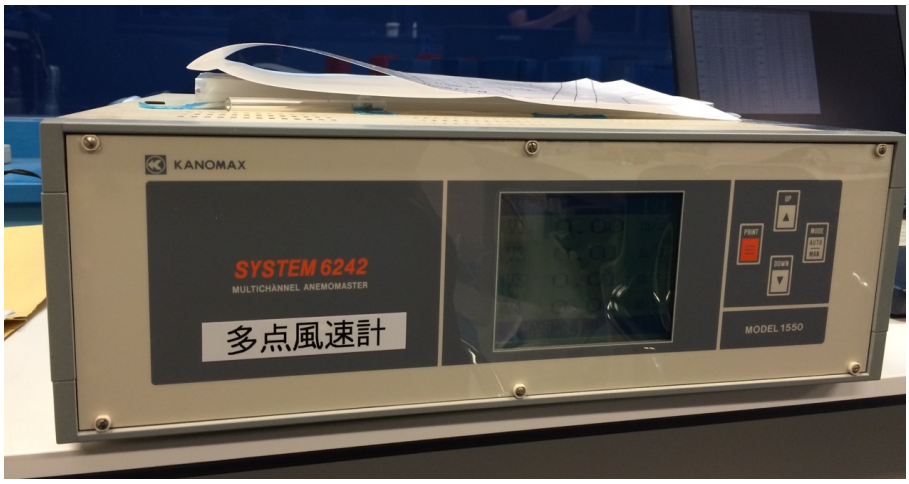


Figure 5-7 Multi-channel anemometer

The experiment recorded the model with multi-channel anemometer and two kinds of wind speed probes at the frequency of once per second for a total of 60 samples. The experimental results were took the average calculation for the follow-up analysis. (Fig. 5-7)

Through the calculation of Eqs. 4 & 5, the simulation wind speed at each point under the dominant wind in winter and summer is calculated. They are marked according to the actual position, and converted into the wind speed value with position information.

The resulting values were imported into the contour drawing software and the contour maps were drawn. The surrounding buildings and contour map were superimposed. With different colours for numerical differentiation, the intuitive simulation results were obtained.

5.2.2. CFD simulation

Computer simulation mainly computes the physical environment of the target area by Computational Fluid Dynamics (CFD) technology. By calculating the physical environment of the target area, the correctness and reliability of the simulation results depends on many factors, including the geometric model, the finite element mesh division, the selection of the fluid physics model, the boundary conditions, the setting of the key parameters.

The main advantage of CFD simulation is the lower cost, shorter operating cycle, a series of simulation calculations can be completed in a short time, at the same time, the verification of simulation results is relatively simple and intuitive. The disadvantage of CFD simulation is that it is necessary to set numbers of physical quantities to match the real environment, the accuracy of the parameter setting directly affects the degree of deviation between the simulation result and the true value. At the same time, for the sampling accuracy of the results, more elaborate samples will take longer time. These are all the note points on designing the CFD simulation experiment.

Computer simulation mainly computes the physical environment of the target area by Computational Fluid Dynamics (CFD) technology. The correctness and reliability of the simulation results depend on many factors, including the geometric model, finite element mesh grid

division, the choice of fluid physics model, the boundary conditions, the setting of key parameters and so on.

The main advantages of CFD simulation are low cost, short cycle time which means a series of simulation calculations can be finished in a short period of time, a relatively simple and intuitive verification of simulation results and so on. The disadvantage of CFD simulation is the need to set a lot of physical quantities of the real environment. The accuracy of the parameter setting directly affects the degree of deviation between the simulation result and the true value. At the same time, on the sampling accuracy of their results, the more elaborate samples the longer it takes. In the design of CFD simulation experiments, these are points should be aware of.

The CFD simulation was conducted using the software named PHOENICS developed by Cham Ltd. to simulate the airflow under the same situations with the wind tunnel. Using the CFD simulation, the detailed wind pressure and air flow path distributions were detected.

Domain size

In CFD simulation, an infinite space is replaced by a finite calculation domain. That is to say, several artificial walls are set far away from the building complex to close the computational domain, and ensure that the wall arrangement will not affect the CFD simulation results of the building complex.

Boundary condition

Inflow boundary conditions

The vertical velocity profile U(z) on flat terrain is usually given by a power law[116]

$$U(z) = U_s(\frac{z}{z_s}) \qquad (6)$$

where Us is the velocity at reference height, z_s and z is the power-law exponent determined by terrain category.

The vertical distribution of turbulent energy k(z) can be obtained from a wind tunnel experiment or an observation of corresponding surroundings. If it is not available, k(z) can be also given by Eq. (6) based on the estimation equation for the vertical profile of turbulent intensity I(z) proposed by AIJ (Architectural Institute of Japan) Recommendations for Loads on Buildings (2004):

$$\mathrm{I}(z) = \frac{\delta u(z)}{U(z)} = 0.1\left(\frac{z}{z_G}\right)^{(-\alpha-0.05)} \qquad (7)$$

Where z_G is the boundary layer height determined by terrain category and δu the RMS value of velocity fluctuation in stream-wise direction.

In the atmospheric boundary layer, the following relation between I(z) and k(z) can be assumed:

$$\mathrm{k}(z) = \frac{\delta u^2(z)+\delta v^2(z)+\delta w^2(z)}{2} \cong \delta u^2(z) = (I_{(z)}U_{(z)})^2 \qquad (8)$$

It is recommended that the values of __ be given by assuming local equilibrium of $P_k = \varepsilon$ (P_k: production term for k equation)

$$\varepsilon(\mathrm{z}) \cong P_k(z) \cong \overline{-\mathrm{u'w'}}\frac{dU(z)}{dz} \cong C_\mu^{\frac{1}{2}}k(z)\frac{dU(z)}{dz} \qquad (9)$$

when the vertical gradient of velocity can be expressed by a power law with exponent α,

$$\varepsilon(\mathrm{z}) \cong C_\mu^{\frac{1}{2}}k(z)\frac{U_s}{Z_s}\alpha\left(\frac{z}{z_s}\right)^{(\alpha-1)} \qquad (10)$$

C_μ is the model constant (=0.09)

Lateral and upper surfaces of computational domain

If the computational domain is large enough, the boundary conditions for lateral and upper surfaces do not have significant influences on the calculated results around the target building [117-119]. Using the inviscid wall condition (normal velocity component and normal gradients of tangential velocity components set to zero) with a large computational domain will make the computation more stable.

Downstream boundary

It is common to set the normal gradients of all variables to zero for the outflow boundary condition. The outflow boundary needs to be placed far from the region where the influence of the target building is negligible.

Grids distribution

A Cartesian grid system across the whole zone was used to divide the research area and surrounding area in consideration of the research area boundaries. The dimensions 900(x)×900(y)×900(z)m were adopted with 233 (x–direction) ×225(y–direction) ×250 (z–direction) cells at each axis. The grids were changed gradually from fine close the central area to coarse nearer the outer boundary.

Turbulence Model

The AIJ guidelines are based on high Reynolds number as well as RANS. Although the results using large eddy simulation (LES) and low Reynolds numbers will be more accurate, it will be difficult to apply them to actual projects that have been time-limited due to the long calculation time of using LES and low Reynolds numbers go with.

The well-known problem of the standard k–ε model is that it cannot reproduce the separation and reverse flow at the roof top of a building due to its overestimation of turbulence energy k at the impinging region of the building wall. Although this problem does not appear near the ground surface as much as it does on the roof, it may affect the prediction accuracy of the value and the location of high velocity. However, many revised k–ε models and differential stress model (DSM) have mitigated this problem and enhanced the prediction accuracy for the strong wind region near the ground surface[117-120].

5.3. Optimization design of open space based on environment simulation I

5.3.1. General info. of original conditions

The wind tunnel simulation results are shown in Fig. 5-8, from which it can be seen that the distribution of air velocity in both summer and winter were roughly the same. Airflow in the western area was lower than in the central and eastern areas. In summer, there was a dark red area in the center and an orange area in the west. The CSV analysis showed that the comfort level in this area was higher than in the green and blue areas in which the air velocity was lower than 1.12m/s. In winter, there were three parts showing orange, which were considered to be unacceptable areas. The green and blue areas were better than the yellow and orange area for people outside.

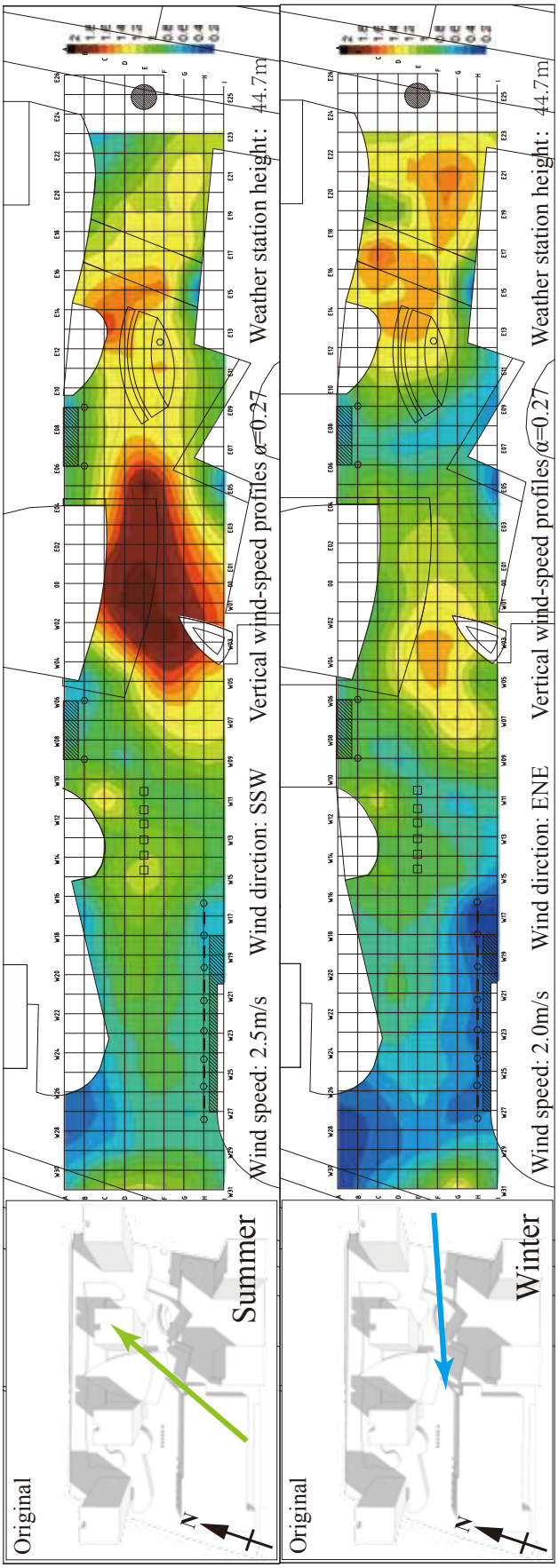


Figure 5-8 Wind situation of the original survey area by wind tunnel simulation

5.3.2. Results and discussion

Previous research has found that the wind attenuation of an individual space is affected by canyon aspect ratios and orientations [70]. Fig. 5-9 shows that when the airflow was parallel, the attenuation factors for the four cases with different aspect ratios were higher than when the airflow was perpendicular.

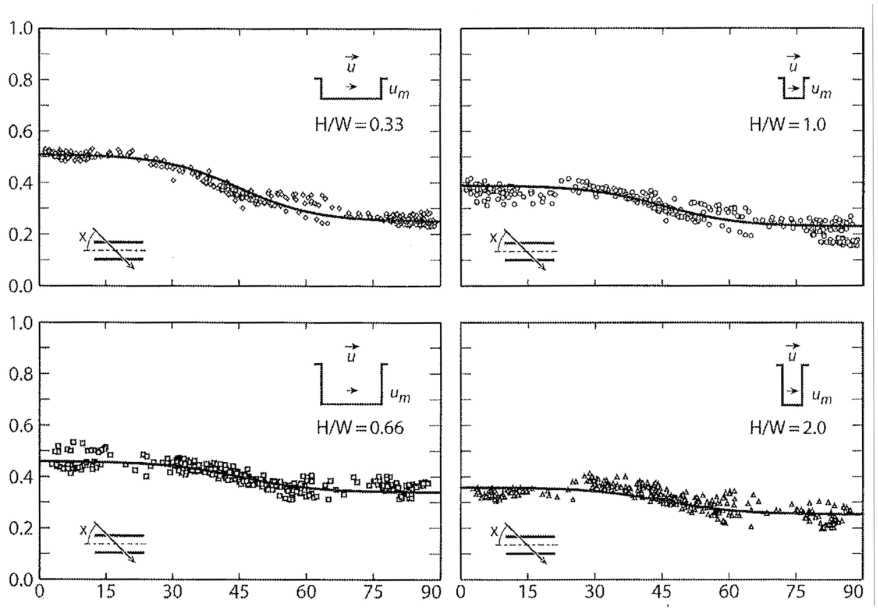


Figure 5-9 Correlation between wind attenuation and angle of attack for street canyons of varying aspect ratios [70]

As the prevailing wind directions were different between summer and winter, there were also fixed angles between the wind direction and the street alignment. Two assumptions are proposed for changing the canyon orientation to satisfy the following situations:

Streets aligned parallel to the summer wind direction have a higher air velocity in summer.

Streets aligned perpendicular to the winter wind direction have less strong wind in winter.

As shown in Fig. 5-10, rotating the street counterclockwise (CCW) 22.5° would make the summer wind parallel to the street. Rotating the street clockwise 90° would make the winter wind perpendicular to the street.

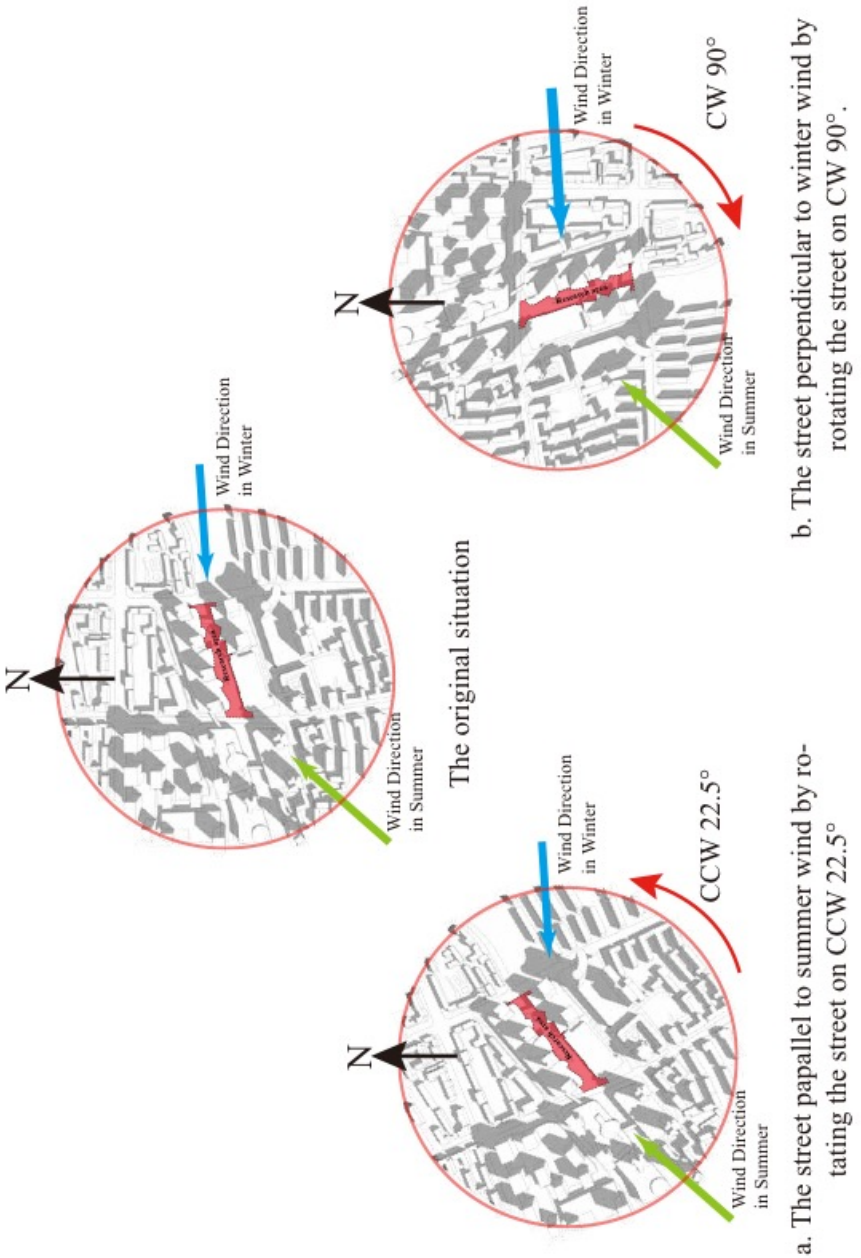


Figure 5-10 Changing the canyon orientation

5.3.3. Results of changing the canyon orientation

As Fig. 5-11 shows, the wind in the rotated streets changed significantly. This illustrates that changing the angles between the streets and the prevailing wind direction can radically change the wind situation. However, the CCW 22.5° could decrease the air velocity area in summer and increase the air velocity in the central and western areas in the winter, which, based on the results, would not meet the requirements for a comfortable wind environment.

In Fig. 5-12, when the street was rotated clockwise (CW) 90°, the wind situation in both summer and winter obviously changed. The street had higher air velocity in summer and lower air velocity in winter, thereby satisfying the requirements for a comfortable wind environment in both seasons; however, for a northern city such as Shenyang, because of its extreme winter temperatures, reducing the wind in winter would be more important than increasing the air velocity in summer. Therefore, prioritizing the long winter period by making the winter wind direction perpendicular to the main street would significantly improve wind comfort.

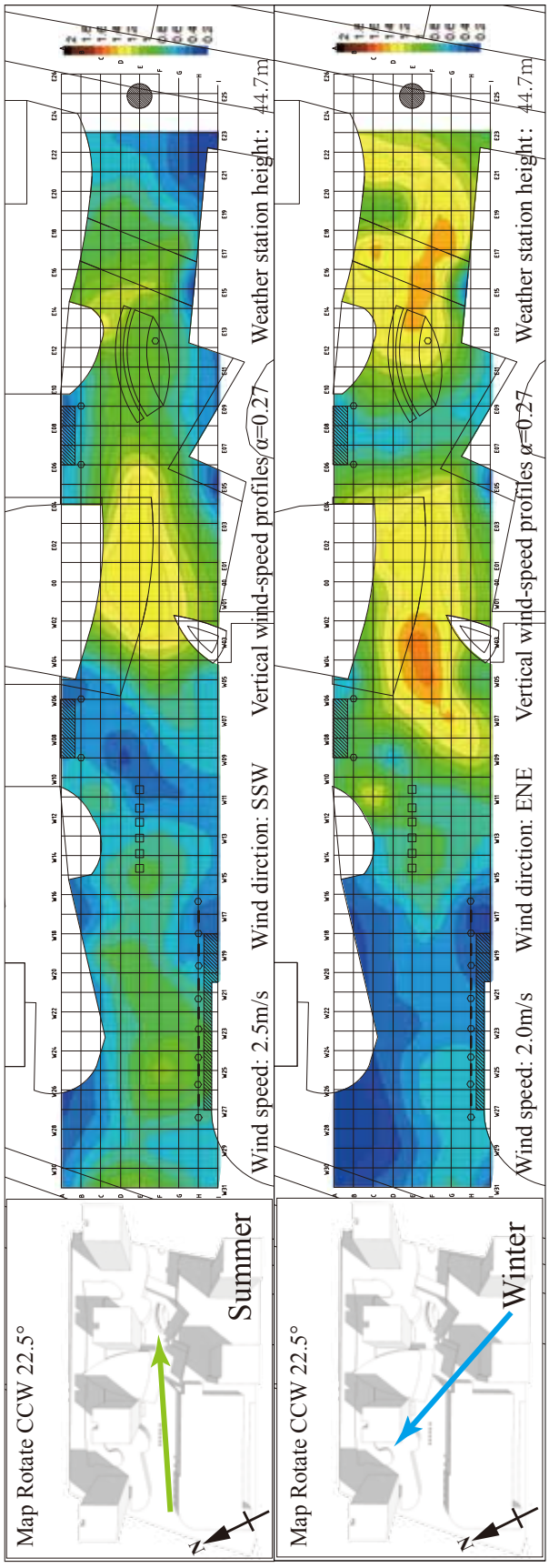


Figure 5-11 Wind situation of the survey area by rotating CCW 22.5°

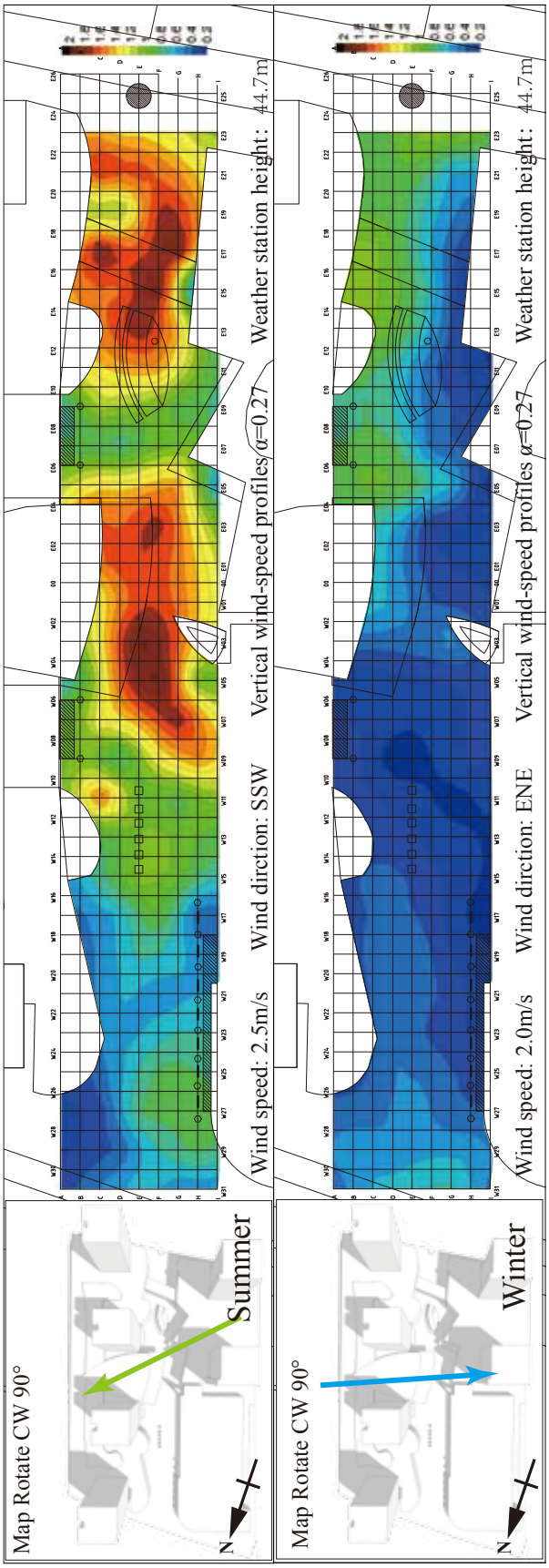


Figure 5-12 Wind situation in the survey area by rotating CW 90°

5.4. Optimization design of open space based on environment simulation II

5.4.1 Proposal building types

On the basis of the simulation results from the original street, several hypotheses were made for the different building types without changing the building floor area ratio. Wind tunnel simulations were conducted on these cases to determine the impact of building type change on wind flow.

As shown in Fig. 5-13, high-rise buildings, podium buildings, and building details' propositions were considered. A1-3 were for high-rise buildings: in A1, two high-rise buildings were set back to determine the impact of the high-rise building position on wind flow; in A2, the high-rise buildings were changed to a plate type to determine the impact of building shape on wind flow; and in A3, the high-rise buildings were shortened and compacted while meeting the same sunshine conditions to determine the impact of building density on wind flow at the pedestrian level.

B1 and B2 were used for podium buildings to determine whether special building shapes or building structures affected wind flow: in B1, the skyway connecting the two main podium buildings was removed to determine whether the skyway affected the wind flow at the street entrance; and in B2, two-side street entrances were broadened by smoothing the irregular building edges, and the alleyway on the south side between the two main buildings was closed off, from which B2-1 was proposed, in which all irregular podium buildings were smoothed and the two podium buildings on the south side were set at the same height.

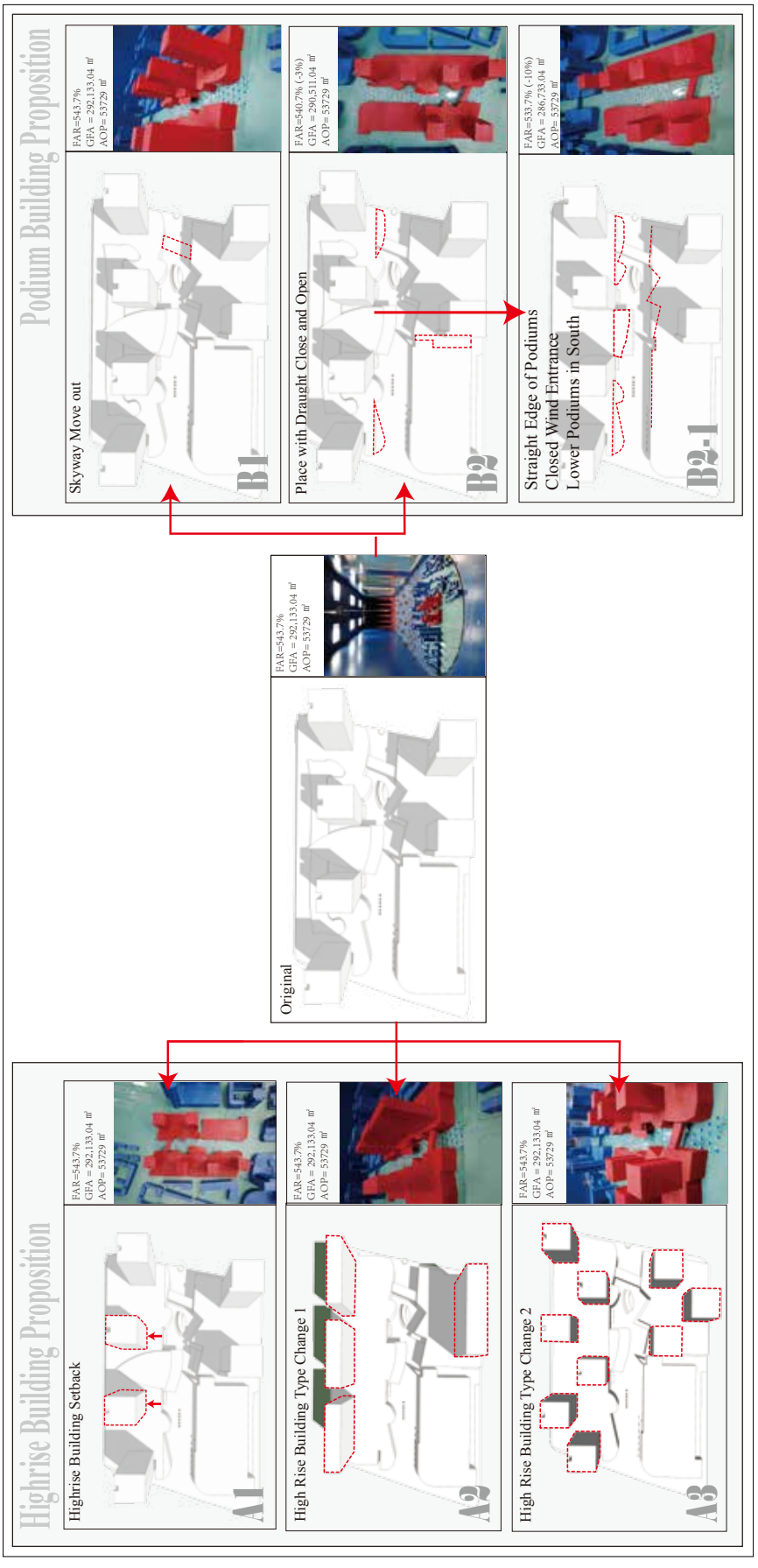


Figure 5-13 Building type propositions

5.4.2. High-rise building proposition

By changing the shape of high-rise buildings, this part tried to find the impact of high-rise building morphology in the layout of urban areas on pedestrian height wind environment.

High-rise building setback (A1)

This case study explores the impact of frontage high-rise buildings on the wind environment around the building. As Fig. 5-14 shows, two high-rise buildings facing the street may have a downdraft wind effect on wind environment at pedestrian height. In this hypothesis, the two high-rise buildings facing the street are retreated to the back of the podium to form the terrace structure of the high-rise and podium to verify its impact on the wind environment.

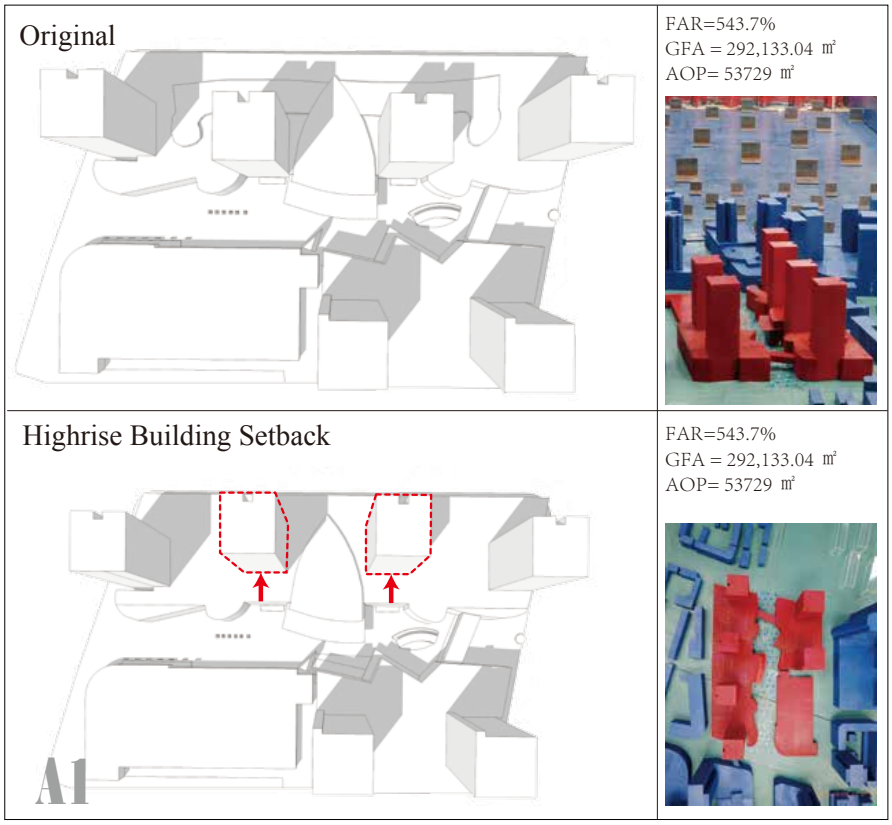


Figure 5-14 High-rise building type proposition A1

According to the comparison results, it can be seen that when the high-rise building is setback to the podium boundary, it does not affect the wind environment around the pedestrian. Podium height is about

24m, it can be considered that the building with height of 24m setback will not affect the pedestrian height of the wind conditions. (Fig. 5-15)

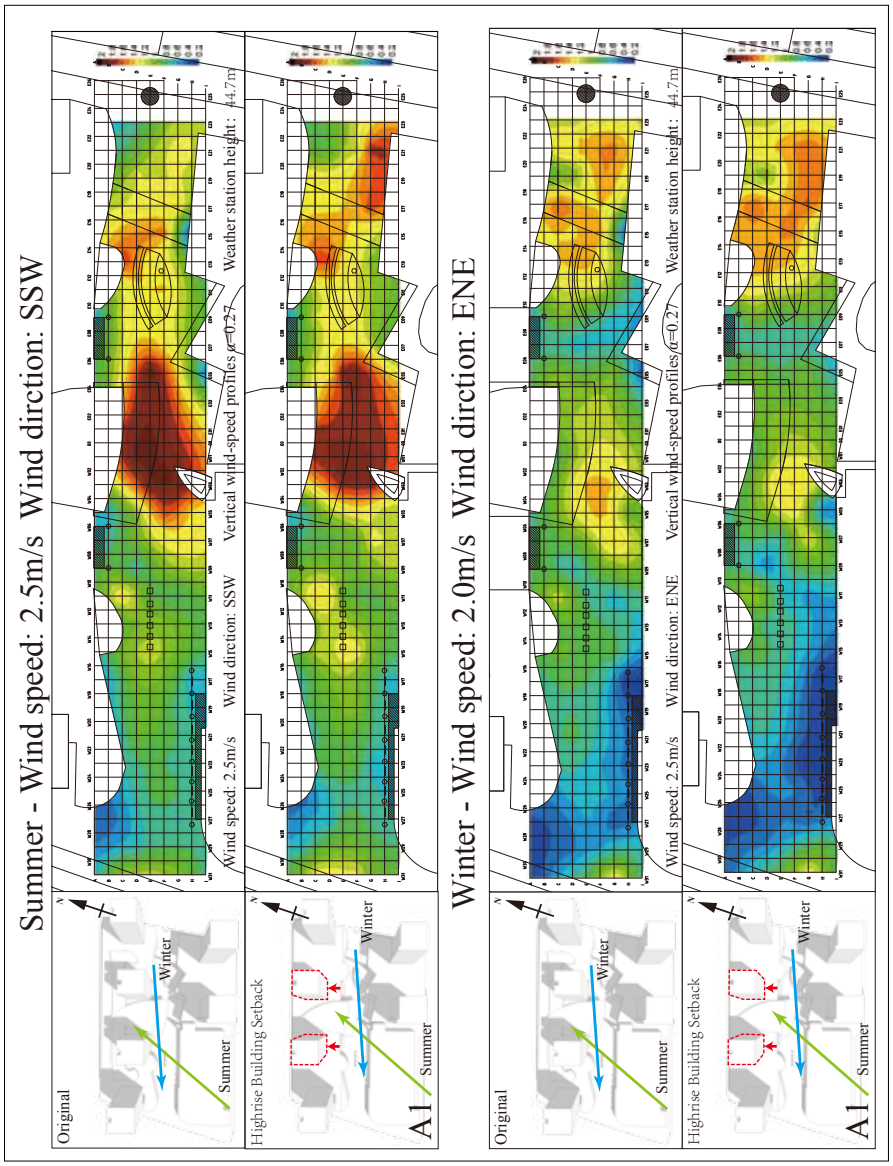


Figure 5-15 Wind tunnel simulation results comparison between original case and A1

It can be seen from the CFD simulation results that the setback of buildings caused the change of the wind condition in the longitudinal section, but the change in the pedestrian height is not obvious. The result can prove the results of the wind tunnel simulation that building with height of 24m setback will not affect the pedestrian height of the wind conditions. (Figs. 5-16 & 5-17)

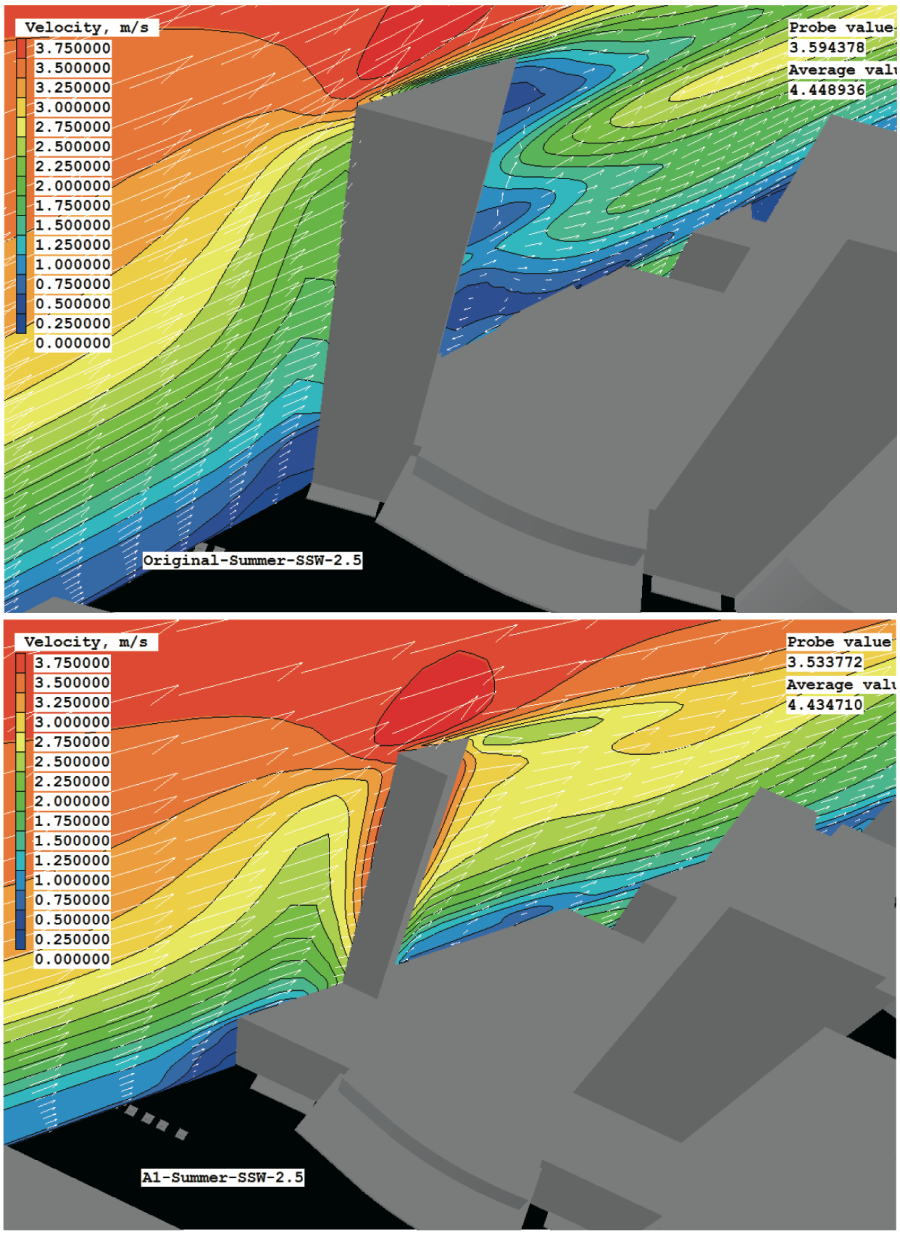


Figure 5-16 CFD simulation results of original case and A1 in summer

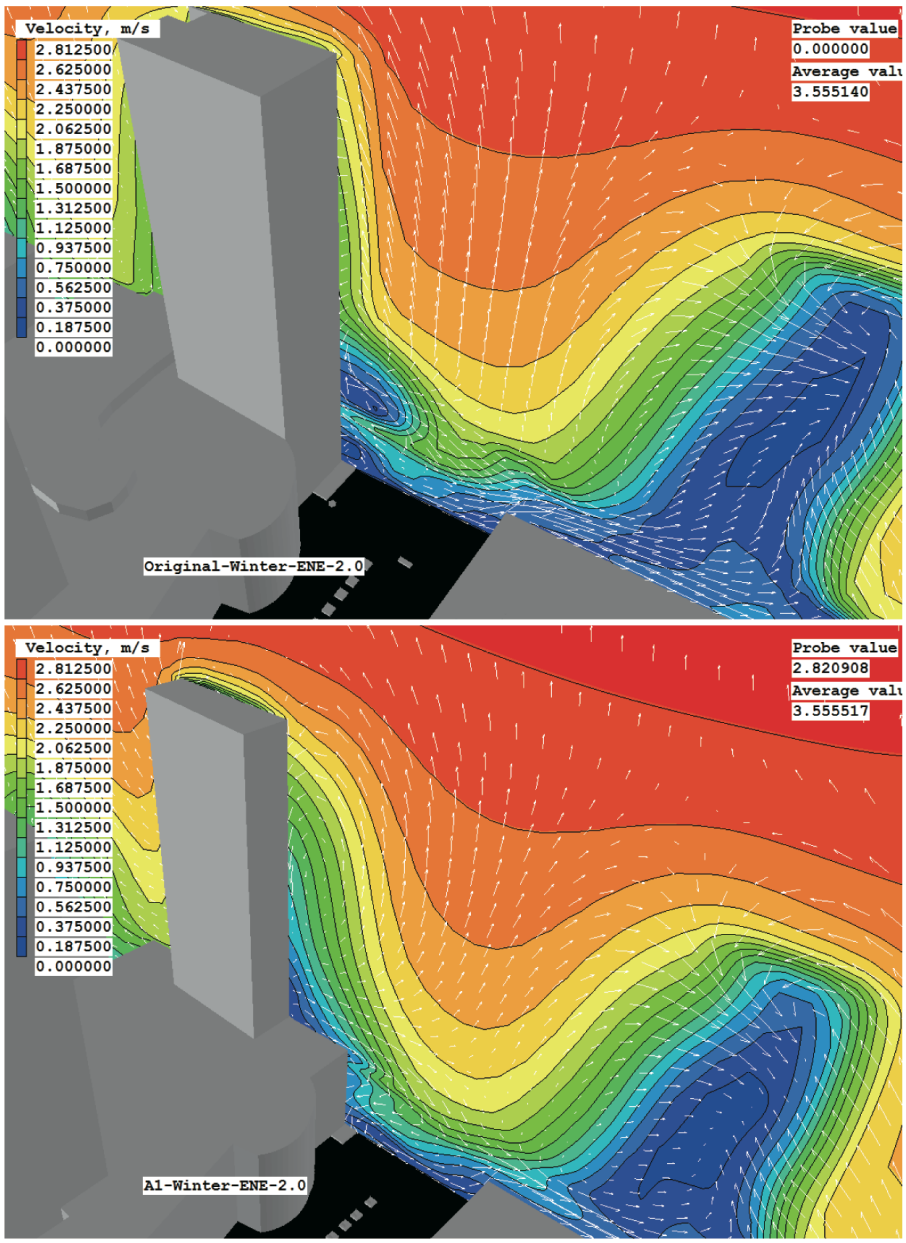


Figure 5-17 CFD simulation results of original case and A1 in winter

High-rise building type change I (A2)

The hypothesis will examine whether the morphology of high-rise buildings can have an impact on the pedestrian height of the wind conditions.

In the hypothesis case, the point-type high-rise building is transformed into a plate-type high-rise building and the wind tunnel test under the same conditions is conducted to observe the comparison result. (Fig. 5-18)

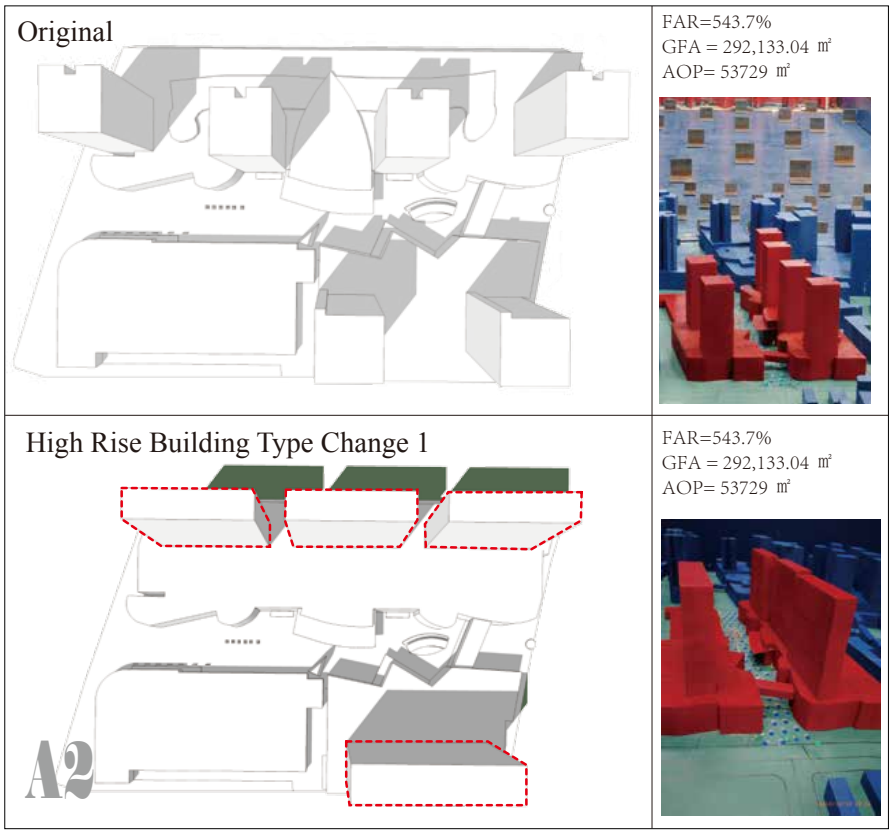


Figure 5-18 High-rise building type proposition A2

According to the experimental results in Fig. 5-19, it can be seen that when the wind direction is SSW (the summer prevailing wind direction), there is no obvious change between the two models. When the wind direction is ENE (the winter prevailing wind direction), the wind speed increases at the entrance and decreases at the exit, which can be judged as the result of the increase of the narrow tube effect. Both the north-south plate-type high-rise buildings at eastern entrance of wind lead to increase the narrow tube effect, and then lead to the high wind speed. There is only northbound high-rise building in the western exit of wind, leading to narrowing or disappearing of the narrow tube effect. As a result, the wind speed of pedestrians on the west side decreased significantly.

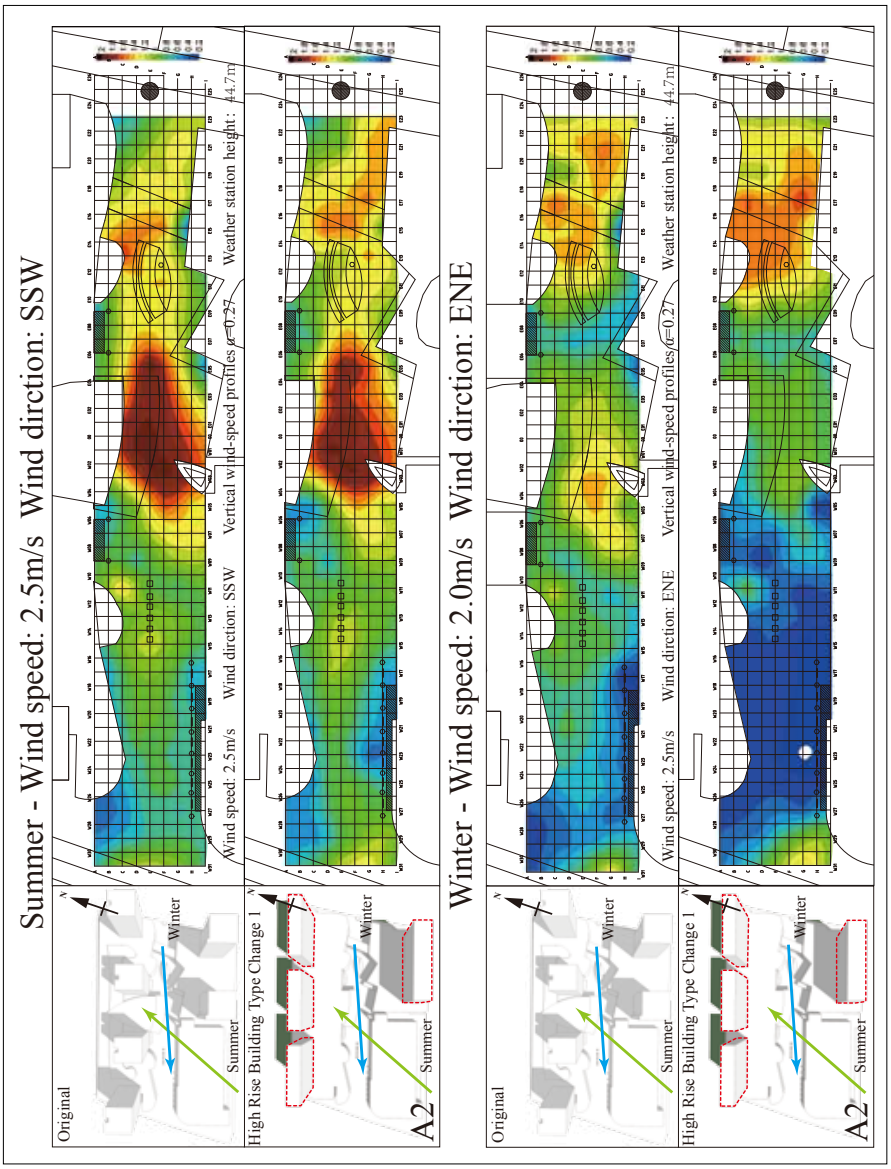


Figure 5-19 Wind tunnel simulation results comparison between original case and A2

From the simulation results of CFD in Figs. 5-20 & 5-21, it can be seen that when the wind direction is SSW, the wind condition in the upper part changes due to the shape change of the high-rise buildings, and the wind-blocking phenomenon exists in the plate-level upper floors but not impact the pedestrian height of wind conditions.

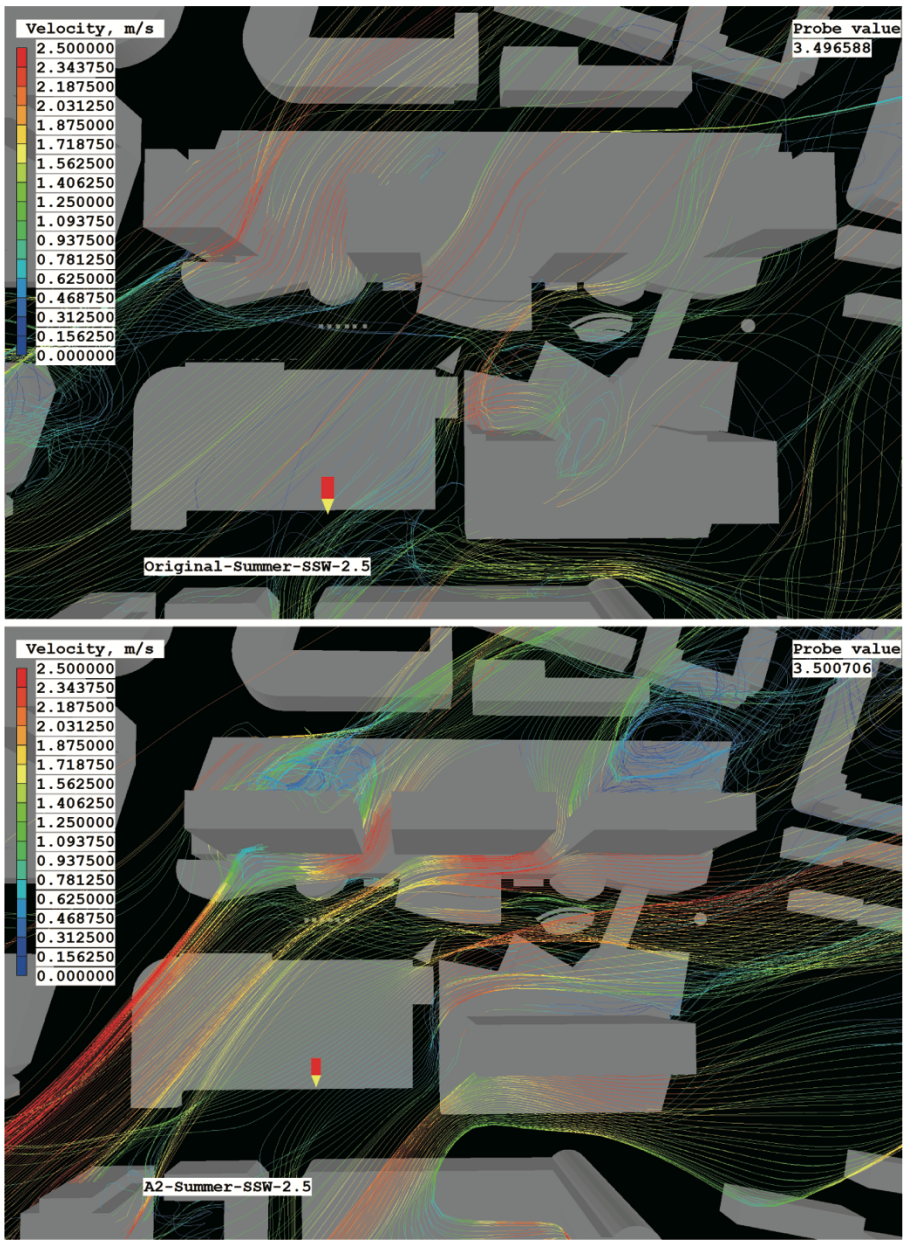


Figure 5-20 CFD simulation results of original case and A2 in summer

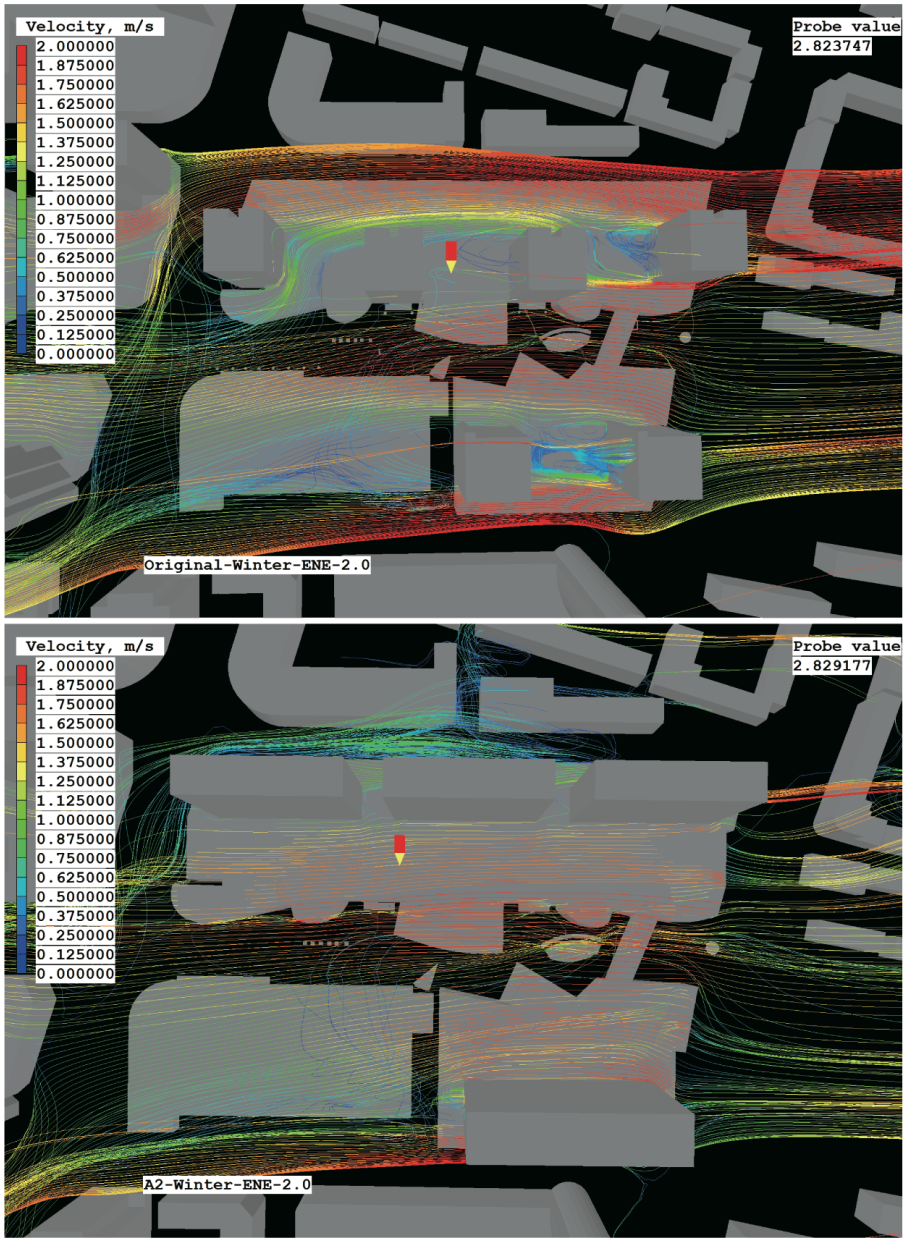


Figure 5-21 CFD simulation results of original case and A2 in winter

High-rise building type change II (A3)

This hypothesis will examine the impact of changes in the density of high-rise buildings on pedestrian height wind conditions. In the hypothetical case, four high-rise buildings on the north side will be converted into six, and two high-rise buildings on the south side will be converted into three, lowering the height of the building to increase the density. Through the simulation observation, comparison was conducted between the results of original program and the hypothetical case. (Fig. 5-22)

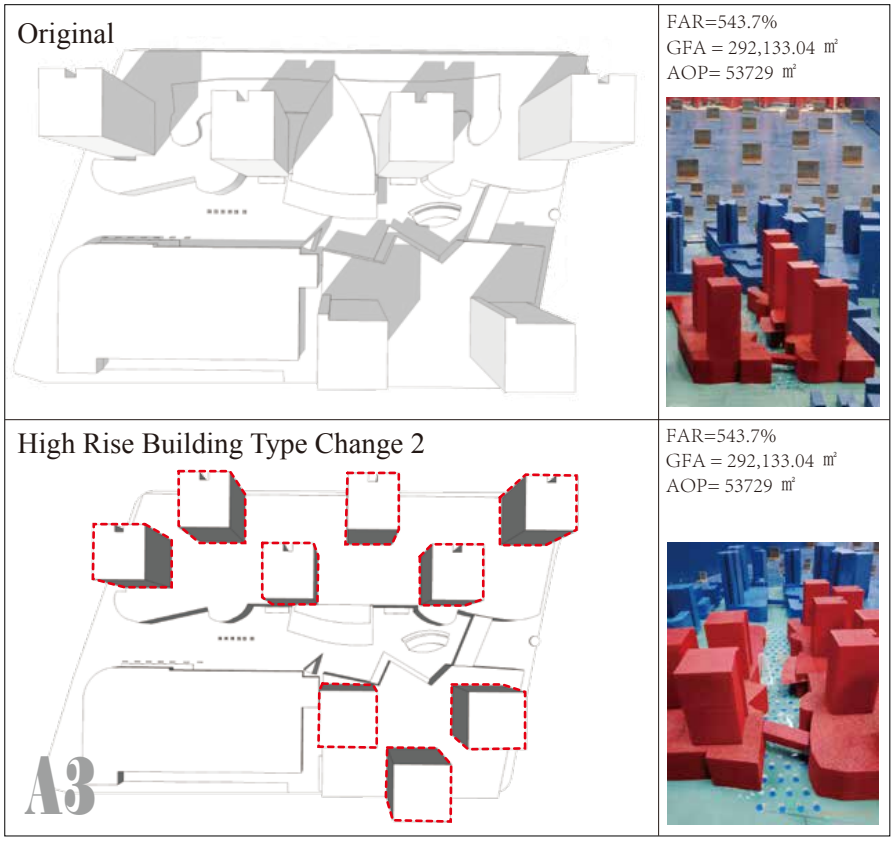


Figure 5-22 High-rise building type proposition A3

According to the comparison results in Fig. 5-23, it can be seen that when the wind direction is SSW, the high wind speed area at the northern end of skyway disappeared. The northern part of the added high-rise building makes the upper part of the skyway airflow blocked, reducing wind speed. The effect of the separation air flow of the skyway is weakened, resulting in the disappearance of the high wind speed zone. When the wind direction is ENE, the high wind speed area in the center of the field disappeared. The area and position of the upper negative pressure zone may be changed due to the change of the position of the high-rise buildings, resulting in the change of pedestrian height wind condition and the disappearance of the high speed wind area.

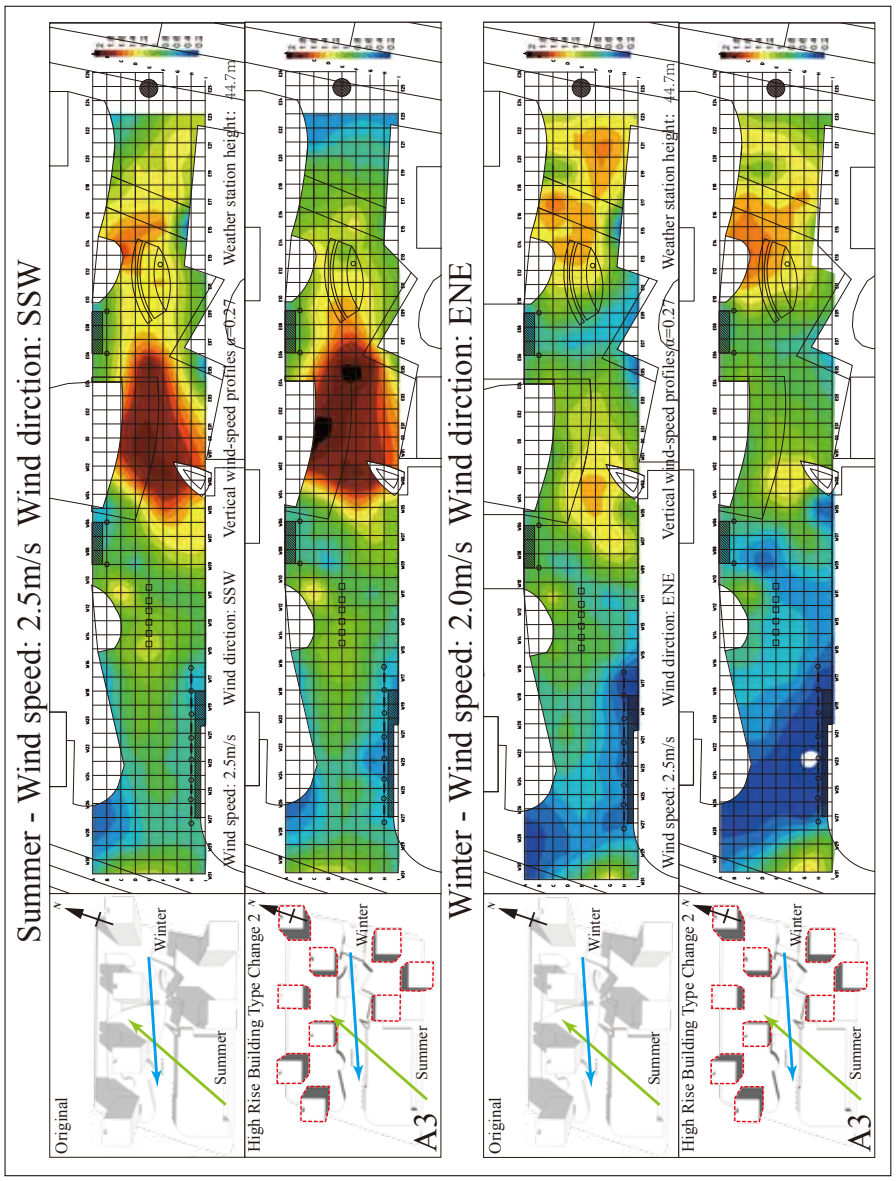


Figure 5-23 Wind tunnel simulation results comparison between original case and A3

It can be seen from the CFD simulation results that when the wind direction is SSW, the upper-level wind conditions change after changing the layout and shape of the high-rise buildings. The air velocity in the north side of skyway is weakened by the blockage of tall buildings. As a result, the downward flow of airflow decreases and the assumptions in the wind tunnel simulation results can be verified. (Fig. 5-24)

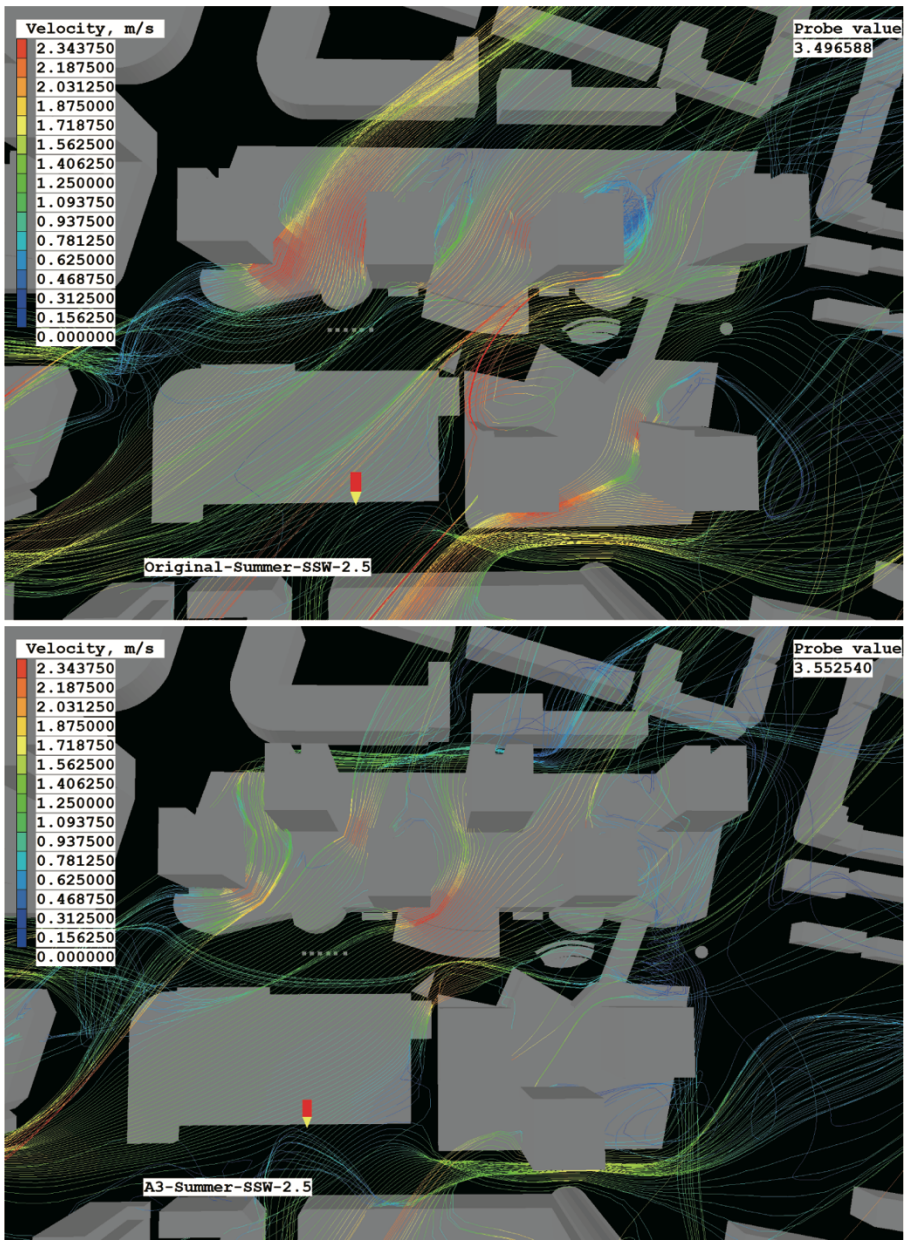


Figure 5-24 CFD simulation results of original case and A3 in summer

According to the CFD simulation results, urban surface roughness increased due to the arrangement changes of high-rise buildings, and leaded to high altitude wind conditions become complicated, also the increased roughness of urban surface resulted in the decrease of the wind speed passing through the site. At the same time, the turbulence on the west side of the three high-rise buildings located in the southeastern side of the research area will affect the wind speed at pedestrian height. (Fig. 5-25)

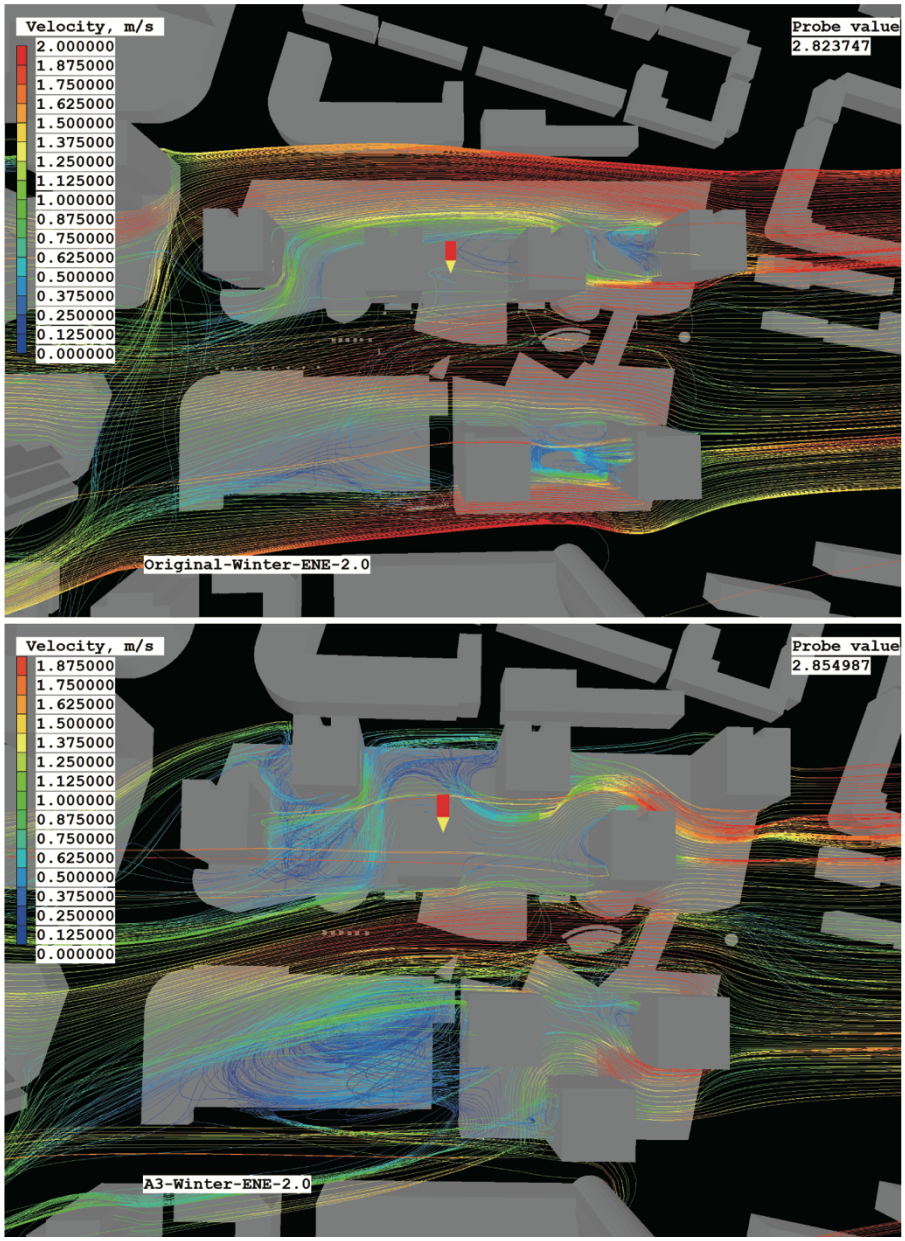


Figure 5-25 CFD simulation results of original case and A3 in winter

5.4.3. Podium building proposition

Skyway move out (B1)

This hypothesis will examine the impact of the skyway connected between two buildings on the wind conditions at pedestrian height. In the hypothetical case, the skyway is removed and the causes of changes of wind environment at pedestrian height are analysed by comparing the simulation results with the original case. (Fig. 5-26)

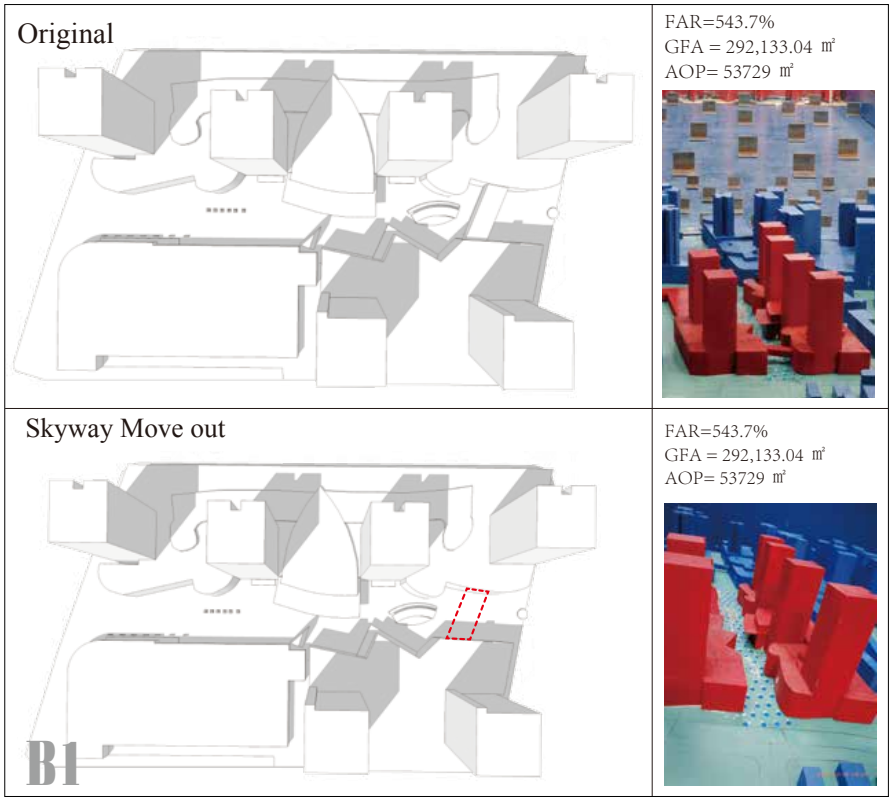


Figure 5-26 Podium building type proposition B1

It can be seen from the simulation results in Figs. 5-27, 5-28 & 5-29 that when the wind direction is SSW, the wind conditions under the skyway change obviously. The high wind speed zone below the skyway disappears and the new high wind speed zone appears at the entrance of the canyon. It can be inferred that the existence of skyway can significantly affect the distribution of pedestrian height wind environment. When the wind blows from the SSW direction and reaches the skyway, the windbreak effect of the skyway causes the airflow to separate into upper and lower sections. Because of the presence of the skyway, the area of the air duct is reduced, resulting in the compression of the airflow through the skyway thereby increasing the wind speed at pedestrian height. When the wind direction is ENE, the high wind speed area in the lower part of the skyway obviously decreases. It can be proved that the skyway has the function of dividing the airflow in the parallel direction into two parts and increasing the wind pressure in the lower part. However, the wind speed at the corner on the south side of the entrance has been increased. When the air duct

becomes clear, the negative pressure at will increase. The airflow into the entrance of the southeastern wind entrance creates a more violent impact with the southeast corner of the building, resulting in an expansion of the high-speed wind area. The northeast corner of the building is a circular edge, when faced with the same incoming wind will not have a violent impact, it will not produce an expansion of the high-speed wind area.

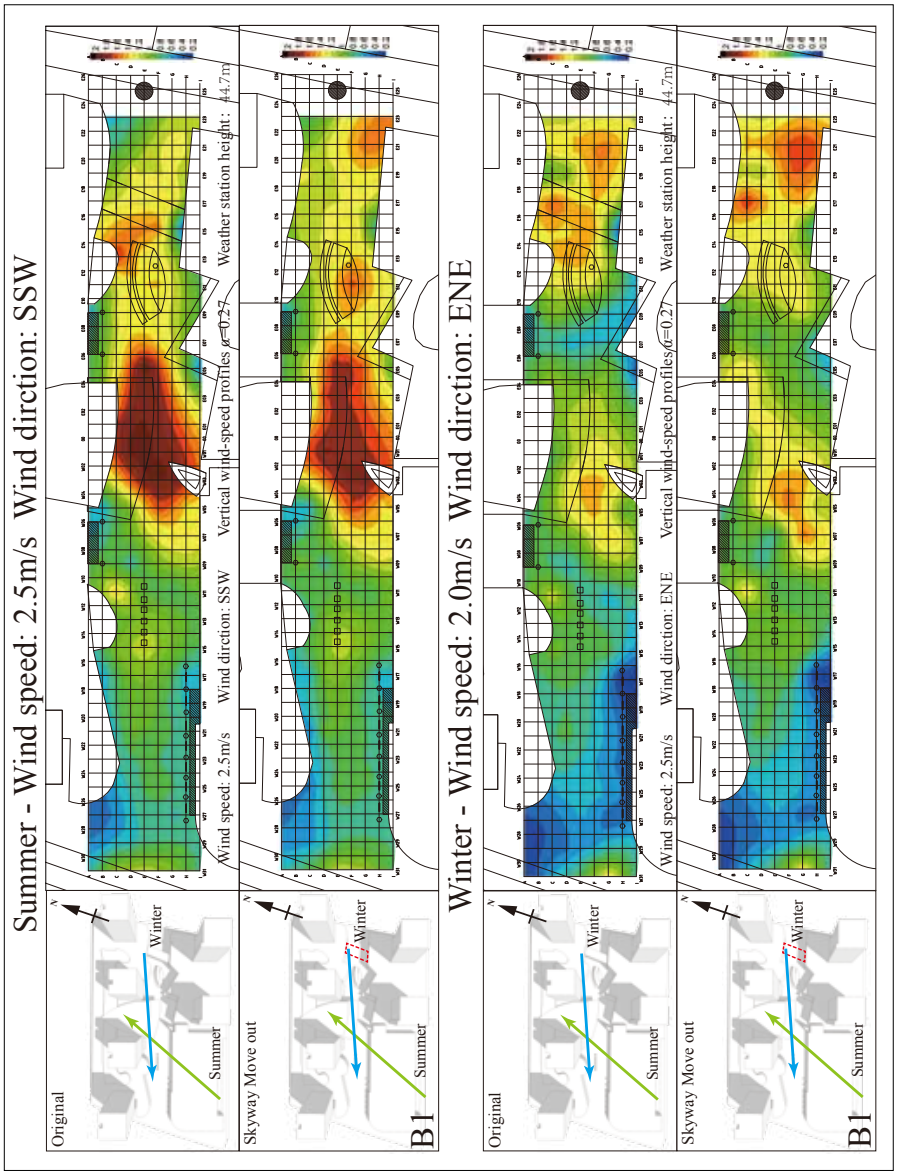


Figure 5-27 Wind tunnel simulation results comparison between original case and B1

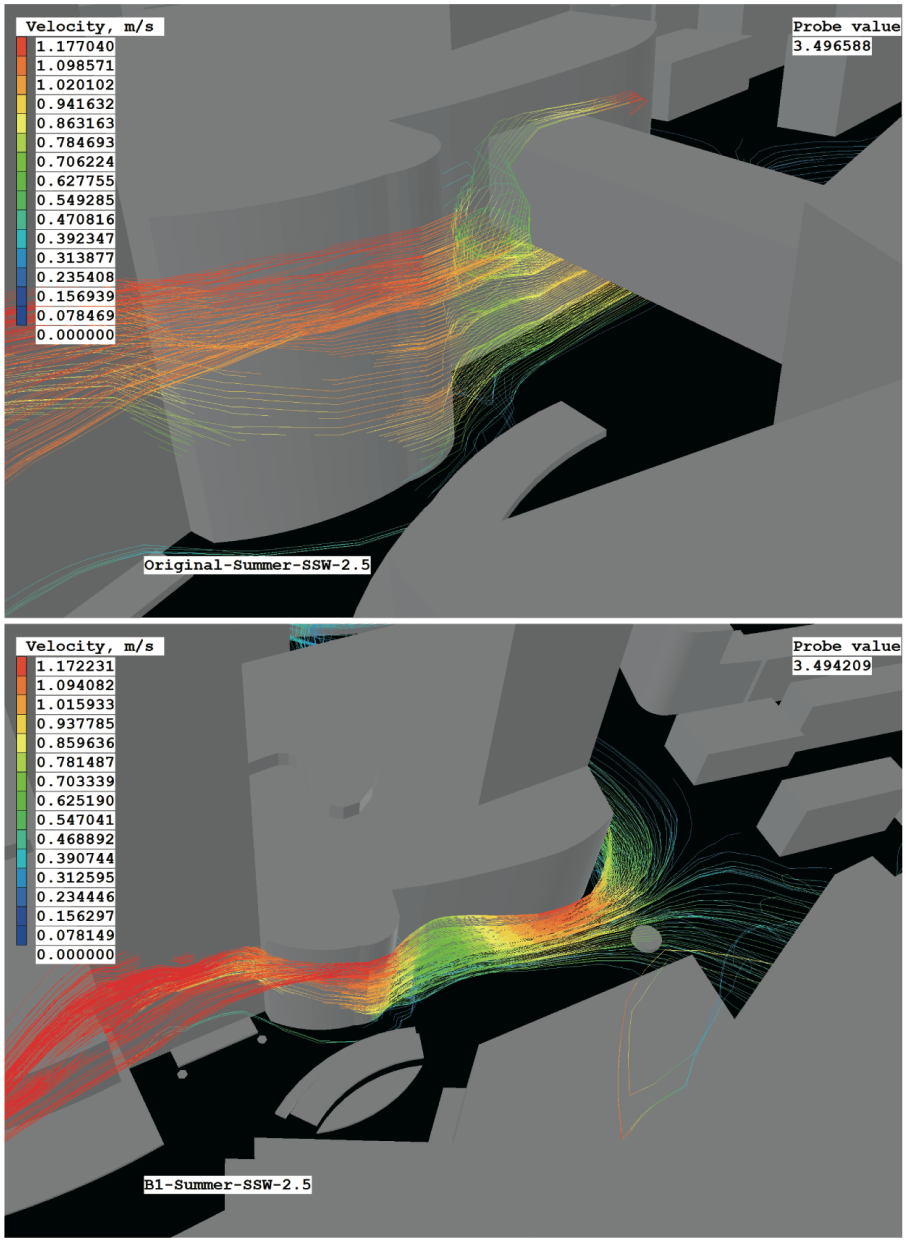


Figure 5-28 CFD simulation results of original case and B1 in summer

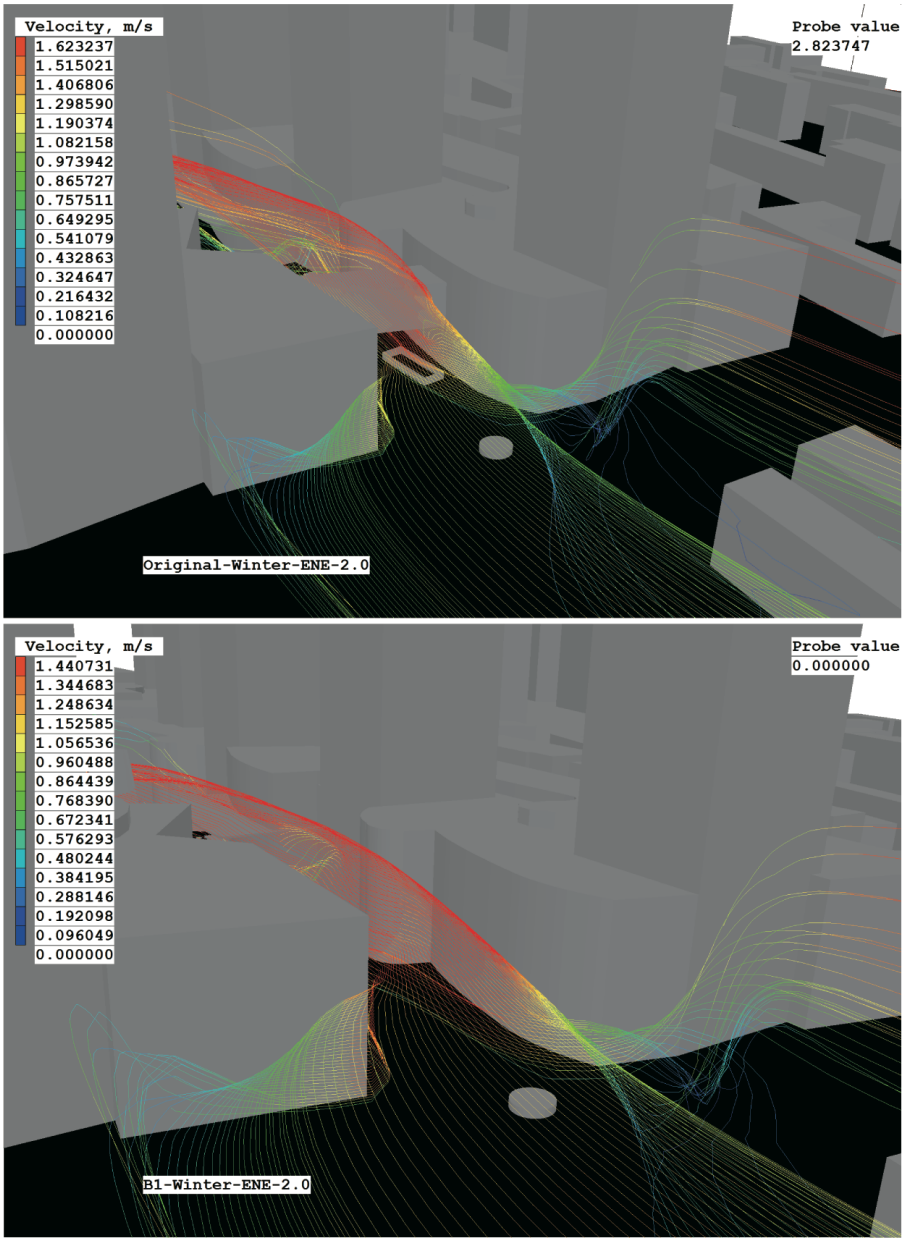


Figure 5-29 CFD simulation results of original case and B1 in winter

Place draught close and open (B2)

The hypothesis studied the impact of the narrow areas of canyon street and the passageway perpendicular to canyon on the wind environment at pedestrian height. In the hypothetical case, the narrow entrance at both ends of the research area were opened, and the vertical passageway were closed. The hypothetical simulation was used to compare with the original case. (Fig. 5-30)

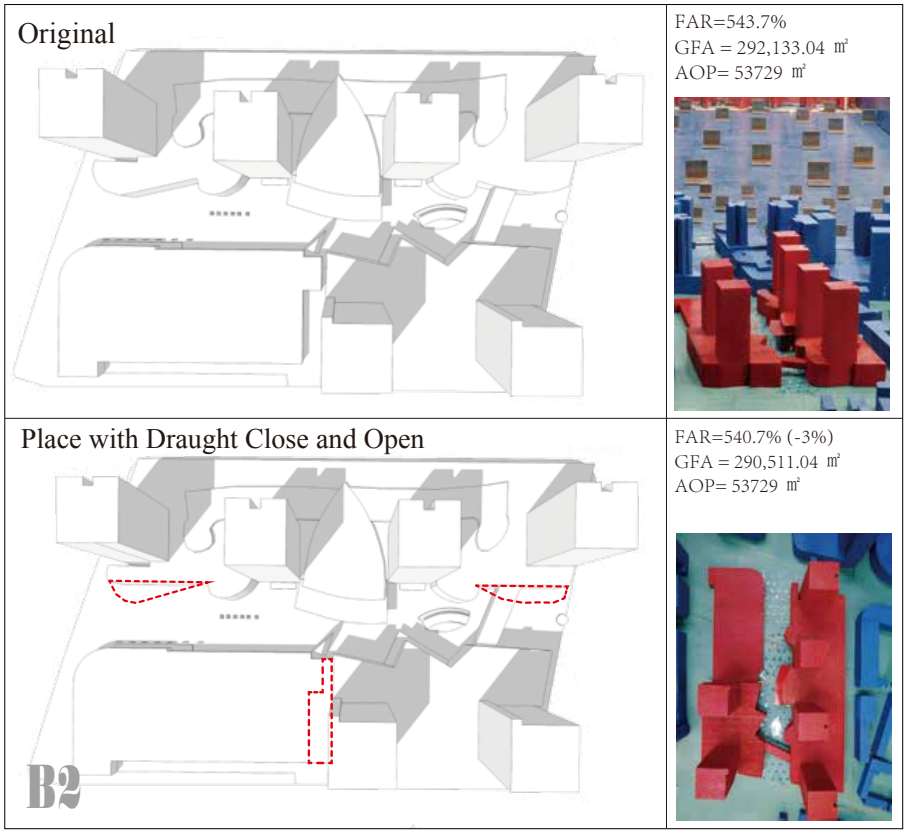


Figure 5-30 Podium building type proposition B2

From the simulation results, when the wind direction is SSW, the widening of both ends of the canyon street and the vertical passageway can not affect the wind condition so much. When the wind direction is ENE, the position of the high wind area at the east entrance moved. The frontal turbulence area is reduced due to the decrease of the included angle of buildings. Wind conditions in the center of the research area may be reduced by blocking vertical passageway. As the opening of the west entrance becomes larger, the wind pressure is reduced and the area of the low wind speed region is increased. (Figs. 5-31 & 5-32)

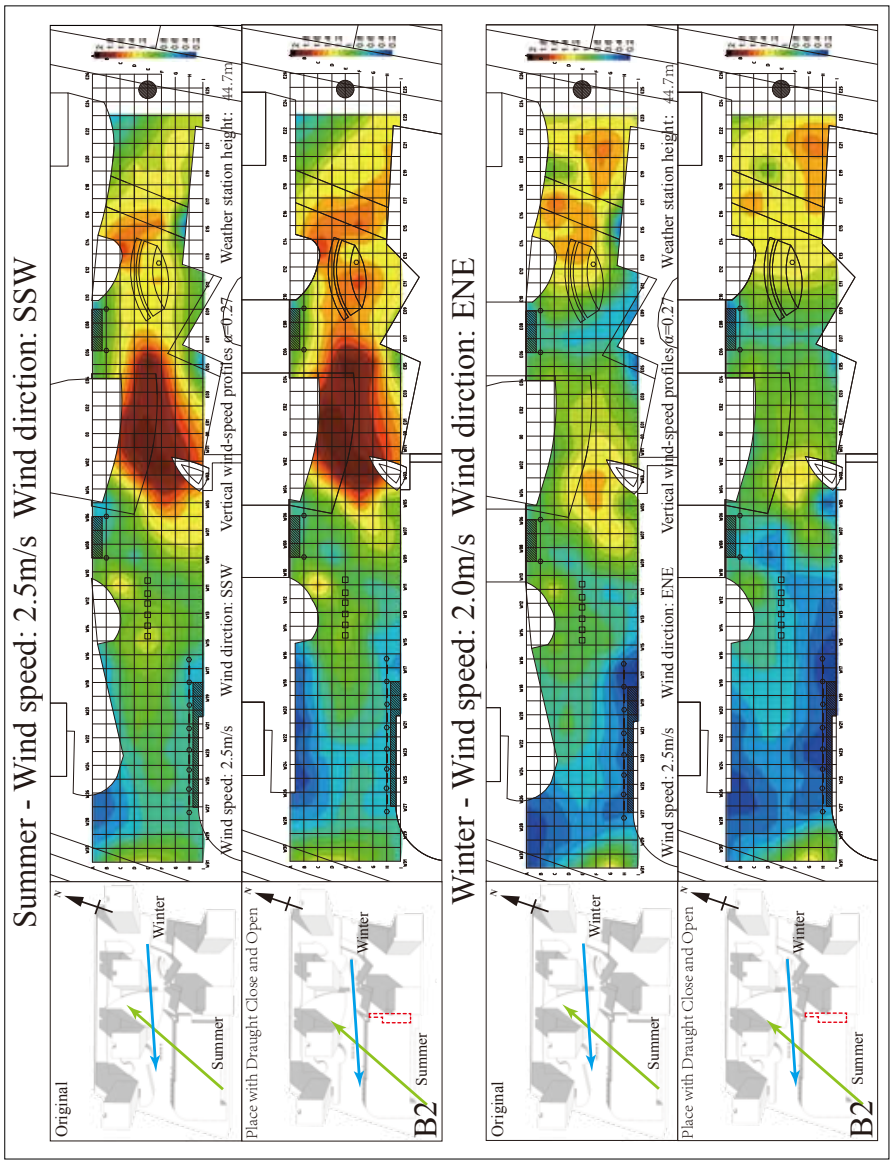


Figure 5-31 Wind tunnel simulation results comparison between original case and B2

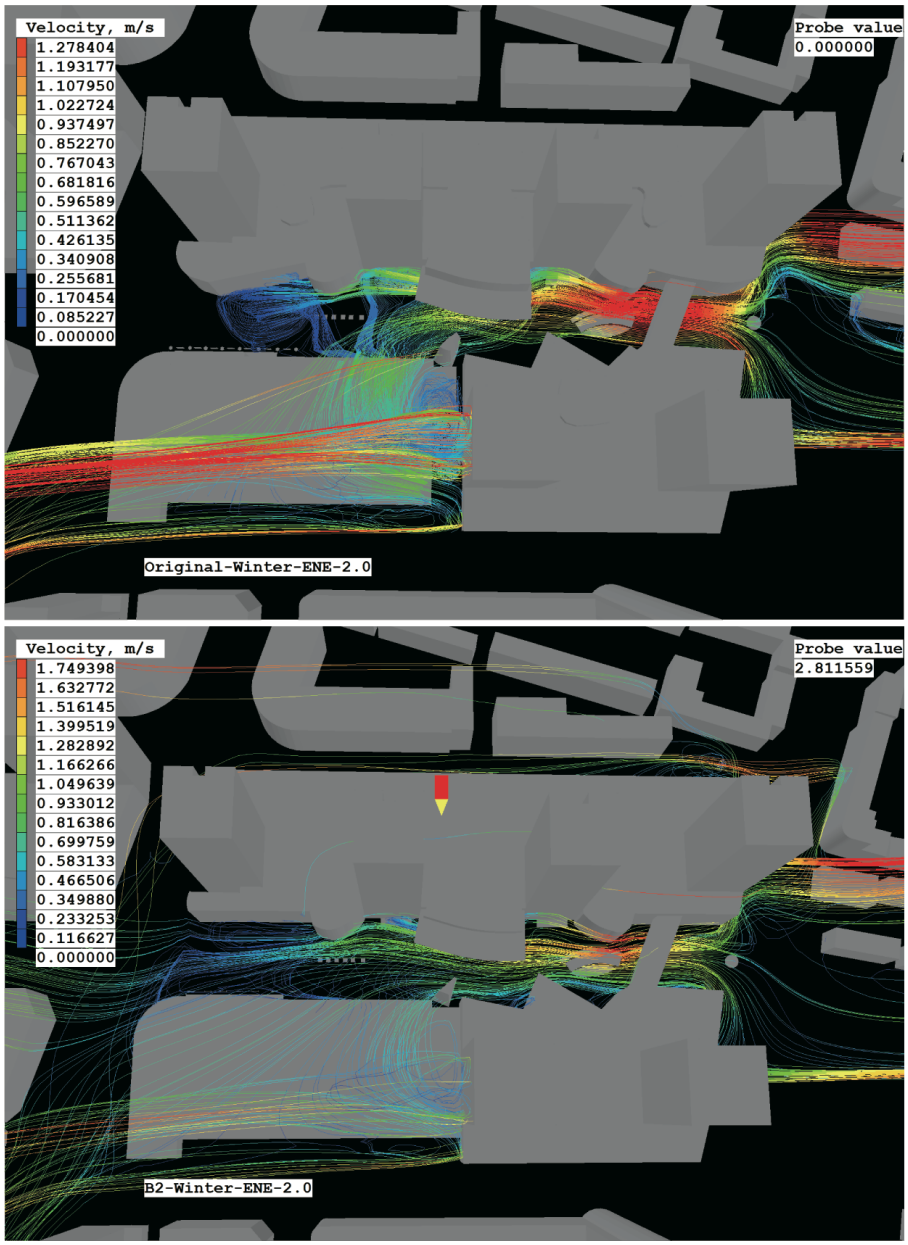


Figure 5-32 CFD simulation results of original case and B2 in winter

Straight edge of podiums; Closed wind entrance; Lower podiums in south (B2-1)

This hypothesis will examine the effect of tortuous building edges on wind conditions at pedestrian height. In the hypothetical case, the uneven edges of the podiums are levelled to form a flat canyon-shaped space. (Fig. 5-33)

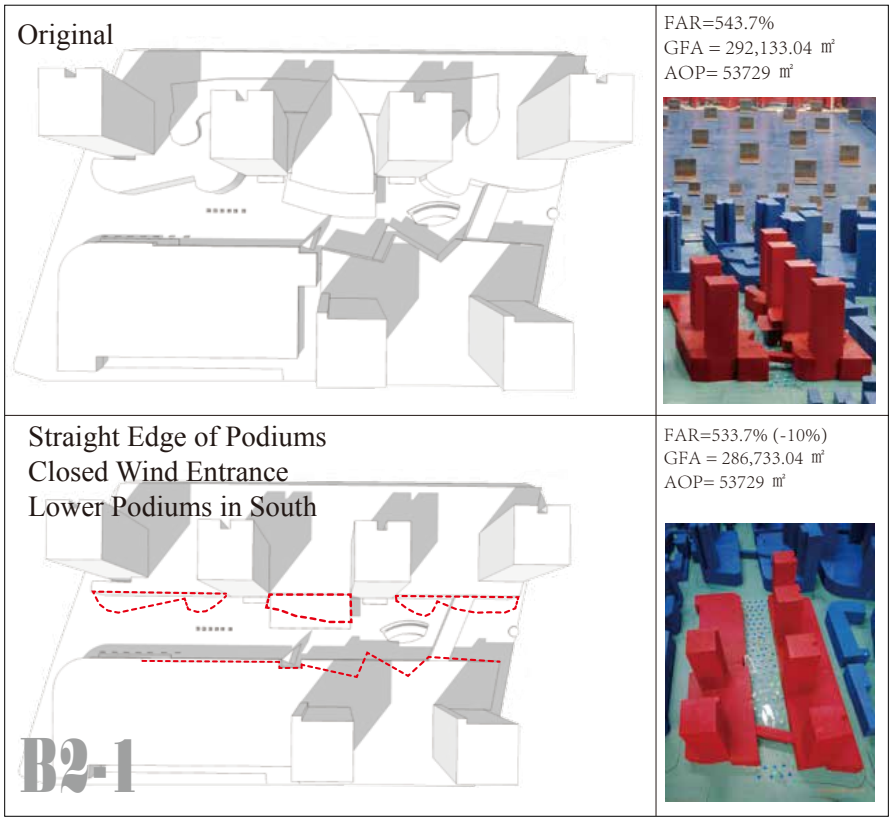


Figure 5-33 Podium building type proposition B2-1

From the simulation results, wind conditions in both winter and summer have undergone significant changes. When the wind direction is SSW, the wind speed at both ends of the research area are improved, especially in the southeastern side, forming a large high-speed wind area. When the wind direction is ENE, the wind speed at both ends of the research area are increased. At the western end, the high-speed wind area under the skyway increases due to the larger opening and the wind division effect of the skyway. Wind speed at southeastern end increases, speculated that it may be due to the turbulence caused by the corner of buildings. (Figs. 5-34, 5-35 & 5-36)

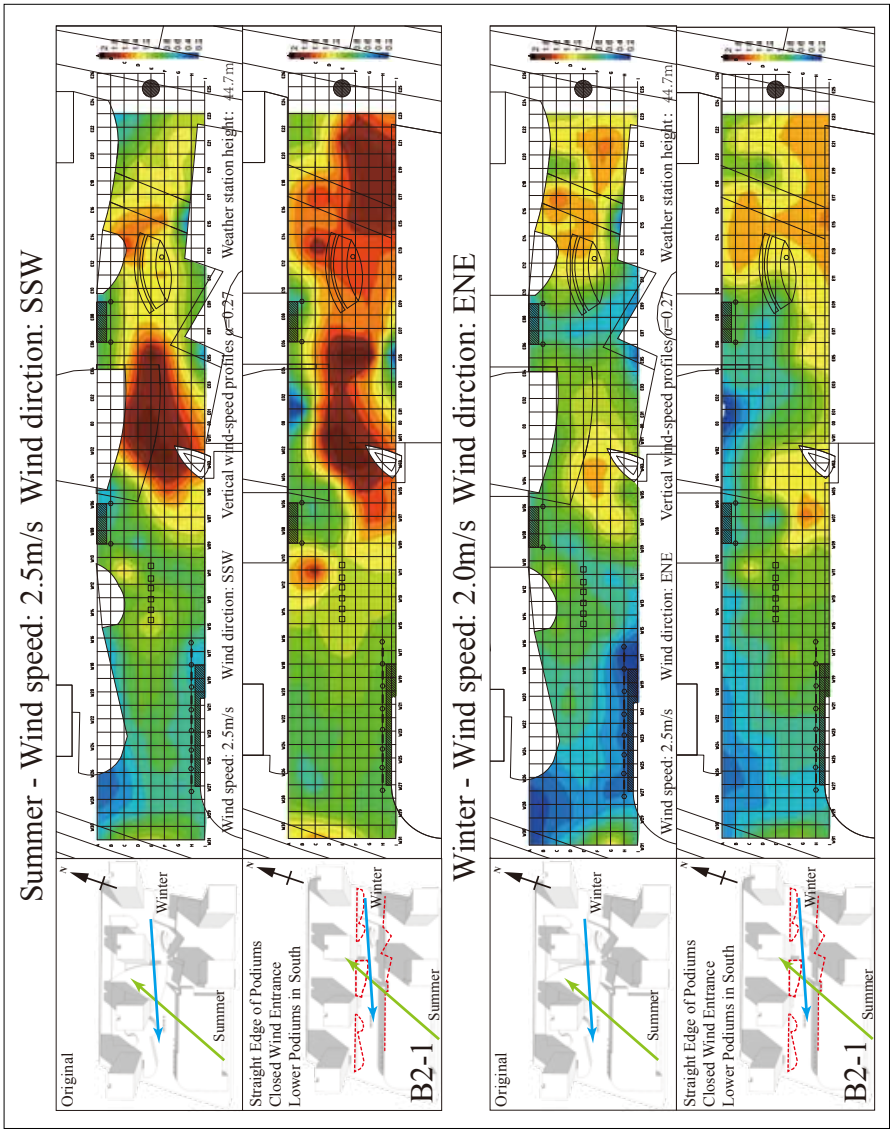


Figure 5-34 Wind tunnel simulation results comparison between original case and B2-1

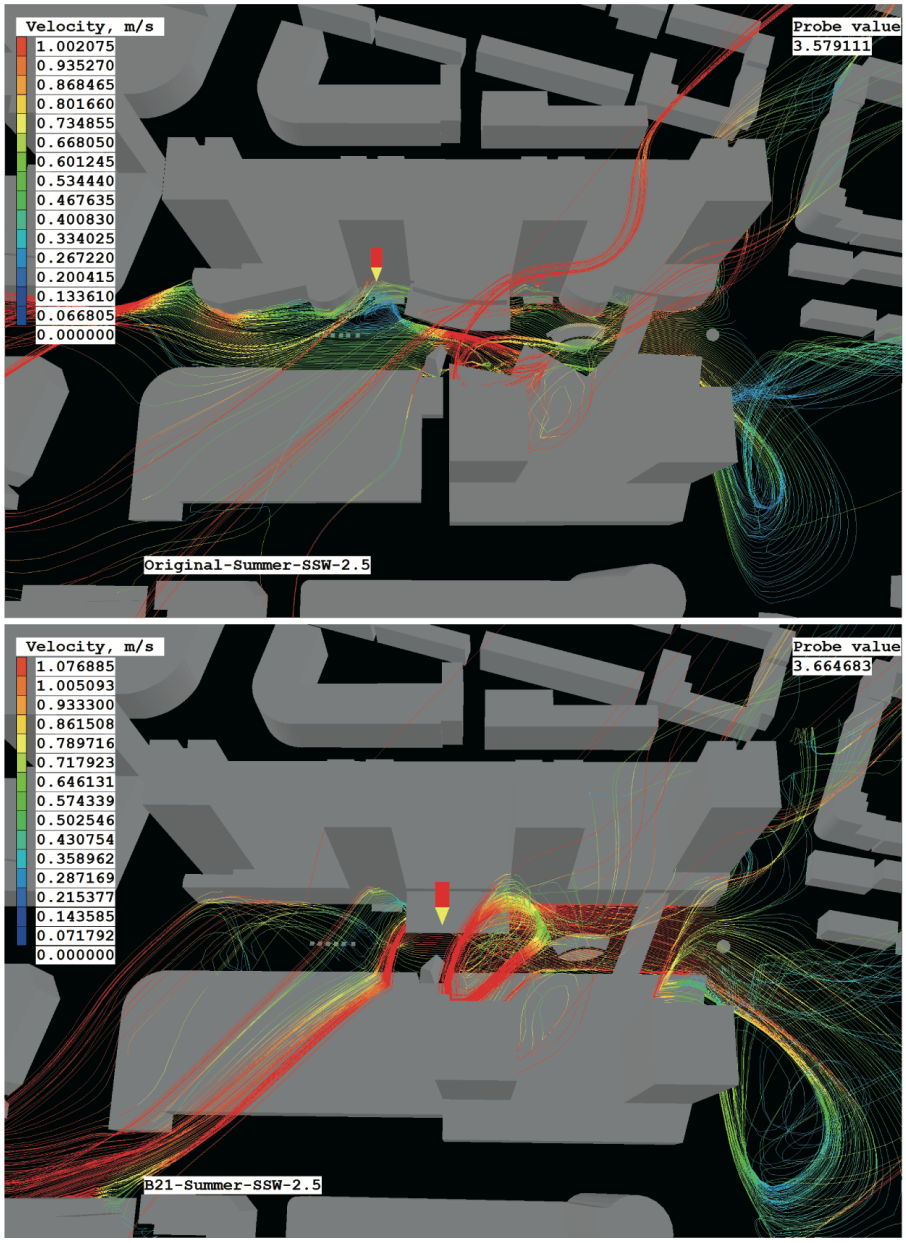


Figure 5-35 CFD simulation results of original case and B2-1 in summer

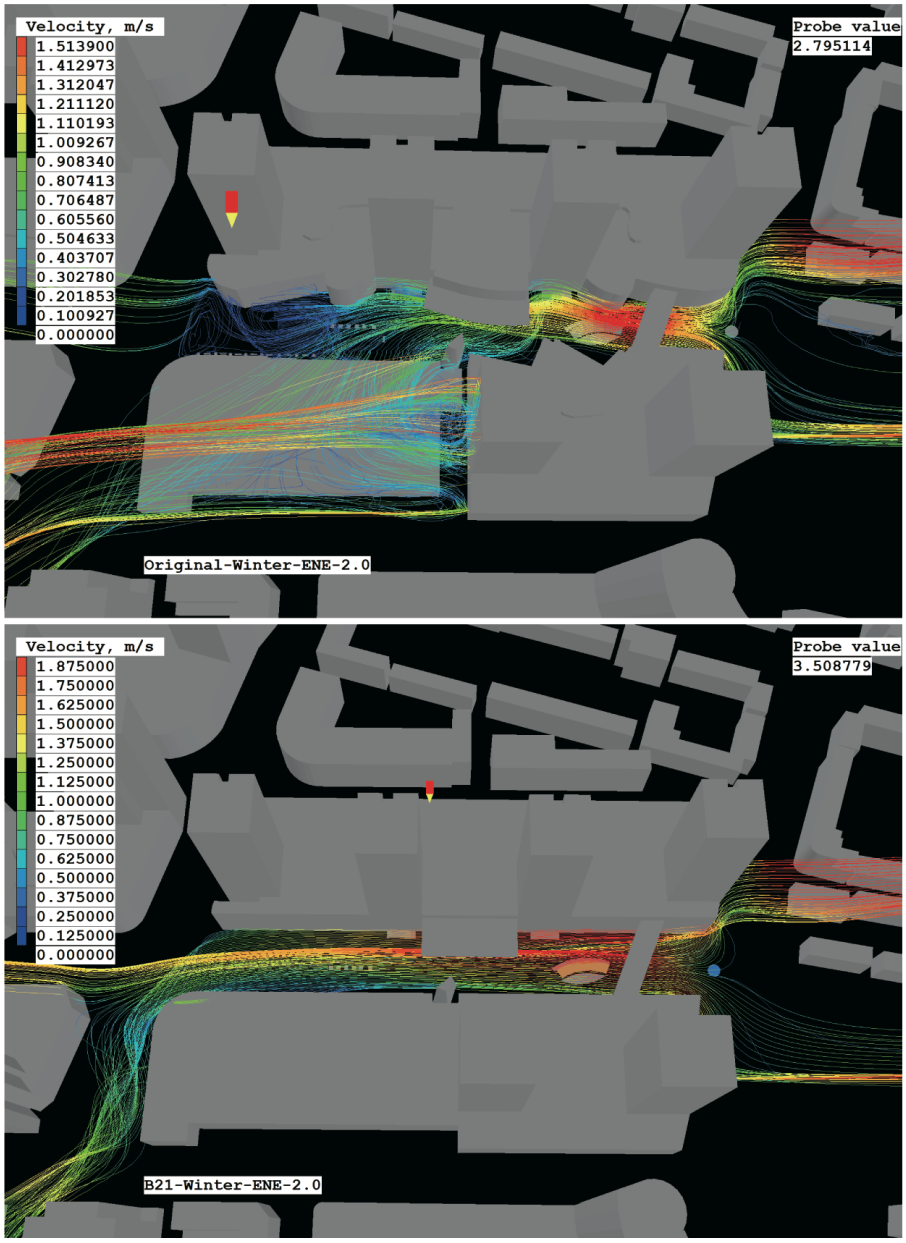


Figure 5-36 CFD simulation results of original case and B2-1 in winter

5.4.4. Wind situation by changing building type and rotating the urban street

Further hypotheses were proposed to clarify the optimal case. By rotating A2 and B2-1 CW 90°, wind tunnel simulations were again conducted.

In summer, as shown in Fig. 5-37a, for A2, the high air velocity areas on the eastern and western sides increased. The high air velocity area on the eastern side was larger than in the original case and the highest air velocity area was also larger; however, the central area air

velocity was lower than in the original case. In B2-1, the air velocity distribution was almost same as the original case and the overall air velocity was higher than the original case. The highest air velocity area in both the central and eastern areas increased.

In winter, the airflow distribution in A2 was similar to the original case, but the air velocity in the eastern and western entrances to the square significantly increased. In B2-1, the low air velocity area was larger than in the original case, but there was no high air velocity area. In summary, by changing the building types and rotating the urban street, B2-1 achieved an optimum result. (Fig. 5-37b)

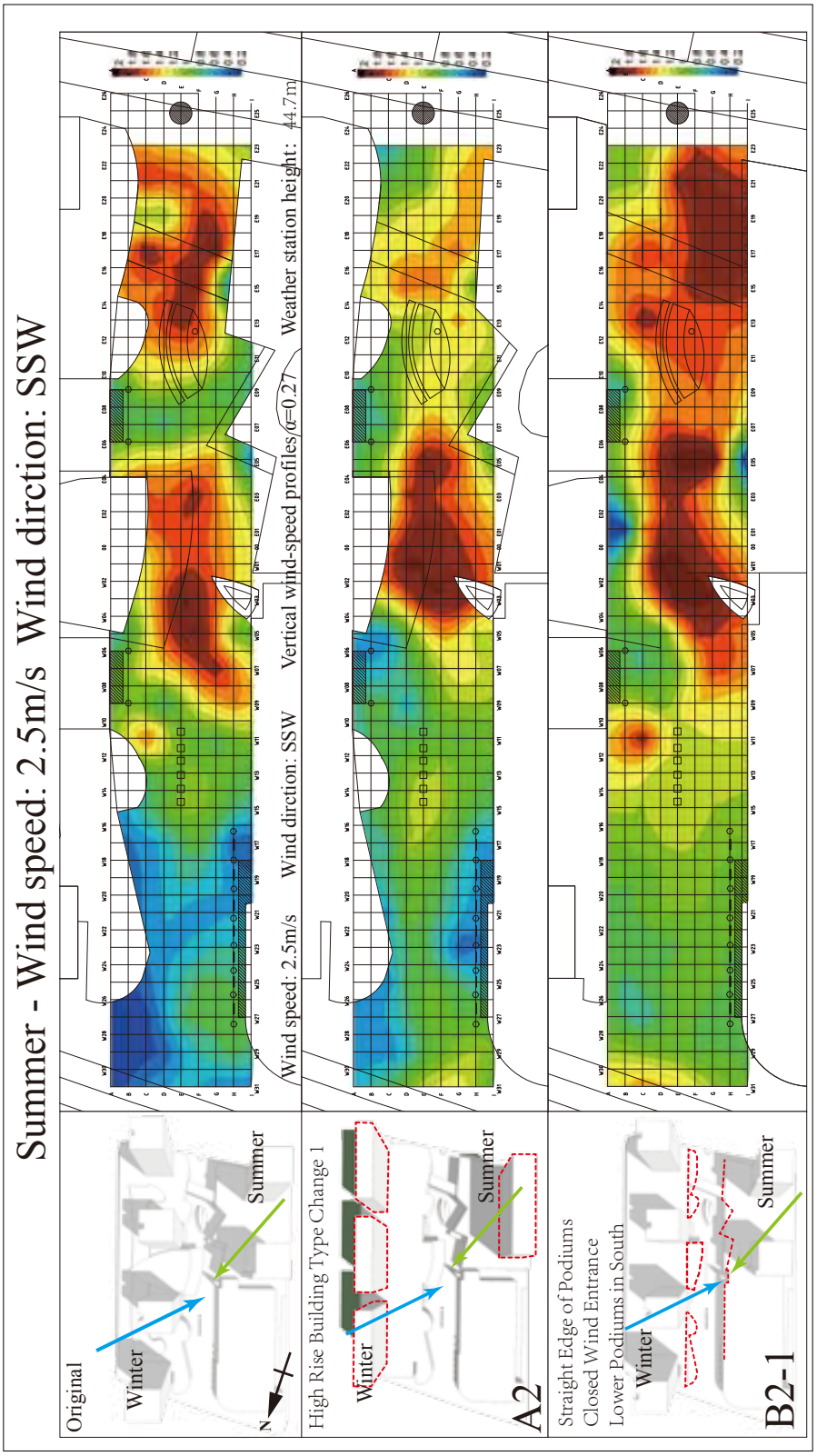


Figure 5-37a Wind situation by changing the building types and changing the canyon orientation in summer

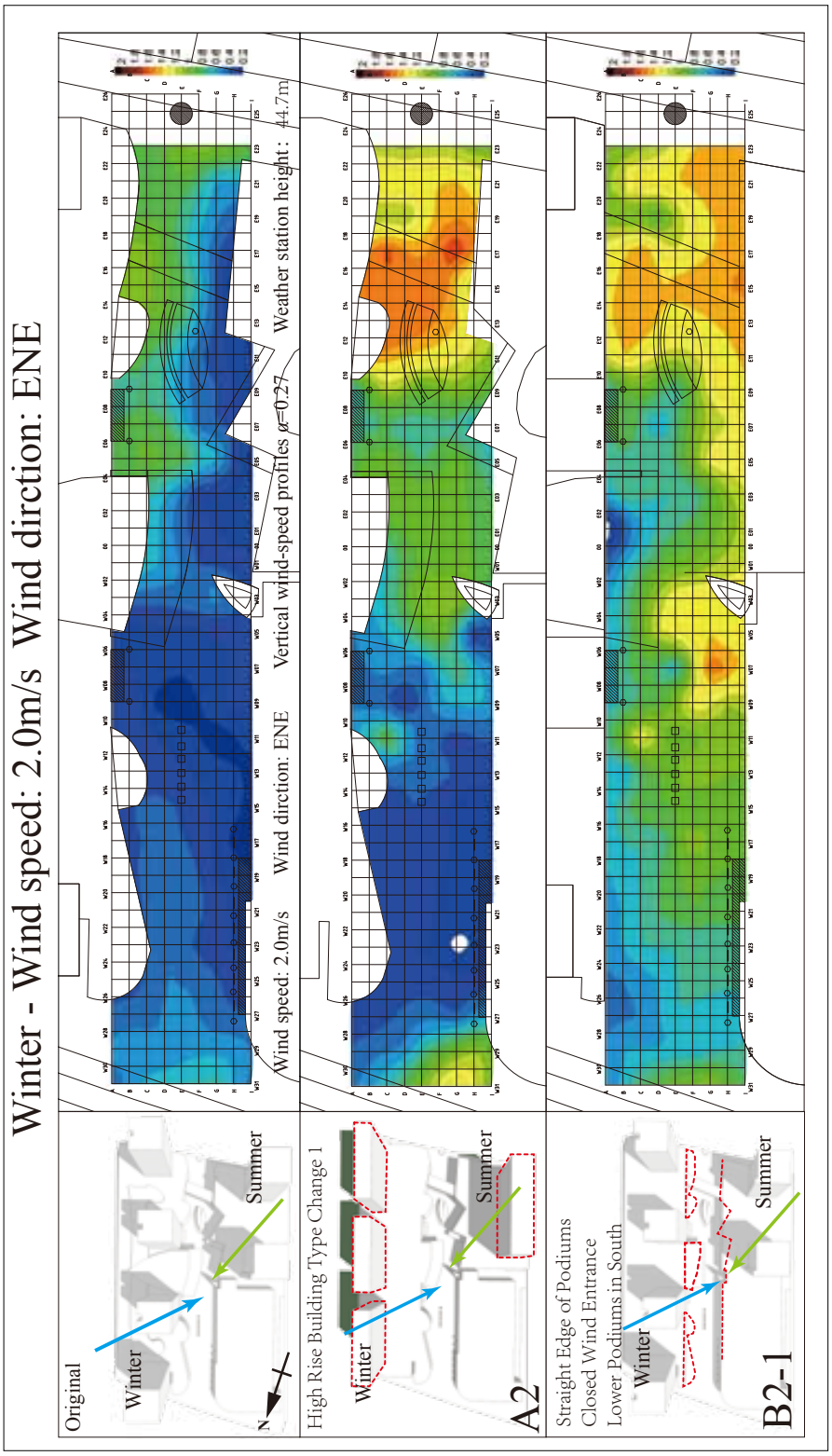


Figure 5-37b Wind situation by changing the building types and changing the canyon orientation in winter

5.5. Conclusion

In this case study, by collecting microclimate and corresponding comfort data for summer and winter, wind comfort criteria were developed to be used as standards for a wind simulation, the results from which were applied to improve wind comfort. While these research methods cannot provide a uniform approach for wind comfort, they give guidance on dealing with wind in special urban areas that have complicated wind environments and individual differences.

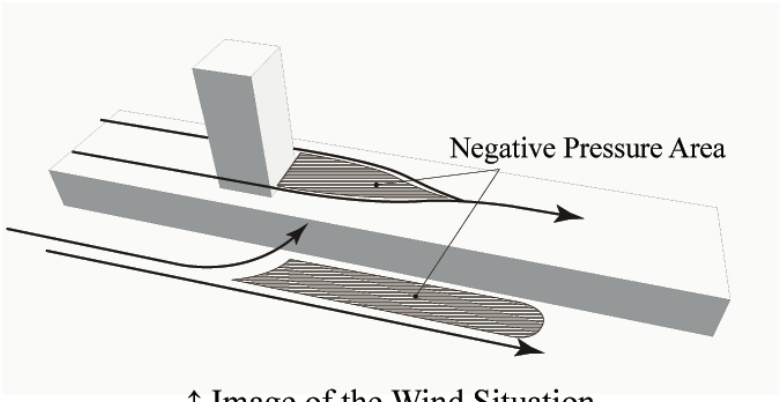
A higher air velocity in summer and taking shelter from the wind in winter would improve comfort levels. The residents in Shenyang were more sensation to the wind in summer. The air velocity of 1.12 m/s in summer is the threshold of neutral air velocity. When the air velocity was higher than 1.67 m/s in winter, it was found to be unacceptable.

The prevailing wind directions during hot and cold periods in a monsoon climate city should be used to decide on urban layout as suitable street orientation can control wind attenuation.

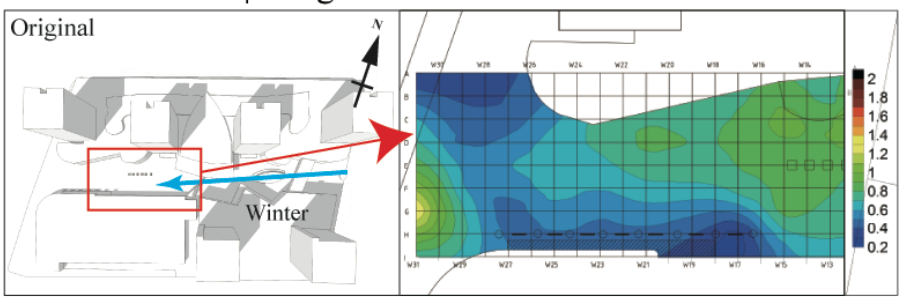
Airflow in open space can affect spatial quality, and building structures can affect airflow. Building structures were found to cause five types of airflow in this research, knowledge that can be used to improve pedestrian comfort.

From the above simulation results, The following conclusions were made:

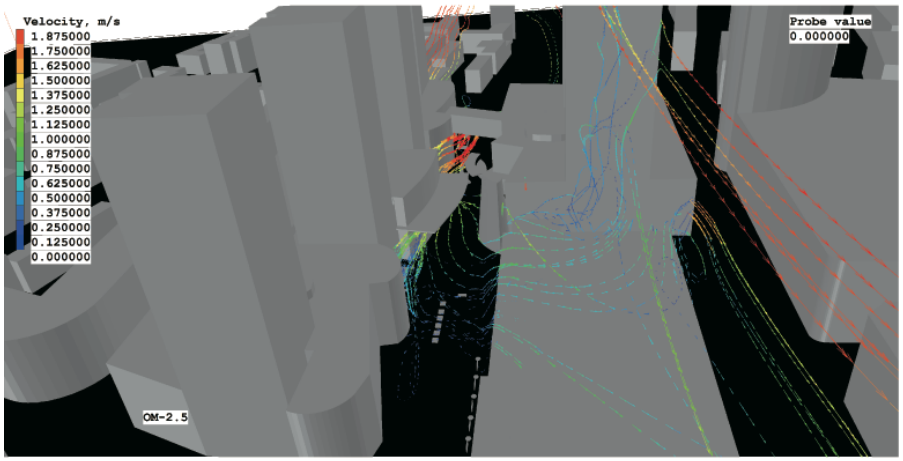
Fig. 5-38 shows that the wind shadow area formed a native pressure zone. The pedestrian-level wind in the lower position moved to a higher native pressure zone, which caused lower air velocity at the pedestrian-level. This principle can be used to create a low air velocity area in cold season. Additionally, by creating the native pressure zone, the area where suffering strong air flow can be controlled.



↑ Image of the Wind Situation



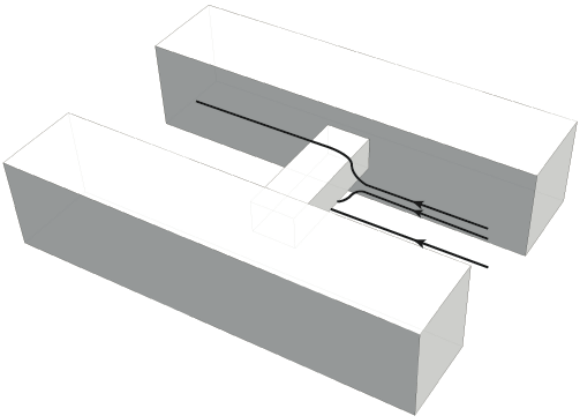
↑ Reference from the Wind Tunnel Simulation



↑ Reference from the CFD Simulation

Figure 5-38 Native pressure zone formed by the wind shadow

Fig. 5-39 shows that the skyway acted as a wind diverter. The wind passing through the skyway was separated into two parts and the air area was decreased by the skyway; however, the air volume per unit area increased, which caused the air velocity under the skyway to increase.



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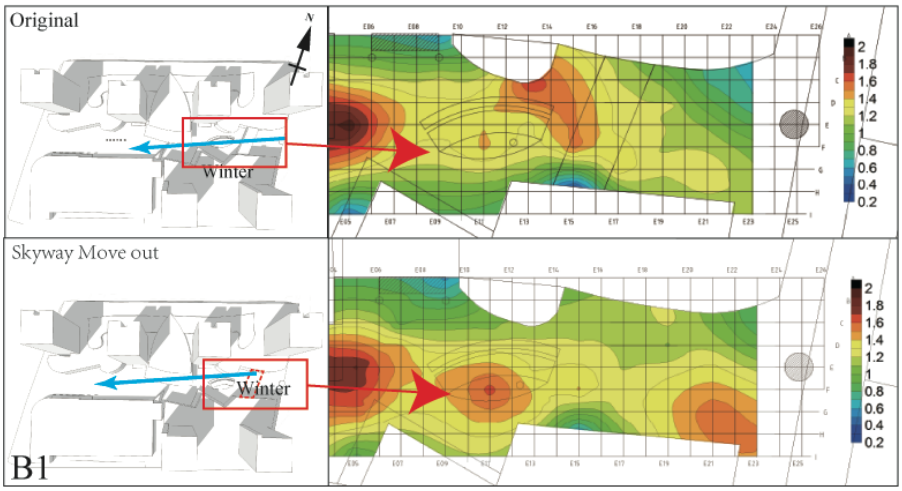

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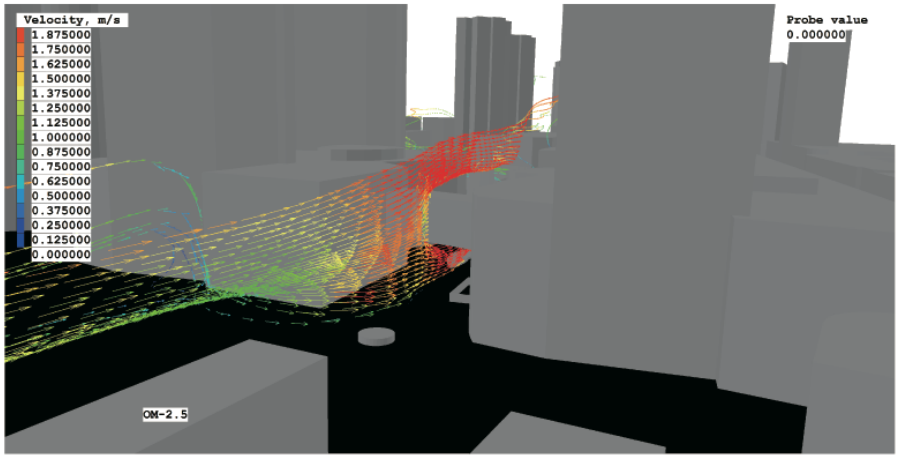
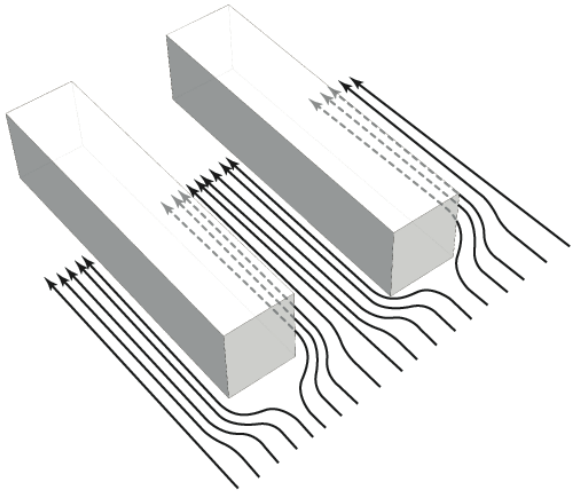


↑ Reference from the CFD Simulation

Figure 5-39 Wind separation effect by skyway

As Fig. 5-40 shows, the airflow went through the air duct formed by the street canyon and the air velocity increased because of the increase in air volume per unit area. This is called a funnel effect, which occurs when narrow canyons cause accelerated air velocity [109].



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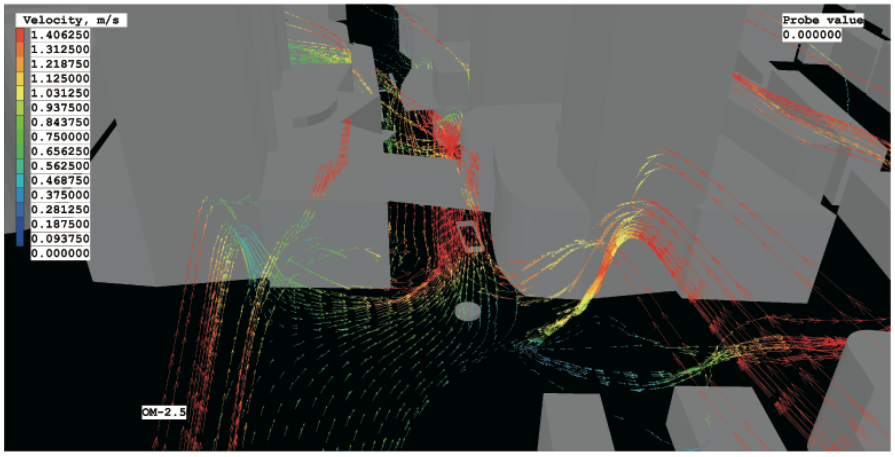
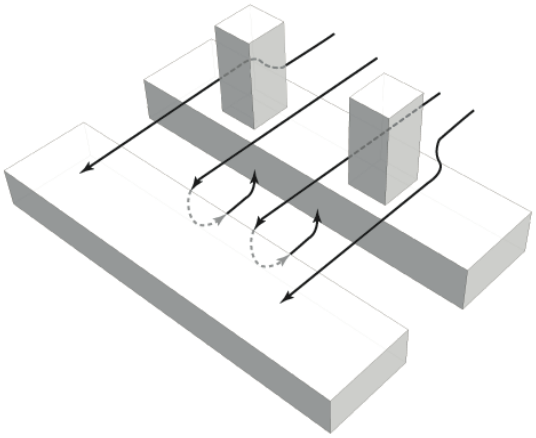


↑ Reference from the CFD Simulation

Figure 5-40 Funnel effect formed by the street canyon

As Fig. 5-41 shows, the airflow coming from the back side of the building crossed the podium from the roof. Parts of the airflow were obstructed by the podium opposite, and went down in a reverse direction, causing a lower pedestrian-level wind.



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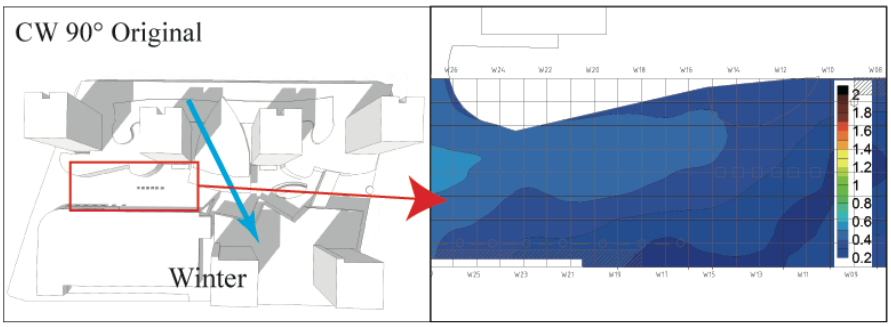

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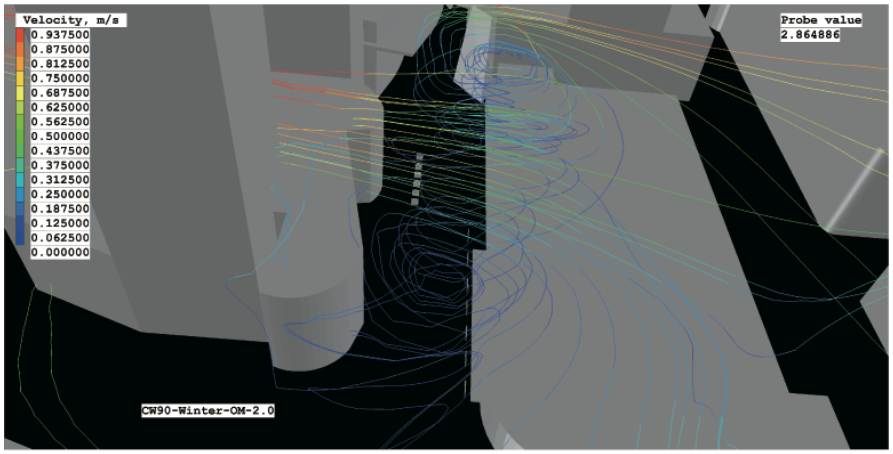
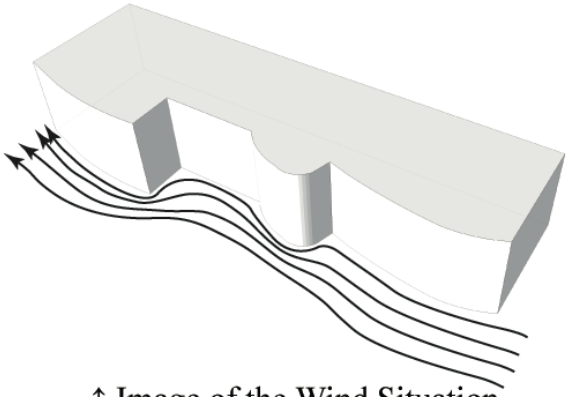


↑ Reference from the CFD Simulation

Figure 5-41 Wind channeling and downdraft wind

As Fig. 5-42 shows, the streamlining of the building edges also changed the air duct area, causing a higher airflow at the narrow section.



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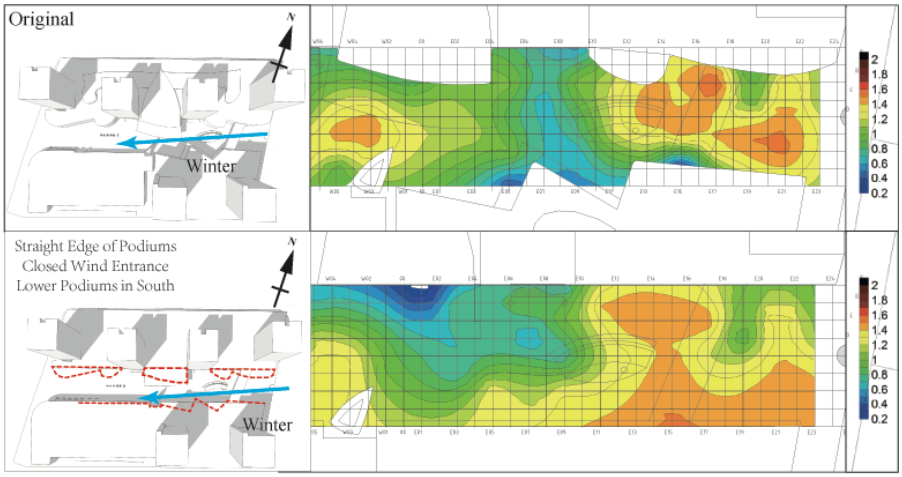

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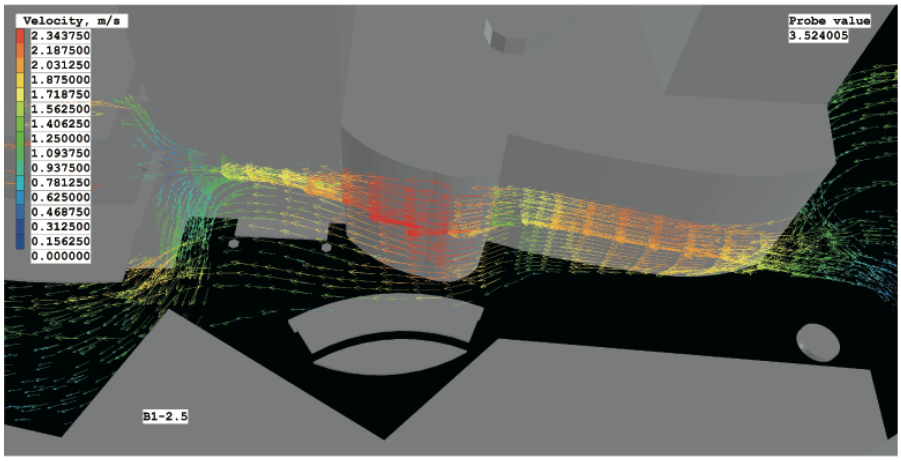


↑ Reference from the CFD Simulation

Figure. 5-42 Higher airflow caused by the narrow section

5.6. References

[110] Takuya TSUTSUMI. (2009). Snowdrift Wind Tunnel. *Wind Engineers., JAWE* 34(1), 36-41.

[111] General Administration of Sport of China. (2015. Nov. 25). *Communique of Nationals ' physique.* Retrieved from http://www.sport.gov.cn/n16/n1077/n1422/7331093.html.

[112] Kaltschmitt, M., Streicher, W., & Wiese, A. (Eds.). (2007). *Renewable energy: technology, economics and environment.* Berlin: Springer Science & Business Media.

[113] Heier, Siegfried. (2005). *Grid Integration of Wind Energy Conversion Systems.* Chichester: John Wiley & Sons. p. 45. ISBN 0-470-86899-6.

[114] China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. (2005). *China Standard Weather Data for Analyzing Building Thermal Conditions*. Beijing: China Building Publishing House.

[115] Meng X W, Setoguchi T. (2010). Development of Urban Design Guidelines with Wind Tunnel Simulations for Downtown Districts in Winter Cities. *Journal of Asian Architecture and Building Engineering*., 9(2): 355-362.

[116] Architectural Institute of Japan, (2004). *Recommendations for loads on buildings*. Tokyo: Architectural Institute of Japan (in Japanese).

[117] Mochida, A., Tominaga, Y., Murakami, S., Yoshie, R., Ishihara, T., Ooka, R., (2002). Comparison of various k–ε models and DSM applied to flow around a high-rise building. *Report on AIJ cooperative project for CFD prediction of wind environment. Wind Struct*. 5 (2–4), 227–244.

[118] Shirasawa, T., Tominaga, T., Yoshie, R., Mochida, A., Yoshino, H., Kataoka, H., Nozu, T., (2003). Development of CFD method for predicting wind environment around a high-rise building part 2: the cross comparison of CFD results using various k-ε models for the flow field around a building model with 4:4:1 shape. *AIJ J. Technol. Des.* 18, 169–174 (in Japanese).

[119] Yoshie, R., Mochida, A., Tominaga, Y., Kataoka, H., Harimoto, K., Nozu, T., Shirasawa, T., (2005a). Cooperative project for CFD prediction of pedestrian wind environment in Architectural Institute of Japan. *J. Wind Eng. Ind. Aerodyn.* 95, 1551–1578.

[120] Tominaga, Y., Mochida, A., Shirasawa, T., Yoshie, R., Kataoka, H., Harimoto, K., Nozu, T., (2004). Cross comparisons of CFD results of wind environment at pedestrian level around a high-rise building and within a building complex. J. Asian Archit. Build. Eng. 3 (1), 63–70.

6. Climate-responsive open space approaches

6.1. Suitable outdoor microclimate situation

Each city has different specific climatic conditions, and urban residents have different abilities to adapt to different climatic conditions. The microclimate is influenced by urban space elements such as urban layout and urban heat island effect in the overall climate of the city. It can be drawn from this study, microclimate obviously affected people's comfort. In addition, the influence effect in hot summer, cold winter and cooling period were distinct. No single parameter will affect the spatial comfort as a leading role. All the factors have come together on the comfort sensation.

6.1.1. Hot summer and cold winter

The field survey conducted in Shenyang during the hot summer and cold winter, over 4900 groups of samples were collected during the surveys. From the research analysis, it can be seen that the residents in Shenyang are more sensitive to hot season than cold season.

In summer, lower T_a, higher air velocity, RH and more shade brought higher CSV. 29.6°C of T_a, 1.1 m/s of air velocity, and 67% of RH were threshold values for whether the environment was comfortable or not.

In winter, higher T_a, lower air velocity and less shade, caused higher CSV. −14.4°C of T_a, −16.5°C of WC, and 1.6 m/s of air velocity were environmental threshold values that can be accepted or not.

6.1.2. Cooling period

Three open space in Sapporo were chosen as research sites for the study during the cooling period. The study of the cooling period is not as easy as the study of extreme climatic conditions. Because in a relatively comfortable environment, microclimate will no longer be the most important factor affecting the comfort of the environment. From the relationship between CSV and microclimate alone, the user's perception of the environment cannot be easily judged. By using the spatial behavior as a reference, based on a sufficient number of samples, combined with the analysis of microclimates, the following conclusions are drawn:

At around 20°C or higher, the outdoor environment did not affect the number, time or location of sitting behaviors, and many sitting behaviors were observed in the public space. In addition, almost no sitting behaviors were observed in public space at temperatures below 8°C. During the cooling period (from 8°C to 20°C), the sitting behaviors decreased with lowering temperatures. However, microclimates influenced by sunlight and wind speed affected the reduction in the number of sitting groups, sitting time, and sitting behaviors. Therefore, it is important to control the microclimates of the outdoor public space and to create desirable outdoor environments in order to promote sitting behaviors during the cooling period.

6.2. Suitable outdoor activity time

According to different seasons and climatic conditions, the choice of time for outdoor activities of urban residents is different, the human

present is related to microclimate that change along with time, that is, in summer, afternoon before sunset is the most unpopular time, but after sunset, more people came outside. From lunchtime to sunset is the most attractive period for people in winter.

As can be seen from the survey results in Shenyang (Fig. 6-1), there are few people who choose outdoor activities during the summer, especially in the afternoon. When is after sunset, there was a noticeable increase in the number of people choosing outdoor activities, especially around the end of dinner. In winter, on the contrary, urban residents choose outdoor activities during sunny hours during the day. When night falls, only highly-targeted pedestrians can be found on the ground. They do not choose to stay too long on the road. (Fig. 6-2)

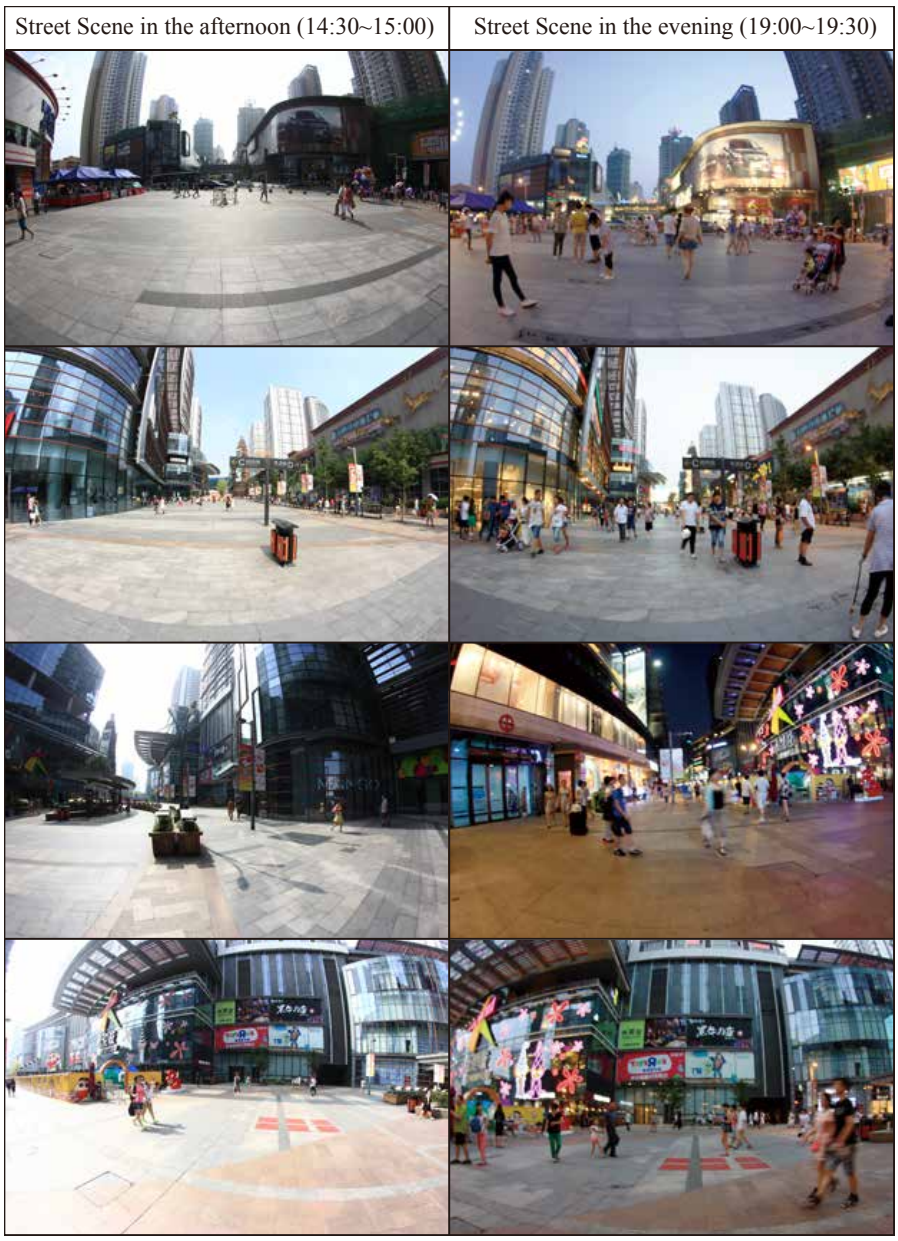


Figure 6-1 Suitable outdoor activity time in summer

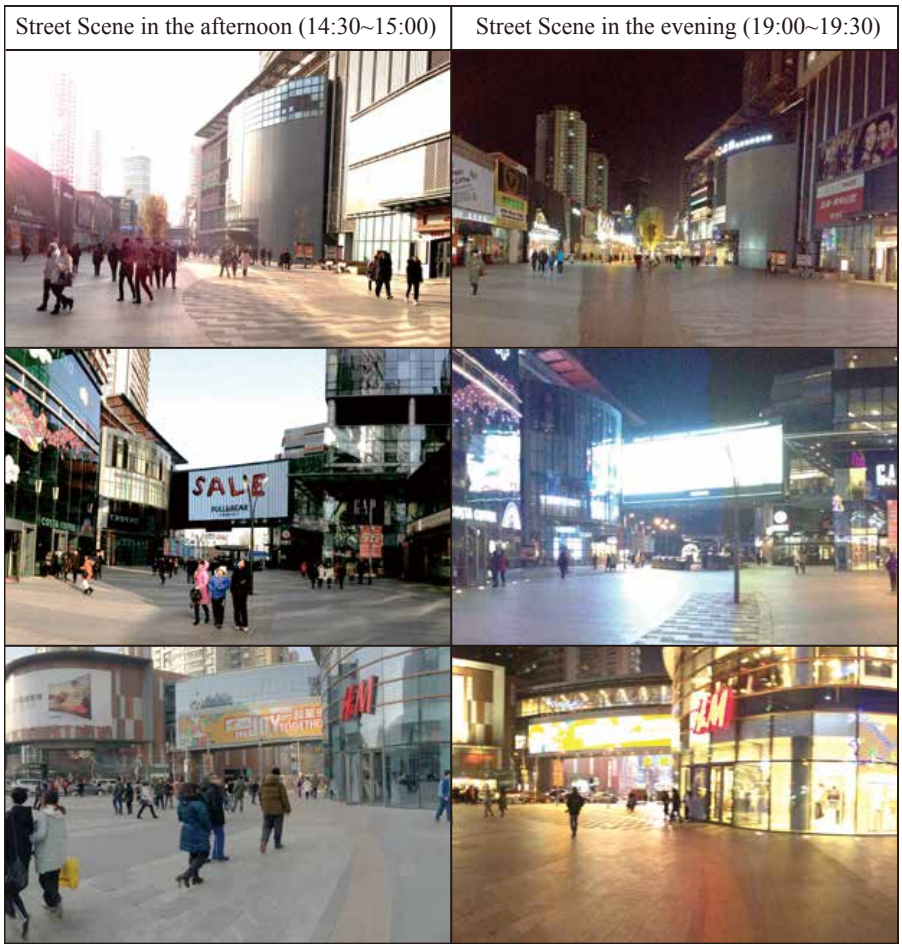


Figure 6-2 Suitable outdoor activity time in winter

6.3. Open space approaches on climate-responsive design

6.3.1. Funnel effect of wind and wind separation effect

According to the conclusion in Chapter 5, the entrance of both ends of the study area is narrower than the width of the site. In terms of environmental construction, it will give people the feeling of limited space and regional entrance.

At the same time, the shape of its funnel pattern will cause a funnel effect when the parallel air flow passes through, i.e., because the unit air volume at the narrow part is the same but the passing area is reduced, the wind speed increases.

In the summer when the wind is parallel to the site, it can provide a pleasant environment experience for pedestrians. With the creation of shade and landscape facilities, it can create a good outdoor environment. However, it should be avoided that the wind speed

higher than the human body's comfort caused by the narrowness of the air duct will result in undesirable effects. When the winter winds are parallel to the site, the combination of high-speed wind and low temperatures will make the outdoor environment very bad. Contrary to the summer season, the entrances at both ends in winter will no longer be suitable for pedestrians.

The skyway that straddles the middle of the site divides the parallel airflow into two parts. For pedestrian height, this separation effect will increase the wind speed in the lower part of the skyway. Like the funnel effect, separation effect will bring a comfortable feeling in summer and the winter experience will be worse. Another function of Skyway is to connect the traffic space of the two buildings. By subjective adjustment of the internal microclimate to a comfortable level, it can make pedestrians have better choices in winter travel.

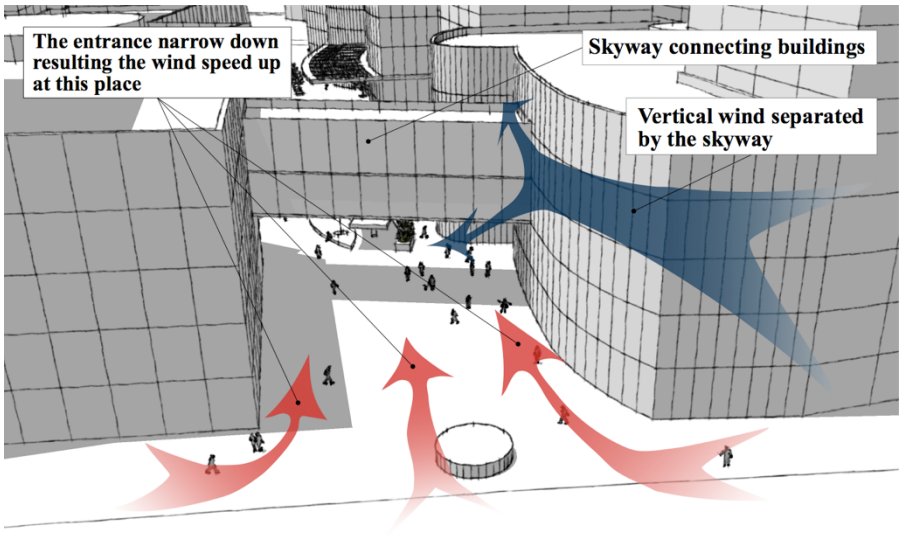


Figure 6-3 Funnel effect of wind and wind separation effect

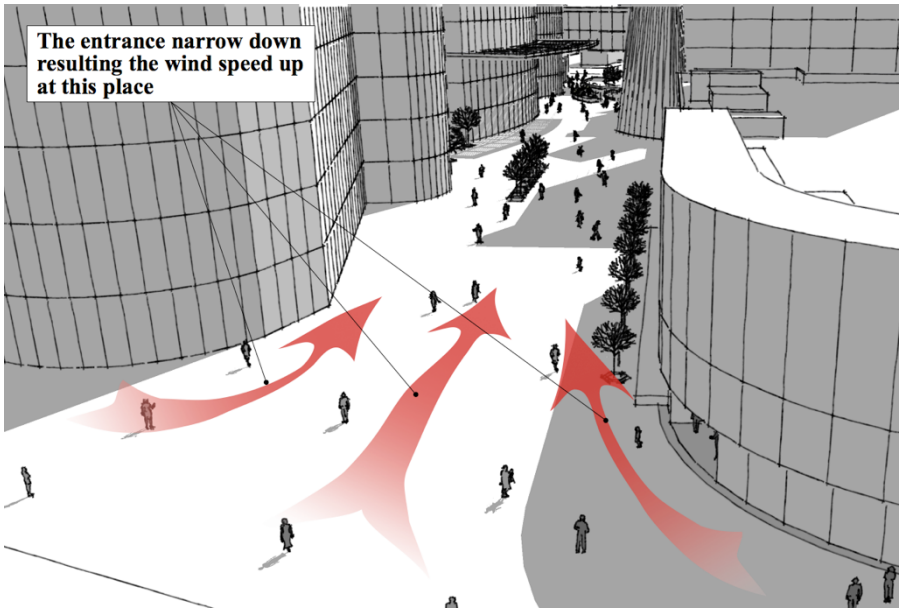


Figure 6-4 Funnel effect of wind by narrow entrance of street canyon

6.3.2. Turbulence and shelter effect due to the building corner

When the airflow passes through the building corner, due to the windbreak effect, the originally smooth airflow is obstructed, and the flow may be turbulent at the included corner. The airflow may also reduce the speed which is below the perceived strength of the body, thus form wind shelter area. The sunny building corner can be a good outdoor activity space in the winter, under the influence of solar radiation. In summer, due to less wind and strong sunlight, it is possible to shade and use the temperature adjustment facilities in the building to cool down and shave the corners, which can also create a good space for outdoor activities.

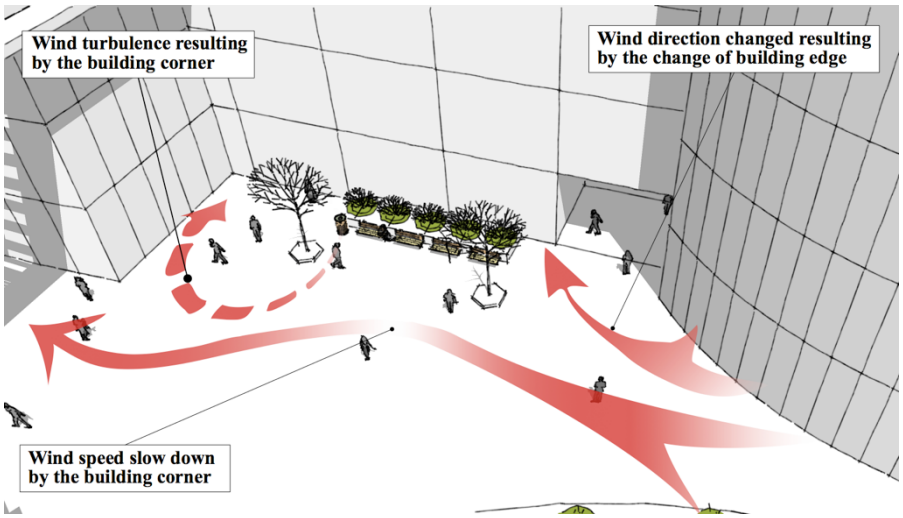


Figure 6-5 Turbulence and shelter effect due to the building corner

6.3.3. Drainage effect in high-altitude negative pressure zone and utilization of low wind speed area on the ground

At the leeward side of a high-rise building, the airflow through the building will form a wind shadow zone here. The size of the wind shadow area has a direct relationship with the flow velocity and the contact angle. The wind shadow area is negative pressure zone. The negative pressure zone will force the air flow at pedestrian height to be drawn upwards. This will cause the pedestrian air flow that originally flowed along the straight line to go upward and form a wind shadow area again at the pedestrian height, which leads to low wind speed area here.

According to the prevailing wind direction and average speed of the site, the wind shadow area can be created by design. By calculating the area of wind shadow zone at pedestrians height and the sunshine design, a sunny and low wind or windless outdoor activity space which is suitable for outdoor activities in winter can be created.

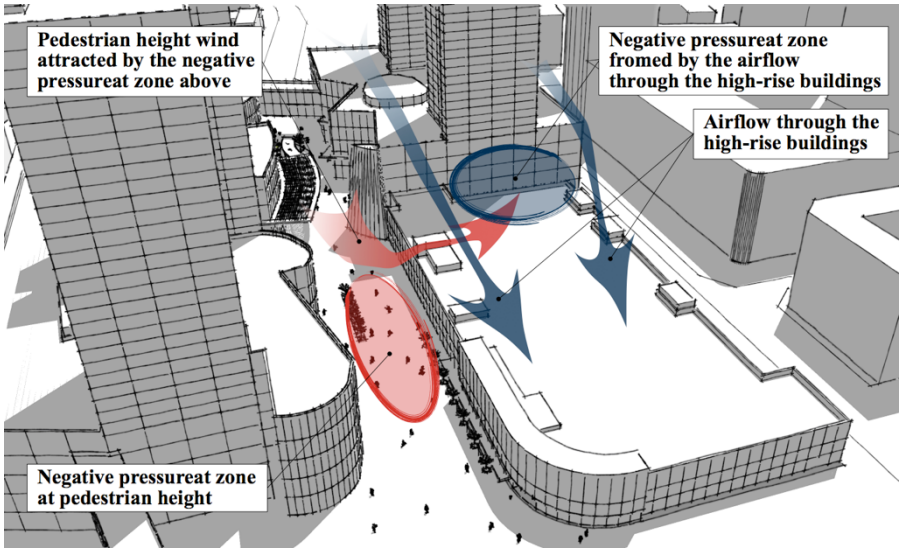


Figure 6-6 Drainage effect in high-altitude negative pressure zone and utilization of low wind speed area on the ground

6.3.4. Downdraft wind with podium

The airflows at high place with high speed and complex changes that do not directly affect pedestrians, they are not in the scope of this study. However, downdraft wind is a kind of wind that acts directly on the height of pedestrians along high-rise buildings. For its research and processing, it will directly affect the wind conditions at pedestrian height.

When the high-rise building setback to form a step, the downdraft wind cannot directly reach the ground, it will change the direction and weaken at the top of the podium, thereby reducing the impact on the height of the pedestrian wind environment. When the high-rise building does not setback, downdraft wind will directly touch the ground and change direction, so that the wind environment at pedestrian height will change.

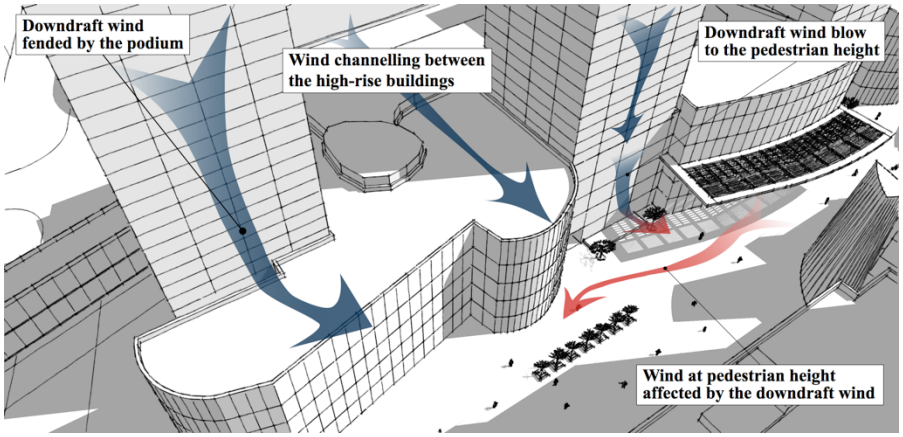


Figure 6-7 Downdraft wind with podium

6.3.5. Solar incident angle with roofs

In the mid-latitudes, the solar incidence angles differ greatly between winter and summer, and the solar incident angle is smaller in summer and larger in winter. The use of large cantilevered roofs can bring large shade area in summer. In winter, due to the large solar incidence angle, shade created by large roof in winter is much smaller than in summer. At the same time, the large roof can be designed with adjustable light transmission facilities, and the amount of transmitted light can be adjusted according to the solar situation, so that the shade of the outdoor space can also be adjusted.

In the design process, the laws of solar situation in winter and summer are fully investigated and analyzed. According to the actual requirements, it can be designed to shade sunlight in summer, and the roof that can also transmit sunlight in winter which can improve the environmental quality of the site.

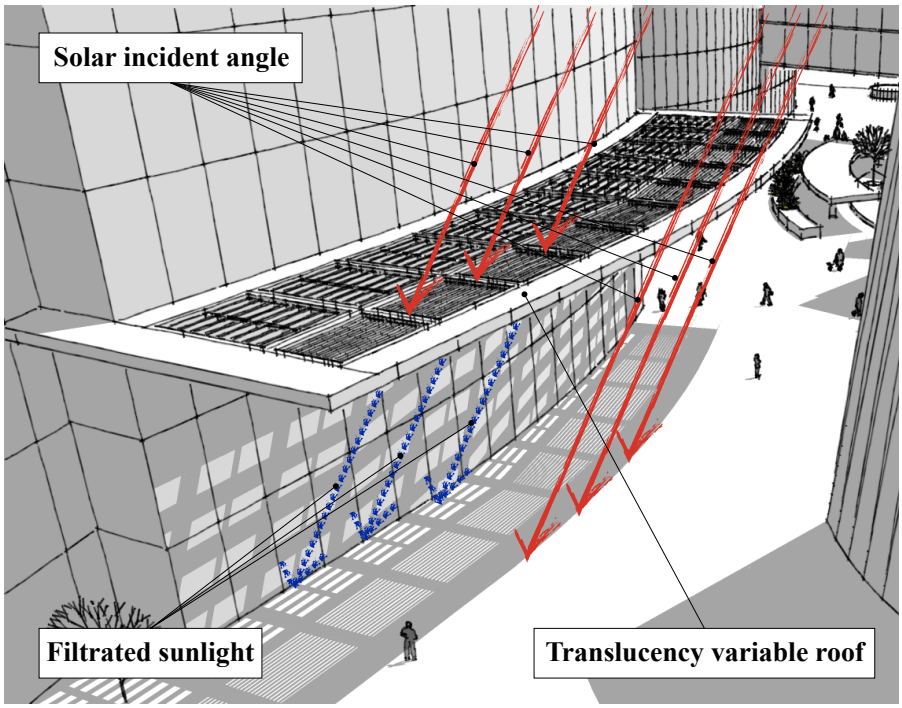


Figure 6-8 Solar incident angle with roofs

6.3.6. Separation of the interference between dynamic and static space

In the same research area, two different types of users are: pedestrians and stationaries. Due to the different fundamental needs of the two kinds of users, the requirements for space are different. According to the characteristics of space, it is very important to plan and design space for different purposes. Dynamic space emphasizes flatness and width, and can appropriately lower the standard of comfort. The static space emphasizes isolation from the dynamic space, and the static space is properly separated from the surrounding environment by means of low walls, shrubs, and height differences. At the same time, the adjustment is a moderate goal and the use of landscape facilities for shade and shelter can create excellent results. Outdoor rest space.

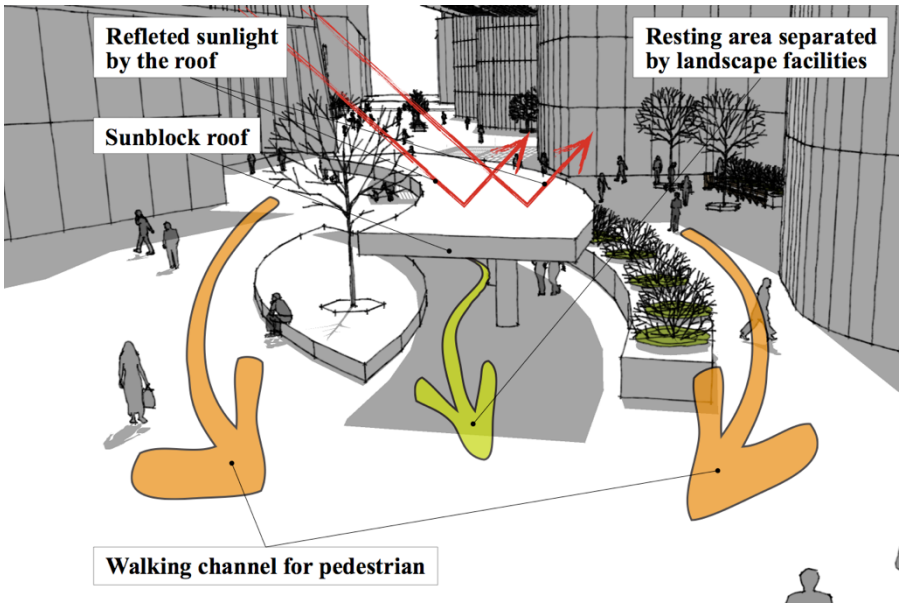


Figure 6-9 Separation of the interference between dynamic and static space

7. Conclusion with optimized open space design guidelines

According to the research above，from the general situation to specific design details，the conclusion with optimized open space design guidelines is proposed from 3 levels as shown in Fig.7-1.

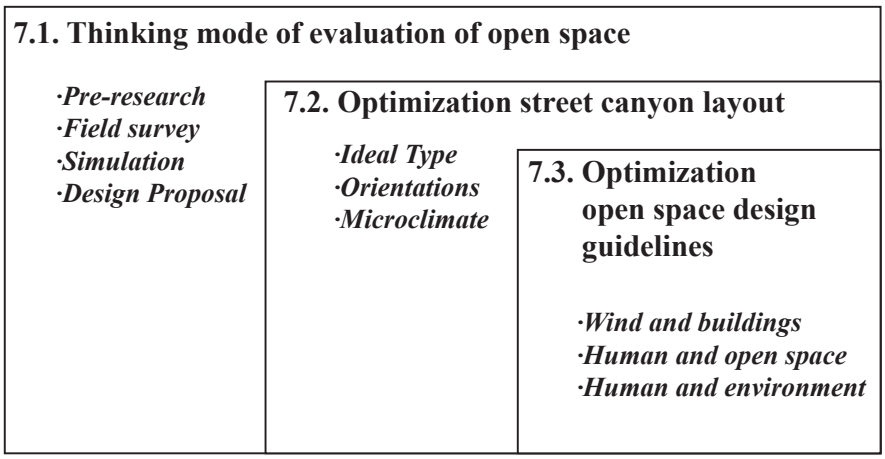


Figure 7-1 Schematic representation for each section

7.1. Thinking mode of evaluation of open space

This research provided a method to evaluate special urban areas with complicated wind environments and individual differences.

As Fig. 7-2 shows, first, pre-research such as basic geographic information and historical climate information is needed on the target area, from which periods of extreme weather that significantly affect human comfort are identified.

Second, field surveys are conducted during the extreme weather periods to collect sufficient microclimate and comfort data. By analyzing the relation between the microclimate data and average comfort, the comfort variation trends corresponding to the microclimate can be identified and threshold comfort values estimated.

Third, using wind tunnel and CFD simulations to evaluate the current environmental situation, the disadvantages of the current situation can be identified.

Fourth, new designs or reconstruction designs can be proposed to improve wind comfort. The wind tunnel and CFD simulations are conducted again to check the new area and evaluate the new environment.

The fourth step is conducted several times until an optimum design is determined.

For new projects, a neighboring urban area or a space with similar functions not far away from the target area should be chosen to conduct the same work.

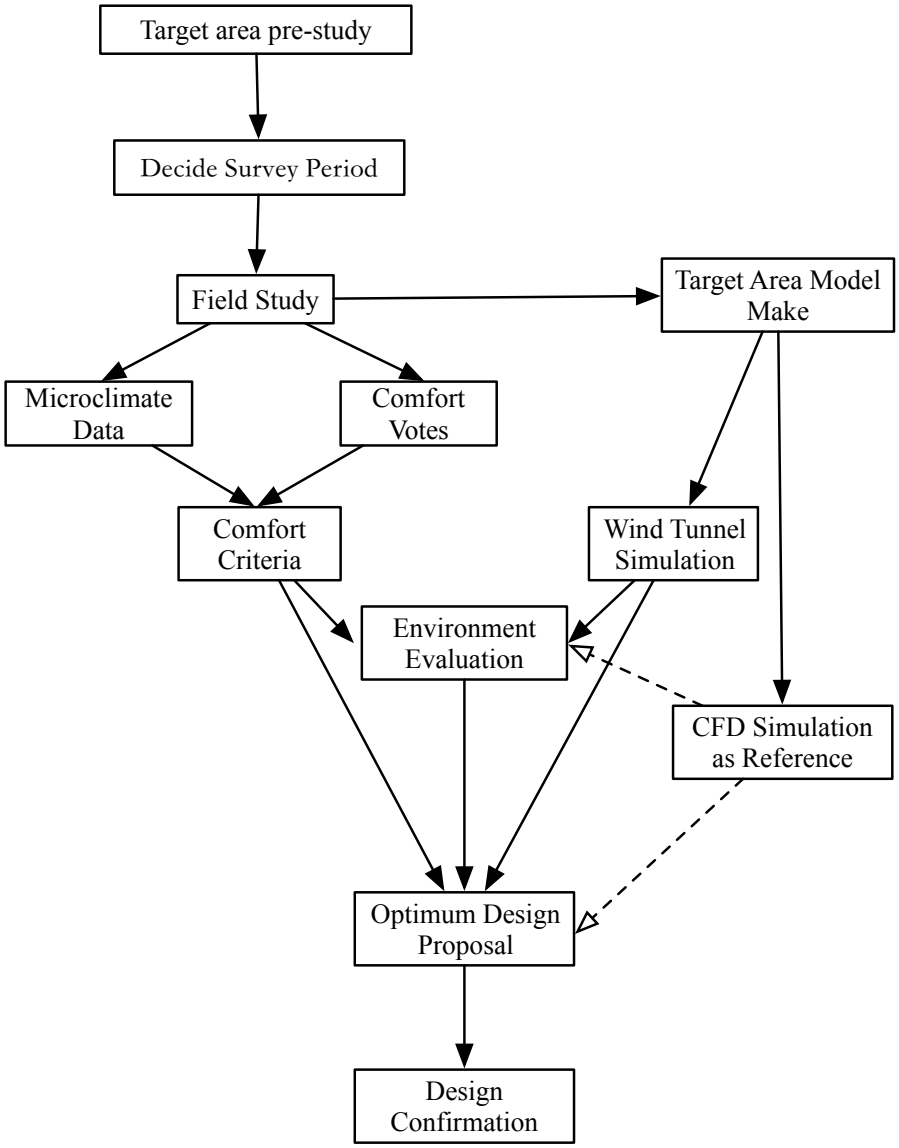


Figure 7-2 Schematic representation for the optimization of public open space design

7.2. Image of the optimization street canyon layout

For this case, shade is an essential requirement for the people who want to be active outside and should be given priority in design. Additionally, using the naturally longer shade on the east side, more static space can be designed. At the west side, more landscape structures should be designed to enlarge the shading area and increase the comfort level here.

Dynamic space and static space should be clearly separated to avoid the space use conflicts to improve space utilization. Avoiding too-wide space without facilities and too narrow space and creating more

comfortable static space with enough facilities can improve the quality of a space. Reducing rectilinear spaces and making more rounded space without angular edges can provide a flowing space for pedestrians and can also decrease the interference between dynamic and static space.

For stationary people, corner space, building edges and the center line area with higher wind speed should be thoughtfully considered to attract more people to stay for longer times. Creating landscape structures that are open to the direction of the prevailing summer wind and providing shade, seats and spatial separations among the above-mentioned places are necessary for a high-quality static space.

Based on the above results and conclusions, designing a canyon open space as a sandwich structure can be realized as a solution for the comfortable sensation and spatial utilization. As Fig. 7-3 shows, the static space should be arranged in the middle side and at the edge of the buildings. The traffic space is placed between these two static space. This design can not only improve the space utilization and decrease interference between stationary people and pedestrians but also offer possibilities for creating a favorable microclimate environment. Because the wind environment in the middle is better than that on the edges, designing the shading structures and humidifiers that are open to the wind direction can create a favorable environment based on the above-mentioned principle of a comfortable microclimate.

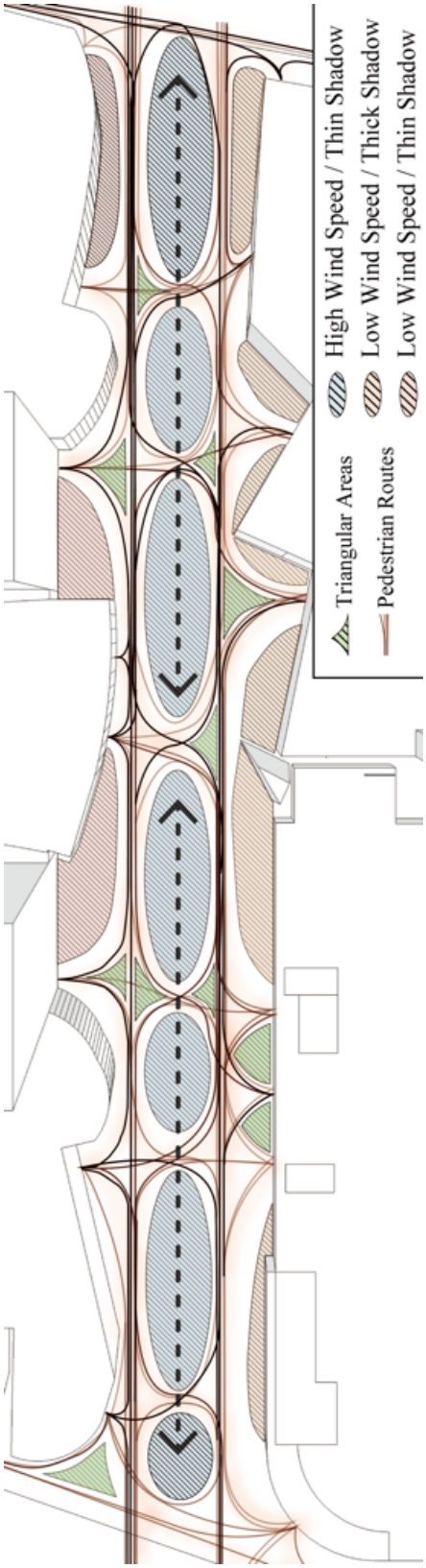


Figure 7-3 Optimization design of canyon open space

7.3. Optimization open space design guidelines

To create a suitable and high-quality open space that is comfortable for both pedestrians and stationary people, the following proposals should be considered:

7.3.1. Wind and buildings

As shown in Fig. 7-4, when street canyon is smooth and straight，the alignment of buildings formed by street canyon led the wind flow into the aisles. It can be called Channeling Effect. When the street canyon narrow down, due to the change in cross-sectional area and the constant air volume, the airflow through the street canyon will be accelerated.

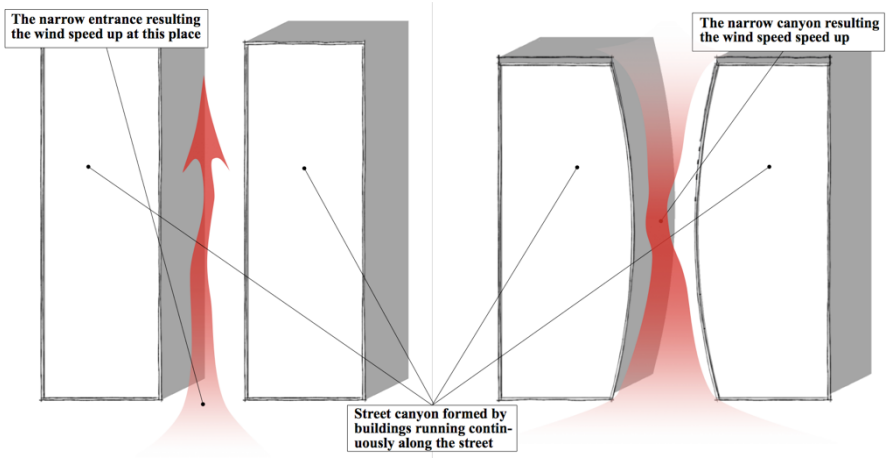


Figure 7-4 Wind through the street canyon causing the channeling effect and funnel effect

According to the study's conclusion, when the headwind hits the surface of the high-rise building, the airflow will move upwards and downwards due to the blockage of the building, the air-flow moves down will cause turbulences on the ground. (Fig.7-5)

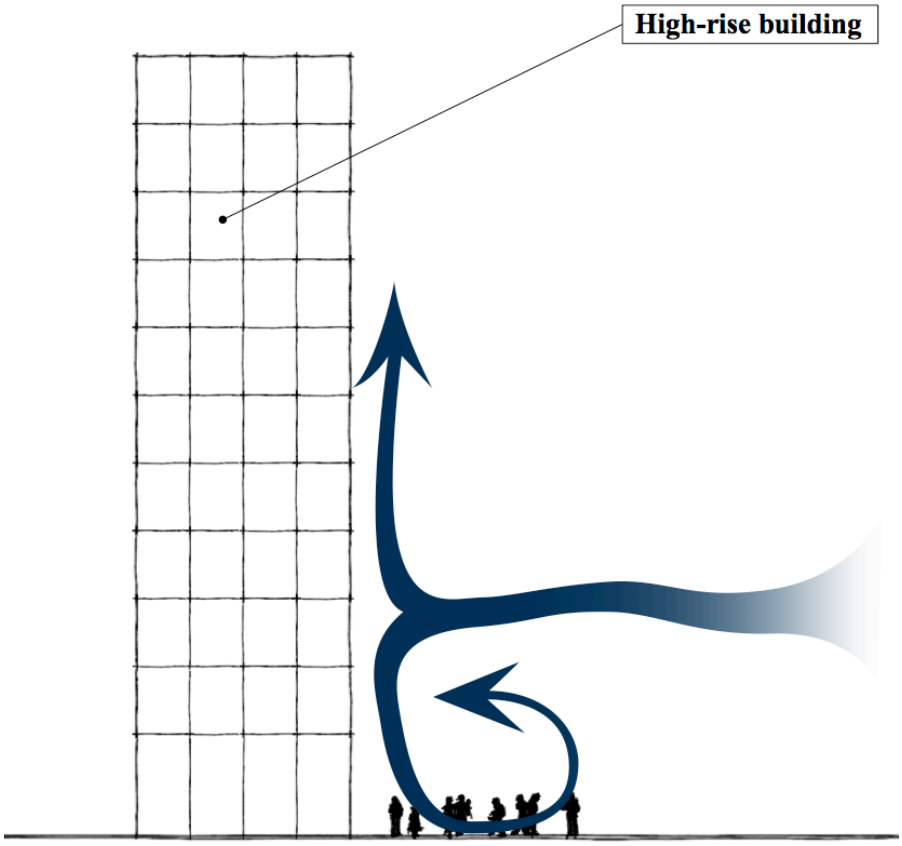


Figure 7-5 Downwash effect

Beranek and Van Koten provided a schematic illustration of wind situation around isolated high-rise building in 1979 [121].

They conducted the coming wind impinged upon the façade of building slab. The following changes of the air-flow have taken place (Fig. 7-6)：

1. Air flow above the building passes over the top of the building.

2. Airflow on both sides of the high place of building bypasses the side of the building.

3, 4, 5. On the windward side, about 70% height of the building has the greatest wind pressure. The air flow begins to disperse to the low wind pressure area on the upward of building and the lower side.

6. The formation of turbulence at ground level by a sufficient amount of downdraft is called standing vortex， frontal vortex or

horseshoe vortex. The direction of the standing vortex is upward, just opposite to the direction of the downdraft air-flow.

7. When the standing vortex meets the downdraft, it will form a low wind speed zone at the front of the building.

8. When the standing vortex moves laterally along the building's extension to the edge of the building, high wind speed zones are formed.

9. The air-flow No. 8 will meet the air-flow No. 9 at the edge of the building to change the direction of No. 9.

10. On the lee side of the building, due to the low wind pressure, an under-pressure zone will be formed, which will cause backflow.

11，12. The backflow No. 10 is opposite to the direction of the air-flow No. 12 flowing through the back of the building, which will result in the formation of a low wind speed zone between them.

13. Due to the effect of airflow No. 9 and No. 10, the recirculation flow will occur on the backside of buildings near the ground. At the same time, due to the effect of air flow No. 1 and No. 10, recirculation flow will also occur at the high altitude on the back of the building.

16. Since the air flow No. 13 is opposite to the No. 9, small turbulence will be generated between them.

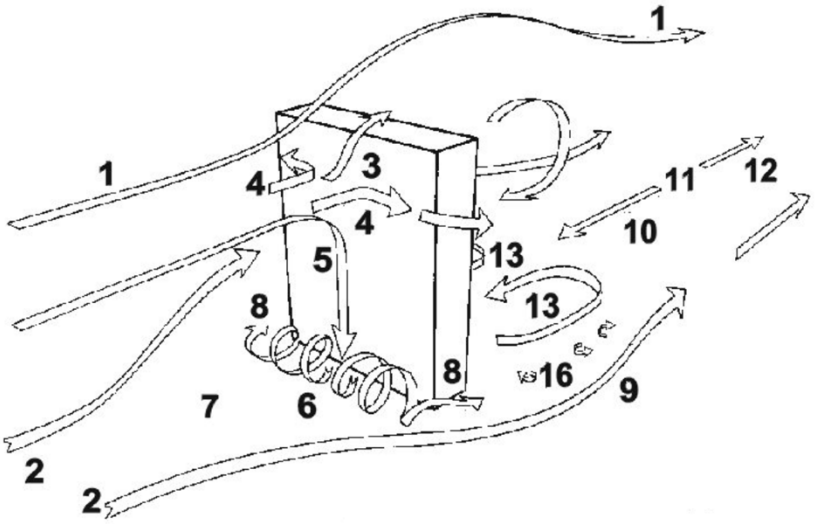


Figure 7-6 Wind situation around isolated high-rise building[121].

The air-flow hitting the facade will create a downwash effect, due to the existence of the podium, the turbulences will remain at the top of the podium and will not reach the pedestrian height, it will create a relatively good wind environment for pedestrians. (Fig. 7-7)

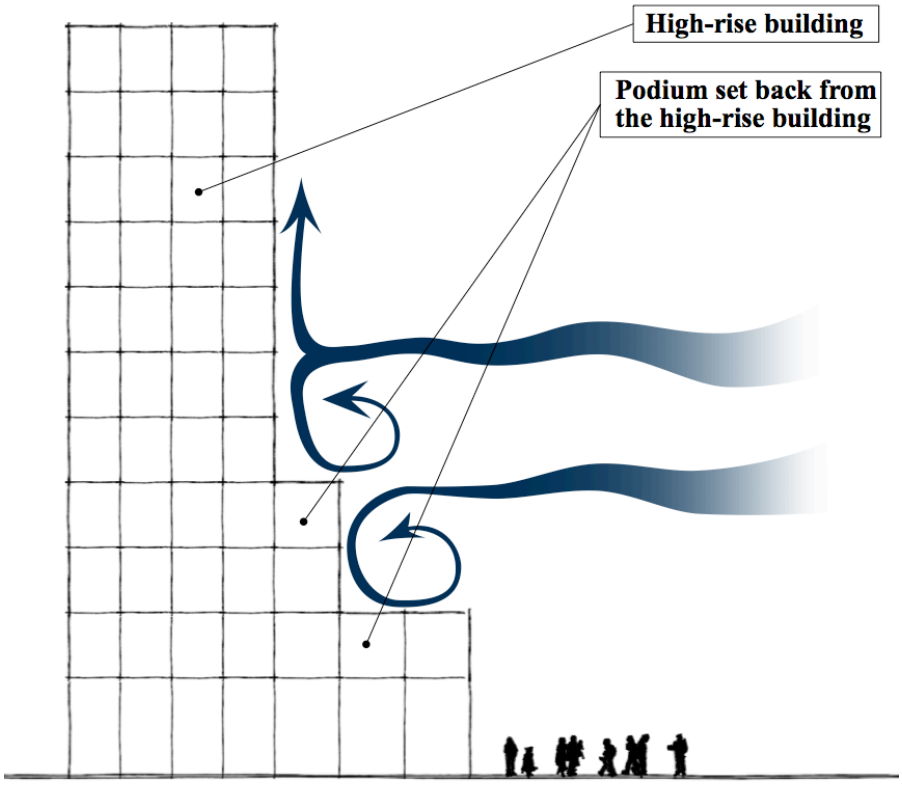


Figure 7-7 Stepping effect

At the street canyon formed by a high-rise slab building and a low-rise building, the airflow heading into a slab building is separated，one part moves toward the upper part of the high-rise building, and the other part moves into the street canyon below the upper part. The airflow that passes over the low-rise building and encounters the downward movement of the upper air flow creates turbulence in the street canyon. (Fig. 7-8) As early as 1965, Wise conducted similar research in smoke visibility wind tunnel simulation [122]. (Fig.7-9)

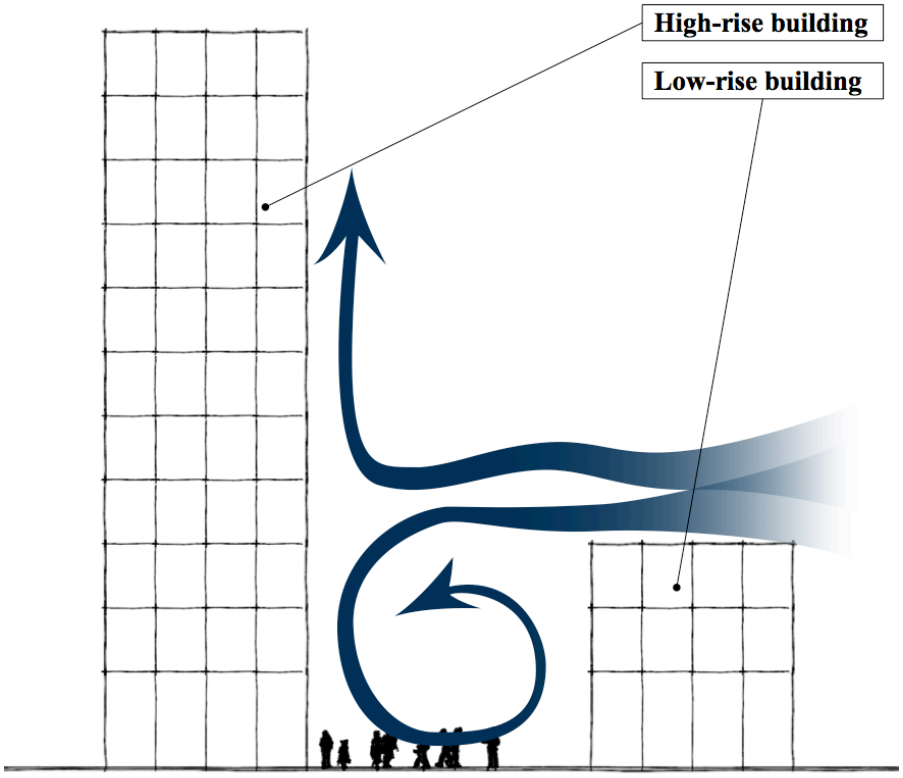


Figure 7-8 Wind situation between high-rise slab building and low-rise building

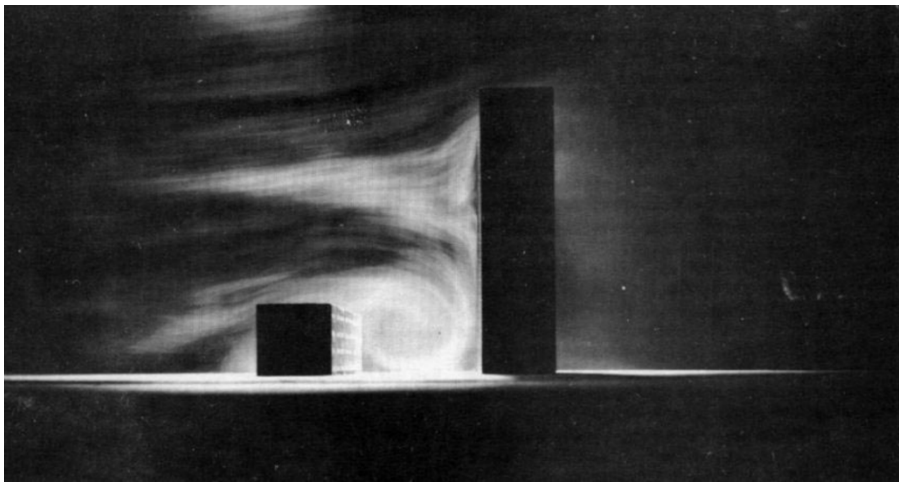


Figure 7-9 Wind situation between high-rise slab building and low-rise building by wind tunnel visualization simulation[122].

Many similar studies have been conducted, but most of the earlier studies were conducted on isolated building. Hussain and Lee(1980) [123] and Oke (1988) [124] conducted the studies on combination of multiple buildings. In their study, the distance between low-rise buildings at the same height was divided and the wind situation changes when the wind passed over the surface of buildings were found out. Their research shows that when the distance between buildings is too large (H/W<0.4), their air-flow areas cannot interfere with each other. When the distance between the two buildings reaches a certain level (0.65>H/W>0.4), the originally independent airflow fields interfere with each other. The originally independent airflow fields interfere with each other, and the original downward-moving airflow is enhanced due to the downward airflow of the rear-side building, thereby forming a wake interference flow. When the two buildings are too close together (H/W > 0.65), the turbulence between the buildings will prevent the airflow at the top of the building from entering the street canyon, forming a skimming flow effect. (Figs. 7-10 & 7-11)

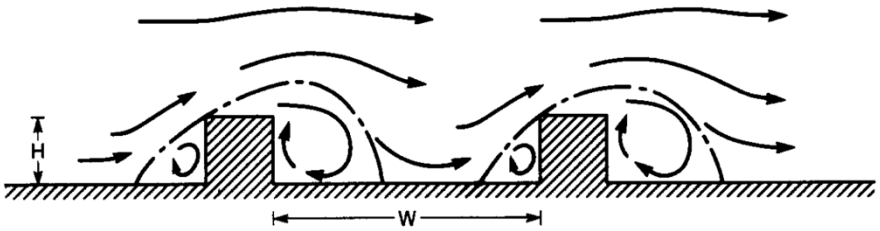


Figure 7-10 Isolated roughness flow by low H/W[124]

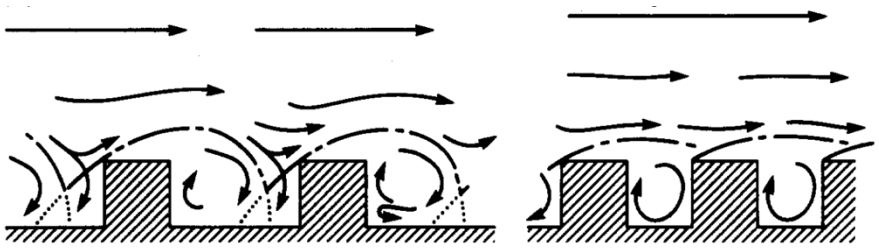


Figure 7-11 Wake interference flow and Skimming flow by increasing H/W [124]

7.3.2. Human and open space

Curved pedestrian routes should be planned with rounded space edges to enhance spatial utilization. The triangular blank area formed by a curved route and an angular boundary can be used for some functional landscape structures such as streamline leading or symbols (Fig. 7-12);

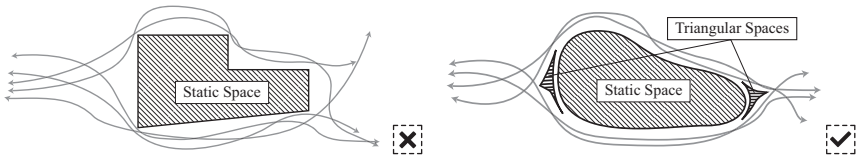


Figure 7-12 Flowing route and curve space

Avoid too-wide square space without any facilities and too-narrow space should be avoided. By providing abundant street facilities with shade, resting areas and spatial separations at suitable places without spatial contradiction and by controlling the width of the traffic space with streamline leading structures, traffic efficiency can be improved by design. Additionally, depending on the shade distribution, setting landscape structures and plants that are open to the prevailing wind direction is necessary to ensure the spatial utilization (Fig. 7-13);

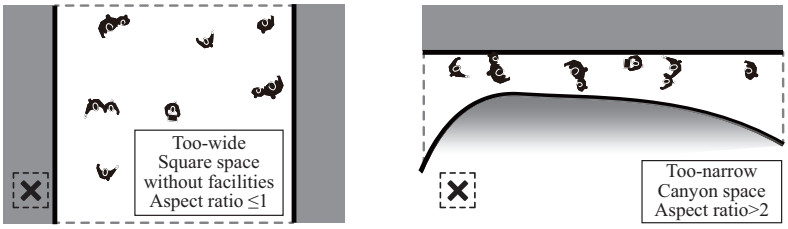


Figure 7-13 Spatial scale

By creating independent static space in the centerline area, edge side area and corners, interference between pedestrians and stationary people can be avoided. Meanwhile, spatial separations, such as fences, billboards, shrubs, height differences, are necessary in areas that could create conflicts. Providing sufficient functional facilities and structures are required to create an attractive place (Fig. 7-14).

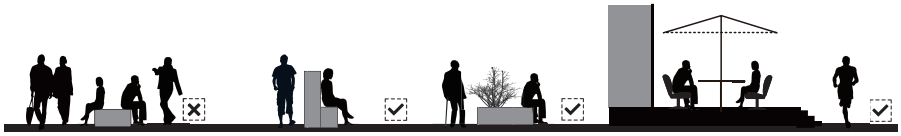


Figure 7-14 Independent static space

7.3.3. Human and environment

At the beginning of the open space design, understand the general microclimate situation and the comfortable threshold in the hottest day. Among all the microclimate elements, shade plays a crucial role and should be considered first. Roofs and plants, etc., that can provide thick enough shade. Based on these parameters, different design methods will be separated by different microclimate situation.

In the early stage of design, according to local weather conditions, the minimum and maximum values of solar incident angle should be investigated to calculate the shadows in the hottest season and the coldest season. According to the principle of avoiding light in the summer and increasing sunlight in winter, the layout and design of the roof are performed in the outdoor open space. The shape, the scale, and the amount of transmitted light of the roof are used to control the

sunlight in the site, so as to adjust the microclimate in the open space. (Fig. 7-15)

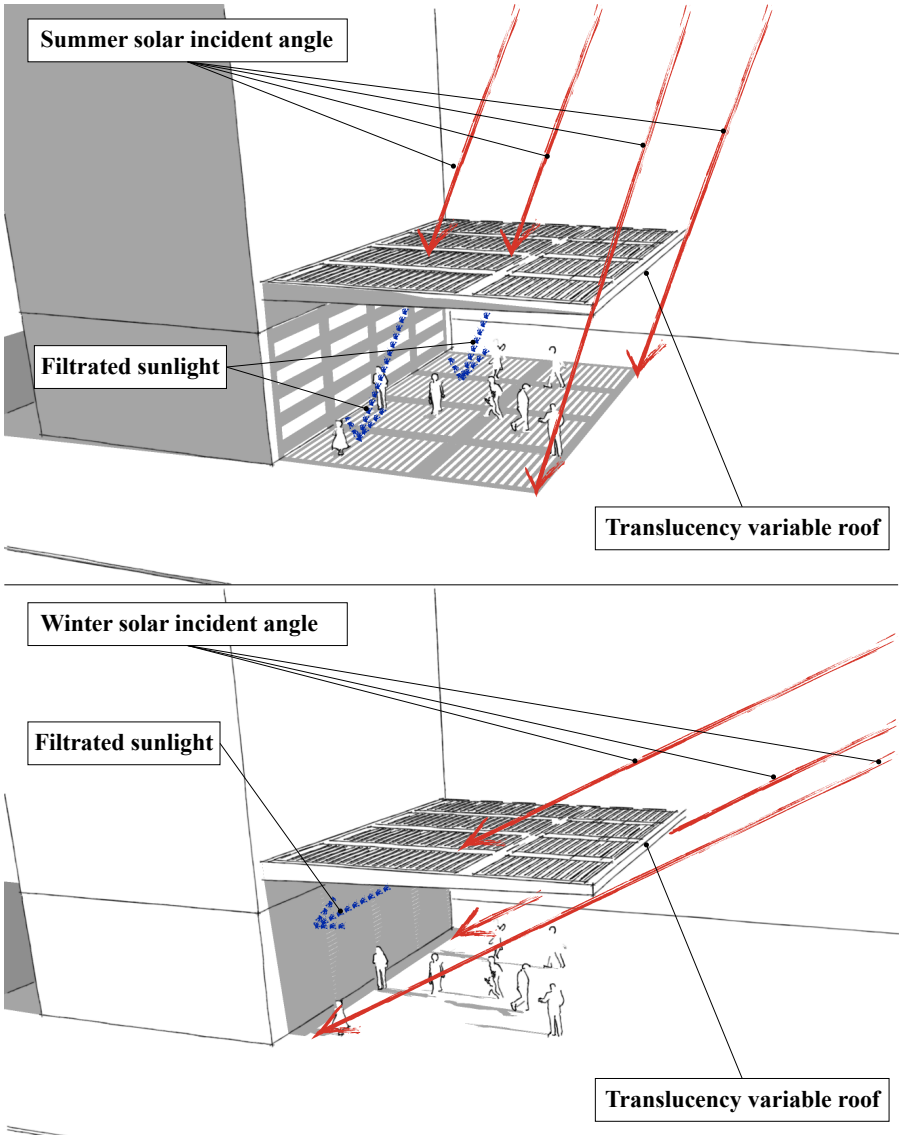


Figure 7-15 Roof design for climate-responsive open space

In an urban space that is dominated by buildings, open spaces are often attached to the main building. In the process of main building design, the design of a large roof or a large provocation will directly affect the environmental quality of the open space attached to the building. Fig. 7-16 shows the main building of the City opera house in Copenhagen and its outdoor space. Such a huge building roof can provide a strong sense of field to the outdoor space attached to it. At the same time, because it changes with the change of sunlight, it can also provide good shade for outdoor space. Together with the

landscape recreational facilities and vegetation, a good open space can be formed around the building.

Figure 7-16 Copenhagen opera house, Denmark [125]

For the hot summer and cold winter areas, the skyway setting can effectively improve the environmental feelings of the users. In summer, the separation effect of the skyway can form a high wind speed area in the lower part of the skyway, and the shadow produced by the skyway with the high wind speed area can create a comfortable outdoor activity space. However, spatial proportions should be paid attention to prevent excessive higher wind speed due to the channeling effect, so that the ventilation environment is not suitable for pedestrians because the over high wind speed. In winter, skyway can replace the outdoor space as an effective transportation space connecting buildings. For the area suffering extreme situation and cannot be adjusted by design， skyway plays important roles on the outdoor life in the city. (Fig. 7-17)

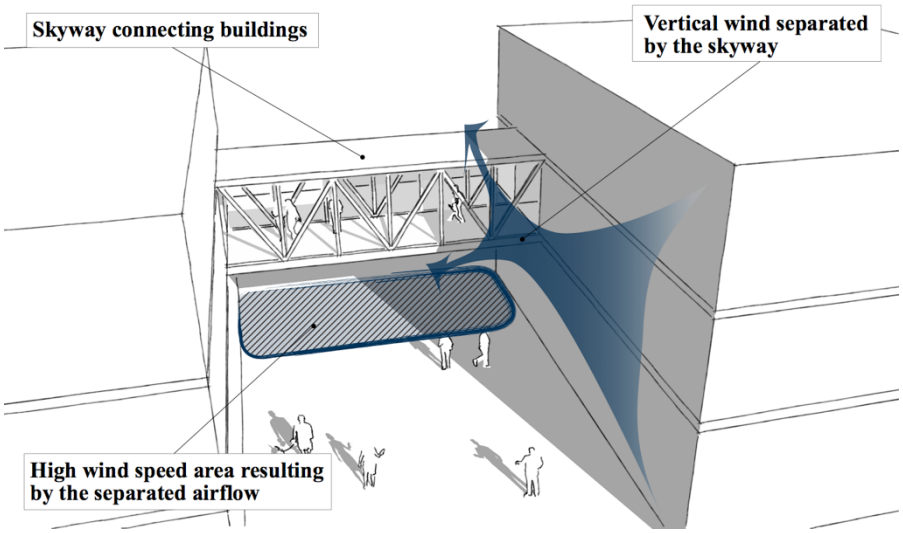


Figure 7-17 Skyway design for climate-responsive open space

Minneapolis is the city in northern America with long and severe cold winter. This city is known for having the largest skyway system in the world with 8 miles of skyways connecting 69 city blocks. As the Fig. 7-18 shows, the red lines on the map indicates the city's skyway system. Such dense skyway system which connect public commercial buildings like shopping malls, restaurants, etc. can provide citizens with a transportation solution that is resistant to adverse weather conditions. For cities suffering from severe cold winter or hot summer, the application of skyway can be regarded as a mature solution. It's wonderful to leave your coats, caps and mittens behind in the cold of winter and not worry about the heat in the blistering days of midsummer [126]. (Fig. 7-19)

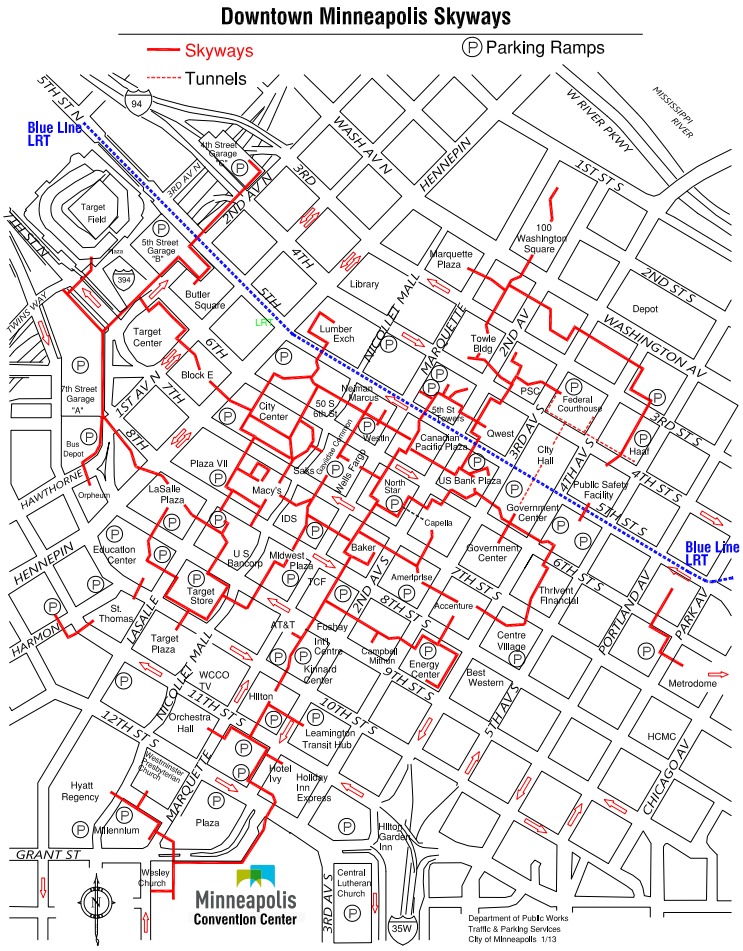


Figure 7-18 Downtown Minneapolis skyways system [127]

Figure 7-19 Skyway in Minneapolis , U.S. [128]

The huge open space with no reliance on it is not a popular outdoor activity place. Excellent outdoor space often needs to rely on buildings, vegetation or landscape structures. In the design process, it is a very effective methods to use the subsidiary parts of the building to regulate the microclimate of the outdoor environment.

In the sunny side of the street, the arrangement of rest areas adjacent to the building can not only effectively block the interference caused by the traffic space, but also can improve the microclimate and improve the quality of the space environment through the design of building accessories. In summer, shadows are formed using dense hardwood trees and shading structures to reduce solar radiation. In winter, leaves of broad-leaved trees fall and sunlight is introduced into the site. At the same time, the sun room can be used to adjust the material not only to introduce sunlight， but also reflect sunlight to the outdoor rest area, so that the sun room and the outdoor space adjacent to the buildings can receive sufficient sunshine. (Fig. 7-20)

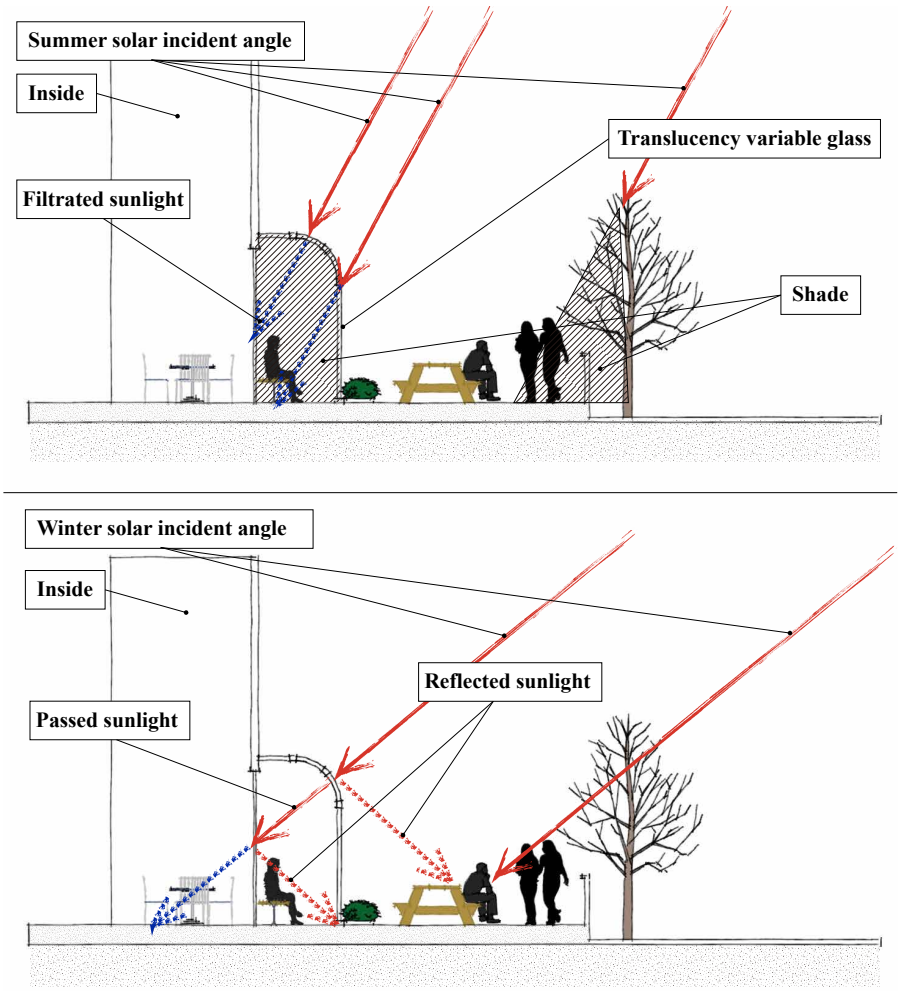


Figure 7-20 Arrangement of rest areas adjacent to the building

In the roadside or square without buildings as the basis, similar microclimate improvement can still be achieved through the landscape facilities. Both the landscape construction and the plants can block the sunlight in summer and block the cold wind in winter. (Fig. 7-21)

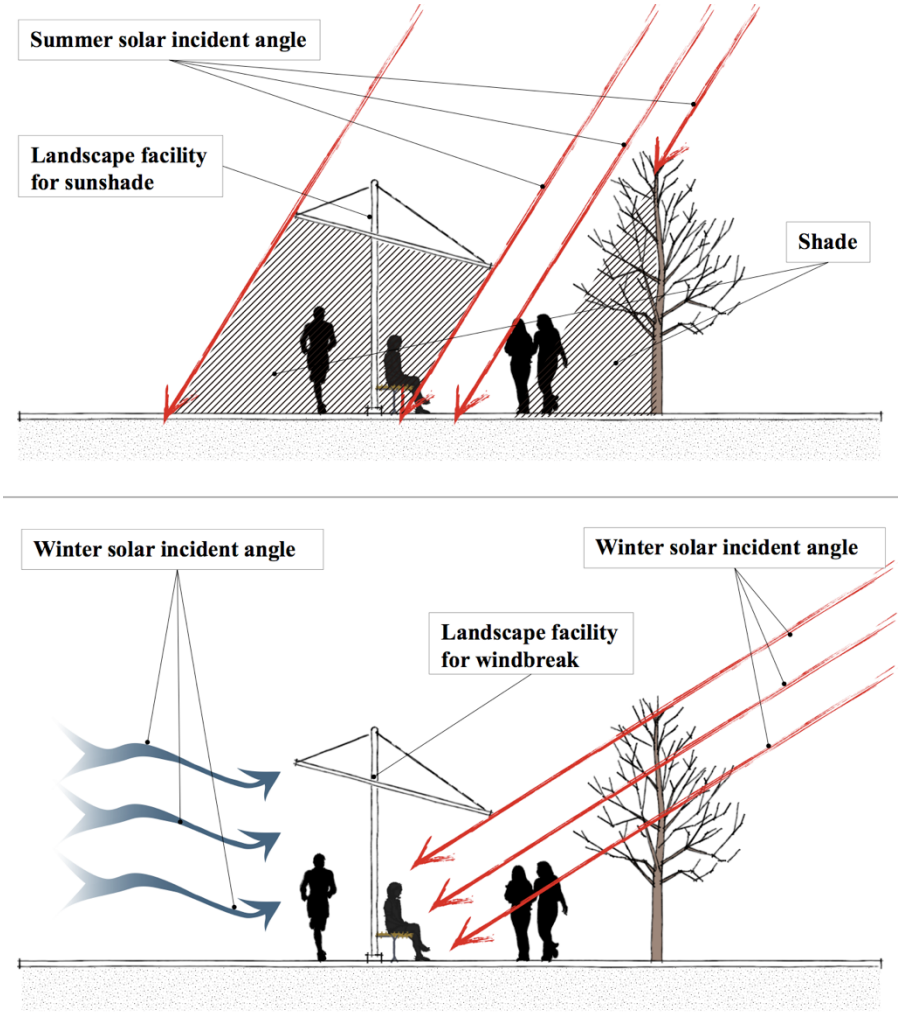


Figure 7-21 Landscape facilities arrangement in the roadside or square

Fig. 7-22 shows the bus stop located at the Sankt Gallen, northern Swiss. With arched truss as the main structure, this bus stop is about 40m east-west and 2-3m above the ground. Such landscape facilities not only provide pedestrians with a strong sense of space, but also can divide people with different spatial behaviors in overly wide street space.

Figure 7-22 The bus stop in Sankt Gallen, Swiss [129]

In areas close to the water surface, using the transpiration of the water body in conjunction with the summer prevailing wind can also regulate the humidity of the site in summer. If the prevailing wind directions in winter and summer can reach a relatively large angle, as shown in the figure, the plants can be used to shield the cold winds in winter, so as to achieve the effect that the waterside open space can be used in both winter and summer. (Fig. 7-23)

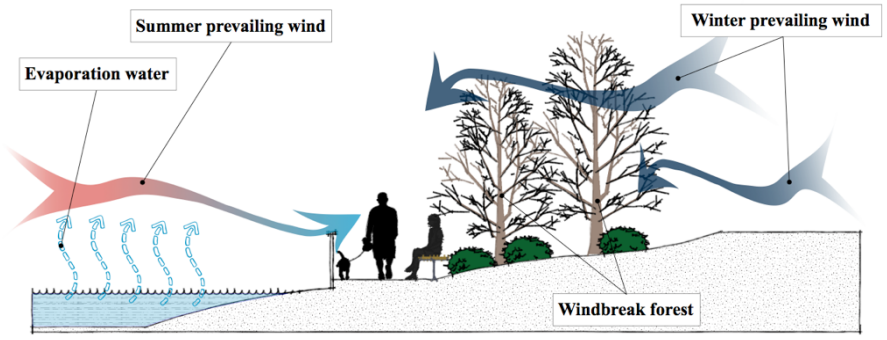
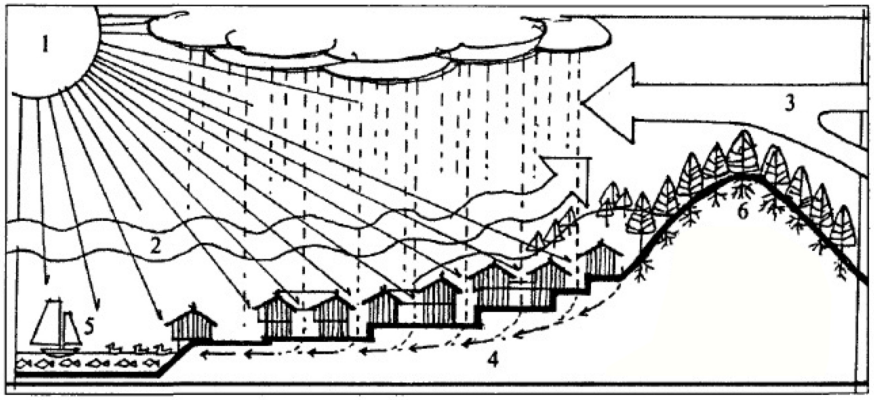


Figure 7-23 Microclimate adjustment by water, vegetation and terrain

In Chinese Fengshui theory, the urban layout has always followed an established rule. In terms of site selection, on the basis of comprehensive analysis of the conditions of natural resources such as topography, topography, hydrology, climate, sunshine, wind direction, landscape, and soil vegetation. Based on this, it serves as a guideline and criterion for guiding the layout of buildings and site selection, and has become a systematic theory based on science.



1. Desirable sunlight
2. Acceptance of the summer wind
3. Shelter against the winter wind
4. Favorable drainage
5. Convenient water transportation
6. Soil and water preservation and microclimate

Figure 7-24 The Feng shui theory on the location of traditional villages and towns in China [130]

Fig. 7-24 shows a schematic diagram of the layout rules for the location of traditional villages and towns in China. In terms of the selection of human activity space, ancient Chinese people have a certain degree of accomplishment on covering the sunlight, introducing sunlight, sheltering the winter cold wind, introducing summer monsoon, adjusting the air humidity through the water body, and draining water through the terrain, maintaining the water and soil and adjustment temperature and humidity through the vegetation.

7.4. Future study

Due to the limitations of research conditions and many other factors, there are still many deficiencies in this study which need to point out for the future study we need to do.

(1). This study selected one case in China and three cases in Japan to research the optimized open space design on concerning about the relation among open space, microclimate and spatial behavior. However, more research cases should be selected to increase the universality of the study. In future studies, other urban open space with similar climatic conditions will be selected for research.

(2). This study focuses on hot summer, cold winter and cooling period. In the future research, we should begin to study the relatively long continuous time in the same site.

(3). The wind environment simulation of this study is based on the existing environment, and reasonable assumptions are made on the existing environment based on simulation results and evaluation. In the future research, more typical and representative different forms of urban space will be selected.

7.5. References

[121] Beranek, W.J. and Van Koten, H. (1979). *Beperken van windhinder om gebouwen,* Deventer： Kluwer Technische Boeken BV. (in Dutch).

[122] Wise, A.F.E., Sexton, D.E. and Lillywhite, M.S.T. (1965). Studies of Air Flow Round Buildings. *The Architects' Journal*, 141: (19th May), 1185–1189.

[123] Hussain, M., & Lee, B. E. (1980). *An Investigation of Wind Forces on Three Dimensional Roughness Elements in a Simulated Atmospheric Boundary Layer*. University of Sheffield, Department of Building Science.

[124] Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and buildings*, 11(1-3), 103-113.

[125] Hans Exner. (2018. Apr. 2). *Design of the Copenhagen Opera House Roof.* Retrieved from http://www.lusas.com/case/civil/copenhagen_opera_house.html

[126] Sharlene Hensrud. (2018. Apr. 2). *Minneapolis skyway system connects 69 city blocks*. Retrieved from http://homesmsp.com/2013/03/minneapolis-is-known-for-having-the-largest-skyway-system-in-the-world-with-8-miles-of-skyways-connecting-69-city-blocks-th.html

[127] Iric Nathanson. (2013. Mar. 7). *Minneapolis' oldest skyway still in use turns 50.* Retrieved from https://www.minnpost.com/minnesota-history/2013/07/minneapolis-oldest-skyway-still-use-turns-50

[128] Jessica Lee. (2015. May. 9). *Minneapolis council considers bird-safe skyway rules*. Retrieved from http://www.startribune.com/minneapolis-council-considers-bird-safe-skyway-design-rules/303148141/

[129] David Baugh. (2018. Apr. 2). *BOHL TRAM SHELTER*. Retrieved from https://www.mimoa.eu/projects/Switzerland/Sankt%20Gallen/Bohl%20Tram%20Shelter/

[130] Qiheng WANG. (1992). *The Feng Shui Theory Research.* Tianjin: Tianjin University Press.

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Appendix. Peer-reviewed papers

1. Guo Zhiming, Setoguchi T., Watanabe N., & Huo K. (2017). Optimization Design of Open Space Based on Microclimate and Behavior in China, Journal of Civil Engineering and Architecture, 11(116),617-634. DOI:10.17265/1934-7359/2017.07.001

2. GUO Zhiming, SETOGUCHI T., WATANABE N., & HUO Ke. (2018). Public Open Space Design Study on the Basis of Microclimate and Spatial Behavior in Hot and Cold Weather Conditions in Downtown Area, Modern Applied Science, 12(2), 128-141 DOI:10.5539/mas.v12n2p128

3. Guo Zhiming, Setoguchi T., Watanabe N., & Tsutsumi T. (2017). Optimization Design of Open Spaces Based on Wind Tunnel and CFD Simulation: Case Study of a Street Canyon in Northern China, Journal of Civil Engineering and Architecture, 11(119), 897-914.DOI: 10.17265/1934-7359/2017.10.001

4. Norihiro Watanabe, Tsuyoshi Setoguchi, Kosuke Maeda, Daiki Iwakuni, Zhiming Guo and Takuya Tsutsumi: Sustainable Block Design Process for High-Rise and High-Density Districts with Snow and Wind Simulations for Winter Cities, Sustainability, Vol. 9, No. 11, 2132, 2017, IF=1.789

5. Norihiro WATANABE, Tsuyoshi SETOGUCHI, Shota YOKOYAMA, Zhiming GUO and Takuya TSUTSUMI: Urban-Design Process with Snow and Wind Simulations: A Study on the Kitami City Hall, Journal of Civil Engineering and Architecture, Vol. 11, No. 2, 107-120, 2016

6. 渡部典大, 瀬戸口剛, 松山倫之, 郭芷銘, 堤拓哉: 積雪寒冷都市における風雪シミュレ ーションを用いたスマート街区の空間形態とエネルギー消費, 日本建築学会計画系論文集, Vol. 82, No. 733, 735-744, 2016

7. Kusaka Minori, Setoguchi T., Watanabe N., Guo Zhiming, & Paukaeva Anasutasiia, (2018). Human Behavior in Downtown Public Spaces during Cooling Periods in Winter Cities, Journal of Civil Engineering and Architecture,(掲載決定済).

Journal of Civil Engineering and Architecture 11 (2017) 617-634
doi: 10.17265/1934-7359/2017.07.001

Optimization Design of Open Space Based on Microclimate and Behavior in China

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Abstract: Traditionally, microclimate, behavior and space design are characterized by a separation among climatologists, behavior researchers and designers. It is also unrealizable to apply the research results to the space design because of the gap created by the interdisciplinarity. In addition, although the relationships among space form, urban microclimate and people are intuitively understood, there are still not reasonable predictions on how a space affects the microclimate, and how the microclimate and space will affect people's sensation and behavior. By recording the microclimate and people's responses, this paper discusses the relationship between people's sensation and microclimate as well as people's behavior and open space in a busy downtown pedestrian street during hot summer. The research finds that shade plays a crucial role in outdoor comfort. All of the other objectively comfortable and acceptable microclimates differ significantly different shade situation. Simultaneously, space contradiction can be considered an essential factor for spatial utilization. This paper also provides proposal on canyon open space design based on this case study.

Key words: Activities, outdoor comfort, urban design, street canyon, northern city.

1. Introduction

As the urbanization continues, the urban forms are constantly changing due to city construction, which change the microclimate significantly. Bonan [1], Hart and Sailor [2], and Stone and Norman [3] have discussed the influence of the urban heat island effects on microclimates based on land use, urban density and urban structures. De Schiller and Evans [4], Evans and De Schiller [5] and Eliasson [6], have discussed the significance of the subtle impact of small-scale climate variations on the urban and regional scales. At the same time, a burgeoning number of studies have examined on the relationship between outdoor thermal comfort and outdoor activities from the perspectives of meteorology and behavioristic [7-14]. There have also been some demonstrations of the influence of microclimate on people's sensation from the view point of architectural design and landscape design [15-17]. Without addressing the microclimate, many studies have been conducted regarding different aspects of public open space and behavior [18-24]. Givoni [25] has discussed the relationships among building, design and the climate and introduced the design principles for different climate regions including the cold region. There are not so many details which were offered for outdoor thermal comfort and design.

Open spaces that accommodate the daily social activities of both pedestrians and stationary people play an important role in cities. The goals of open space design are gradually evolving toward attracting more people to stay outside door and enhancing the spatial utilization [26-29]. Street canyons can be considered one of the main types of urban open space. The term "street canyon" refers to narrow street with buildings running continuously along both sides [30]. The urban canyon is an important and basic part of urban climatology and urban design [31-33]. The urban canyon can be classified into three types based on the aspect ratio (W/H means width/height): regular canyon

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(an aspect ratio of approximately 1), avenue canyon (aspect ratio < 0.5) and deep canyon (an aspect ratio of approximately 2) [34]. In most cases, the commercial zones are planned in a central area, densely populated and convenient traffic area. These properties lead to its crucial status in the city. For field surveys, researching the commercial area always has more obvious applications and value [35].

For the open space design, microclimate and people's sensation and behavior in an urban open space have great references. However, research has seldom combined these viewpoints. Erell et al. [36] have discussed design and planning approaches for urban microclimates and presented two case studies at the street scale. From the viewpoint of microclimate, Erell has provided architects and urban designers a new perspective on the interaction between microclimate and each of the elements of urban landscape. However, people's behavior which can be realized as an objective standard of comfortable environment is not mentioned so much.

Using people's sensation and behavior as the standards to evaluate open space, this paper discusses the relationship between people's sensation and microclimate as well as between people's behavior and open space through a case study in a city central area in northern China. This study was discussed as follows:

(1) By analyzing the relationship between the different microclimates and people's sensations in urban canyon space in hot summer, comfortable microclimate levels and their change rules were estimated;

(2) From the viewpoint of microclimate and spatial behavior, the comfortable open space forms were discussed, and then proposals of regional open space optimizationdesign are proposed for the future sustainable urban construction or reconstruction.

2. Methods

2.1 Field Survey

The study case is a typical urban open space located in central area of Shenyang, China (41°48′01.11″ N, 123°27′49.33″ E, ASL (above sea level) = 55 m). This place can be realised as one of the commercial centres with multitudinous visitors every day. In this case, the pedestrian street canyon is between two large scale mixed-used buildings with shopping malls, subway station, super market, hotels and high rise apartments (Fig. 1). The densely-populated area can provide more samples and more accurate reference for the research. In the center of the research area, during the survey time, there was a temporary exhibition zone which leads to a more complicated behavior situation. This study excluded the exhibition zone from the behavior research.

Based on the history daily maximum temperature data from July to September in the period of 2009-2014 from the National Meteorological Information Center in China (Fig. 2) [37], this study selected July 28th to August 9th, 2015 (12 days) as the summer high temperature survey period.

2.2Microclimate and Sensation

As Fig. 3 shows, depending on the space situation, 11 types of spaces were considered. The positions, space styles, aspect ratios and facilities were used to define these spaces. Then, 15 measurement points were chosen according to the space types and the spatial distributions. These 15 points were separated in 3 groups with 5 points in each group. Microclimate data of each point were collected every 15 minutes during the daytime, including: air temperature (T_a), air velocity (V), relative humidity (RH), globe temperature (T_g) and shade situations. Table 1 shows the measurement factors of micrometeorological parameters.

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 actual non-uniform enclosure" [38]. It is put forward based on the exchange of radiant energy between two objects by emitting and adsorbing heat. In this study, the T_{mrt} is

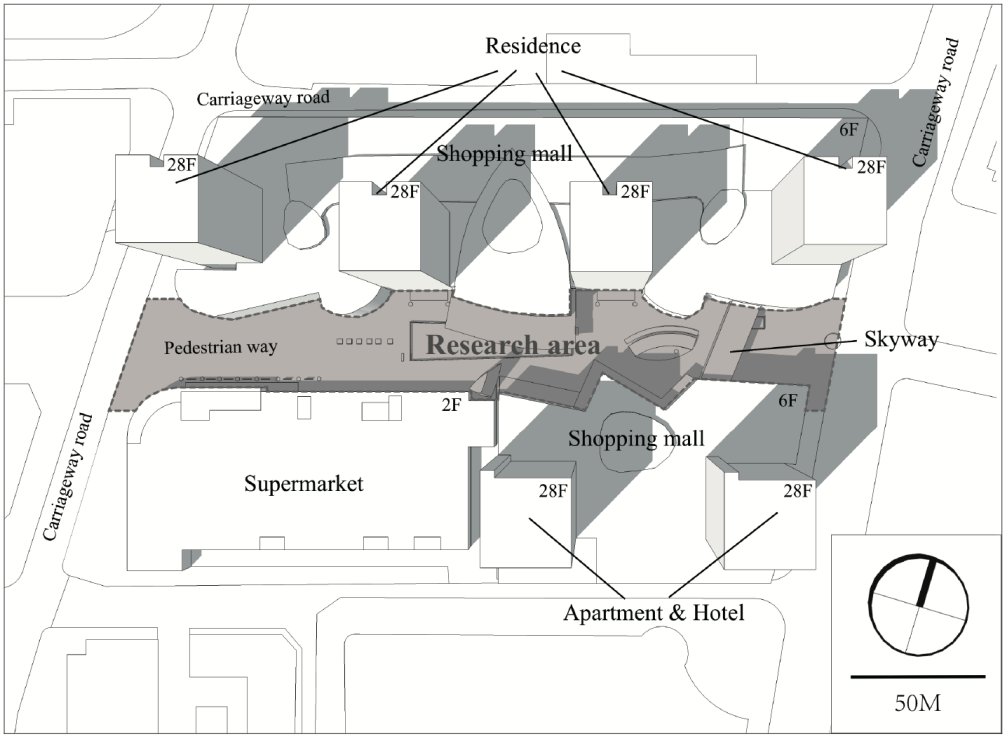


Fig. 1 Research area.

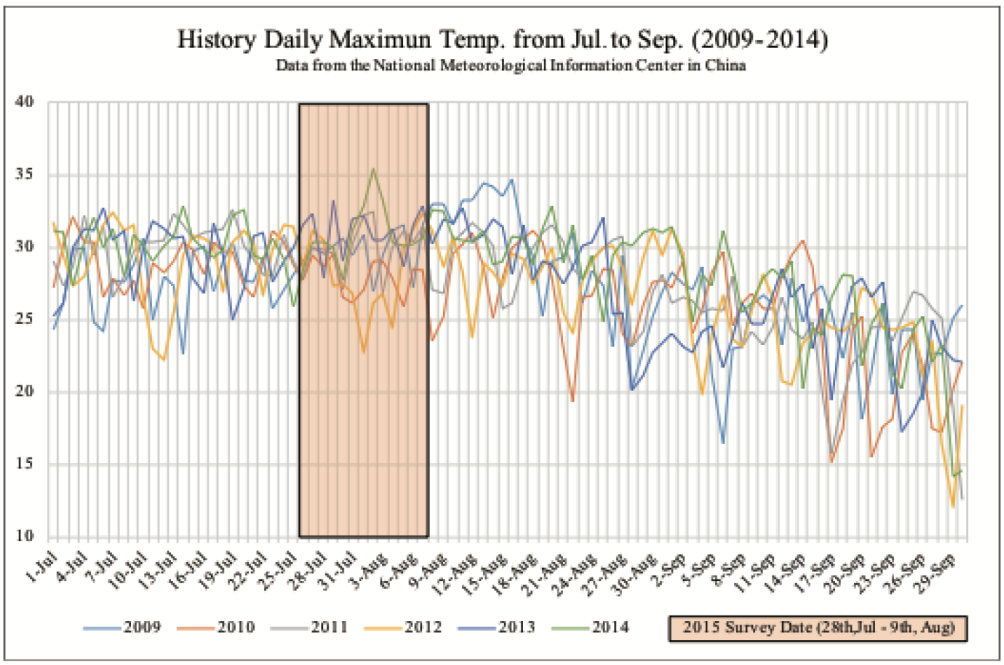


Fig. 2 History of daily maximum air temperature from July to September, 2009-2014.

Note: Weather station No.: 54342 coordinates: 41°44 N, 123°31 E, ASL = 49 m.

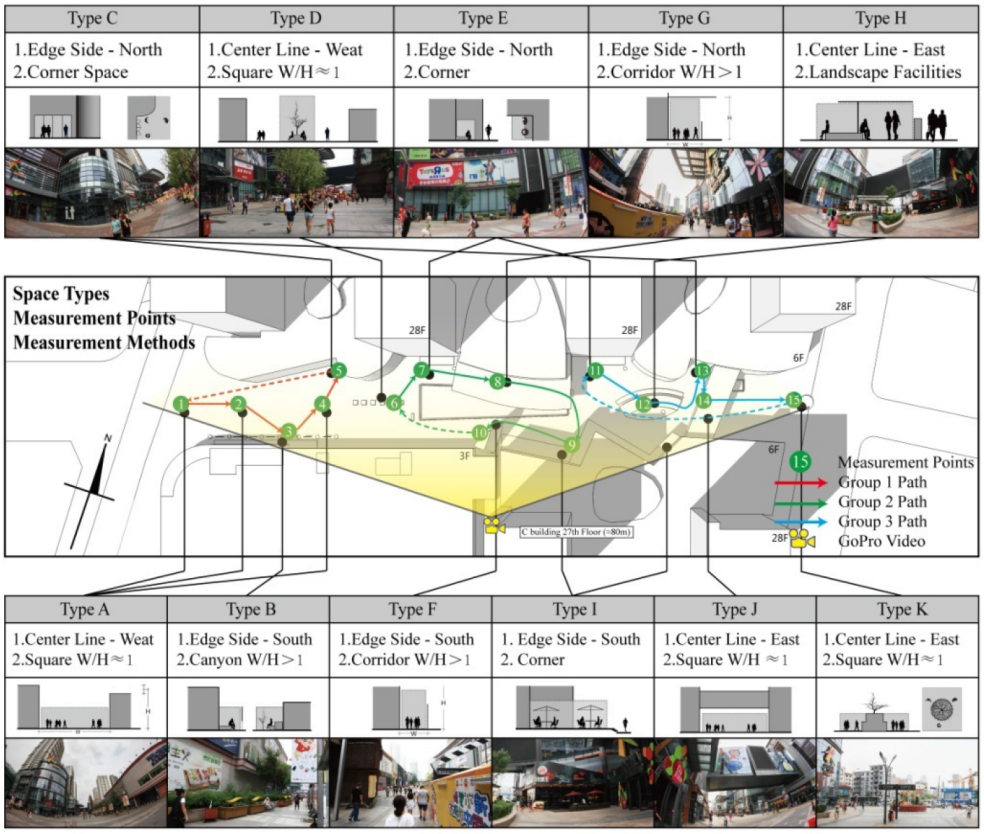


Fig. 3 Space types, position information and measurement methods.

Table 1 Measurement factors of microclimate parameters

Parameter	Accuracy	Resolution	Range	Setting
V	3%	0.1 m/s	0.6 to 40.0 m/s	
T_a	0.5 °C	0.1 °C	-29.0 to 70.0 °C	Measurement Point No. 1 to No. 15, 1.5 m in height
RH	3.0%	0.1%	5% to 95%	
T_g	0.6 °C	0.1 °C	0-80 °C	

estimated by the globe temperature method. Depending on the previous study, there are relatively small differences between the globe temperature methods and other complicated methods [39]. T_{mrt} is calculated based on the following equation [37]:

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10\times10^8 V^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273 \quad (1)$$

where, T_{mrt} is the mean radiant temperature (°C), T_g is the globe temperature (°C), T_a is air temperature, V is air velocity (m/s), D is globe diameter (m) (in this study $D = 0.075$ m), ε is emissivity (0.95 for black-colored globe).

Combined with the real-time microclimate data, a 7-point CSV (comfort sensation vote) [40] for the subjective responses of preferred change was used by the subjects to record their comfort levels. According to this scale, -3 is very uncomfortable, 0 is neutral and 3 is very comfortable; any recording higher than -1 is defined as acceptable. For the 15 points, during the survey days, in total, more than 2,400 groups of effective data were recorded. In the high position (27th floor in a high-rise building, approximately 80-m tall),

a Hi-Q video camera was used to record people's behavior during the survey. Panorama images were taken every 30 min at measurement points 1, 3, 10 and 14 simultaneously to record the positions of people.

Depending on the solar incident angle based on the CSWD (Chinese Standard Weather Data) [41] and the Chinese standard for Assessment Parameters of Sunlight on Building (GB/T50947- 2014) [42], this study used software to simulate the shadows in August 1st before sunset as a reference of the general shade situation.

2.3 Open Space and Behavior

This study analyzed the spatial behavior in August 1st and 4th as a comparison of sunny and overcast days. By analyzing the panorama images and the time lapse videos, the spatial behavior was analyzed including position maps and pedestrian routes. In the position maps, the study drew down people's position for every 30 min from 9:30 to 20:00, including the pedestrians and stationaries, and integrated them into one picture and counted the quantity of users, including the pedestrians and stationary people. In the pedestrian routes, the study used the time lapse video to draw down the moving path of the pedestrians with the same quantity (210 pedestrians in each day) during the lunch time (12:00-12:30) which can be realized as the busiest period during one day to analyze the different behaviors between different microclimate situations.

3. Results

3.1 Sensation with Microclimate

Over 2,400 groups of microclimate data and corresponding CSV were collected. The measured temperature range during the survey was 24.4-35.9 °C. The air velocity between 0-7.1 m/s was recorded. The measured relative humidity range was between 36% and 100%. The weather situations, e.g., clear days, overcast days, thunderstorm and partly cloudy days, were included during the survey.

Table 2 shows the correlation analysis between CSV and shade, T_{mrt}, T_a, T_g, V and RH by using the software IBM SPSS Statistics (Version 20.0.0). Bivariate correlation algorithms were used to analyze the correlation [43]. The Pearson correlation is a measure of the linear correlation between the two variables X and Y, giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation.

As the Pearson correlation shows, all the correlations are significant at the 0.01 level. That is, all the measured microclimate factors will affect the CSV, respectively. Among them, shade has the highest correlation (r = -0.464) with CSV, followed by RH (r = 0.449), T_a (r = -0.421). Consequently, the shade situation was the main factor to affect people's satisfaction of environment.

Measured air temperature and calculated mean radiant temperature (T_{mrt}) on clear and overcast days

Table 2 Correlations between CSV and measured microclimates (n = 2,489).

	CSV	Shade	T_a	V	*RH*	T_g
CSV	1					
Shade	-0.464**	1				
T_a	-0.421**	0.288**	1			
V	0.222**	-0.080**	-0.157**	1		
RH	0.449**	-0.287**	-0.685**	0.165**	1	
T_g	-0.354**	0.312**	0.415**	-0.078**	-0.438**	1

** Correlation is significant at the 0.01 level (2-tailed).

CSV—comfort sensation votes, T_a—air temperature, T_{mrt}—mean temperature radiant, V—air velocity, *RH*—relative humidity, T_g—globe temperature.

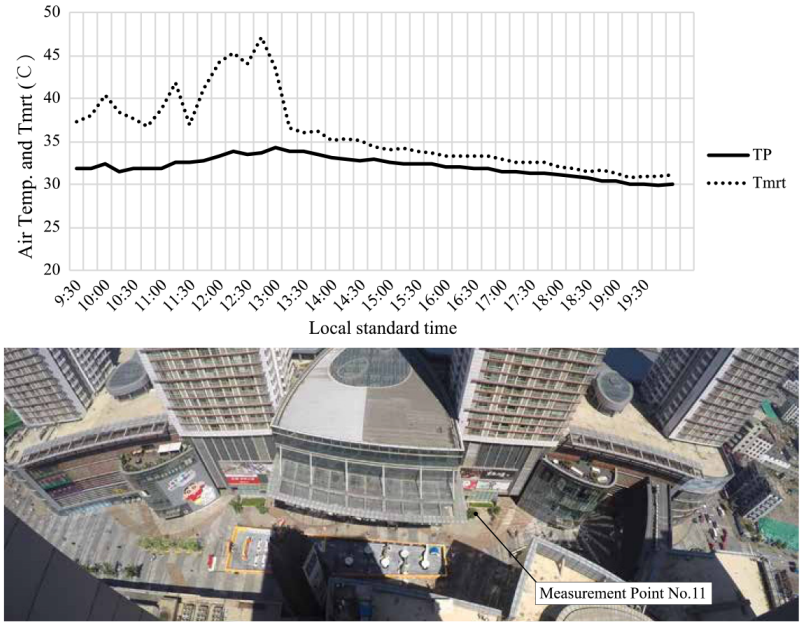


Fig. 4 Measured air temperature and calculated mean radiant temperature on a clear day (August 5th, 2015) and the photograph at 10:30.

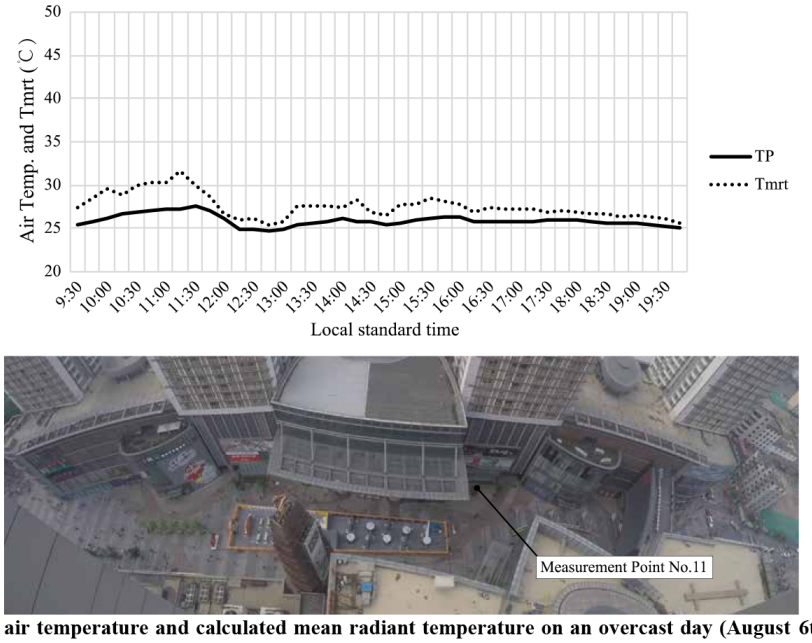


Fig. 5 Measured air temperature and calculated mean radiant temperature on an overcast day (August 6th, 2015) and the photograph at 10:30.

were shown in Figs. 4 and 5. The measurement point for this comparison was set on Point No. 11 where it can get sunlight before afternoon on clear day and change slightly on air velocity during whole day.

The difference of air temperature and mean radiant temperature between clear day and overcast day was

shown. The difference of mean air temperature between two days was 6.13 °C. During the clear day, higher temperature was recorded. The effect of shade on the magnitude of T_{mrt} was also clearly shown. Depending on Figs. 4 and 5, on the clear day, when the measurement point was exposed in sunlight before 13:00, T_{mrt} is significantly higher than the air temperature. When the building shade fell over the measurement point, slightly higher T_{mrt} than air temperature was recorded. The same result was also found in overcast day.

It should note that, however, the results in specific days may be subject to several errors. Nevertheless, combining with the above correlation results, and several previous studies, shade will play an important role on people's comfort [44-47]. It can be considered as higher priority to separate the other factors on analyzingthe outdoor situation.

The general relationships between CSV, and mean microclimate in each period in different shade situations were analyzed. As shown in Fig. 6, the following results were obtained: First, the CSV tendency of "not in the shade" is significantly lower than "in the shade". When subjects are in the shade, they are comfortable with a CSV of 0 to 1 all day. However, when they are out of the shade, all the measured CSV belong to the uncomfortable level. Second, the temperature and humidity indicate the general variation of the CSV. Higher temperature and lower humidity in the noon decrease the CSV. Third, the ruler guides of Nos. 1-8 indicated the extremums of CSV. It can be found that, instantaneous variations of the CSV are related to the wind speed. Higher wind speed made the CSV lower, lower wind speed made the CSV higher.

By using microclimate data and mean CSV (n = 2,520), the detailed relationships between CSV and microclimate in the shade are plotted in Fig. 7. In

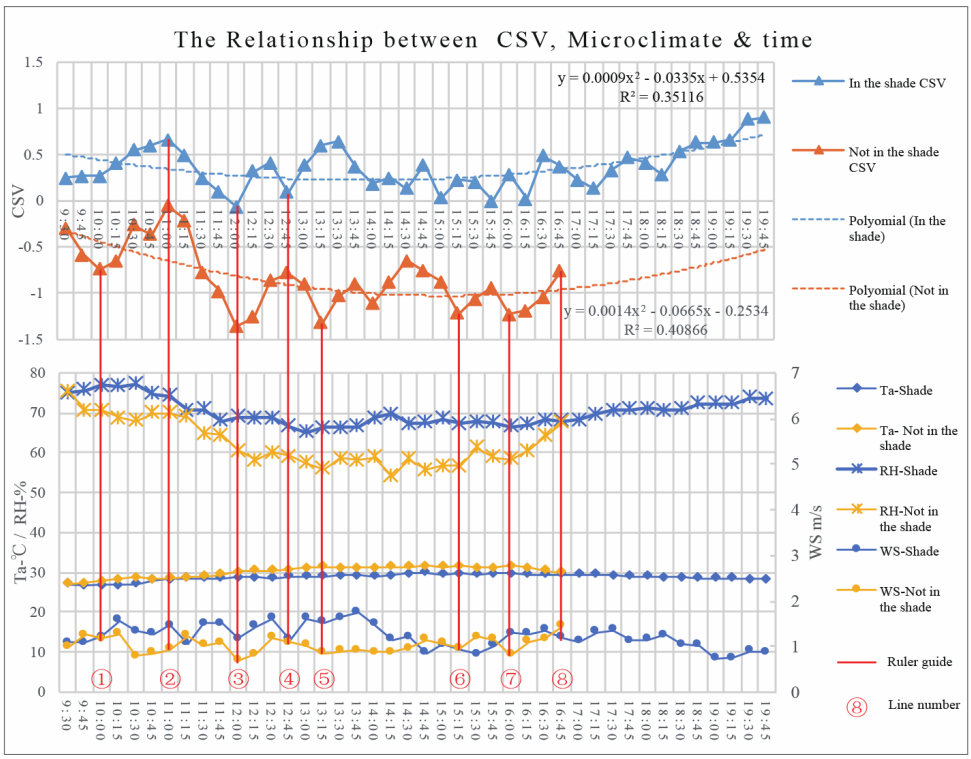
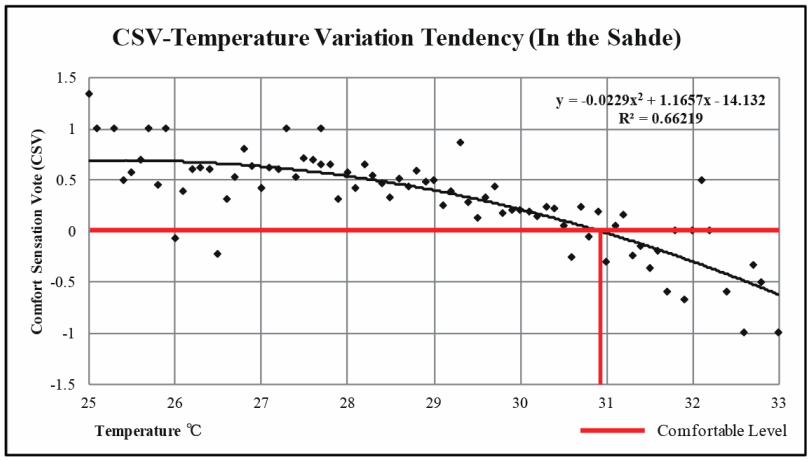
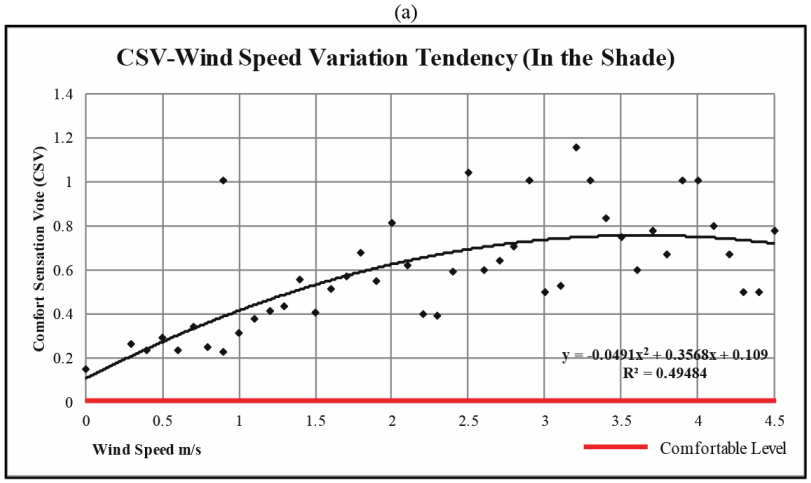


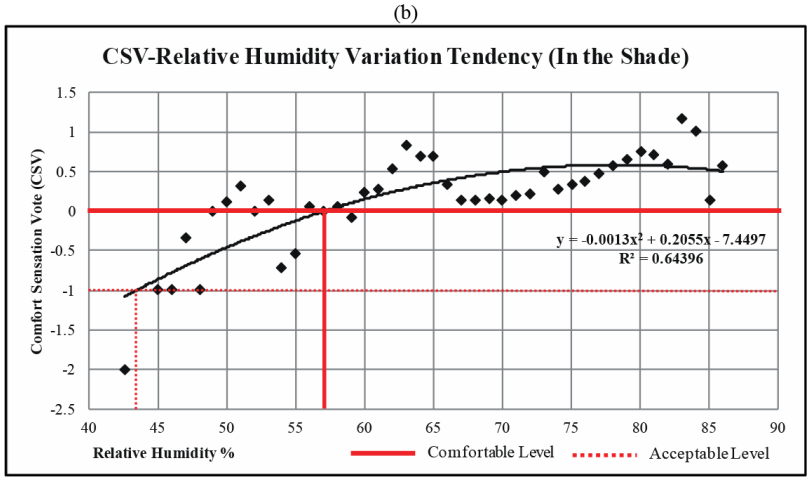
Fig. 6 The general relationships between CSV and mean microclimate in each period in different shade situations (n = 2,520).



(a)



(b)



(c)

Fig. 7 CSV: (a) mean T_a (in the shade); (b) mean V (in the shade); (c) mean RH variation tendency (in the shade).

the shade, CSV will decrease with increasing temperature and belong to the comfortable range of -1 to 1. As the equations binomial curve fitting shows, a temperature of ≤ 30.9 °C can be considered comfortable. The CSV increases with increasing wind speed, and all the measured wind speeds belong to the comfortable level of 0 to 1 in the shade. However, when the wind speed is in the range of 0~3.5 m/s, the comfortable level increases. When the wind speed is over 3.5 m/s, the comfortable level decreases. The CSV increases with increasing relative humidity. A relative humidity that is higher than 57% can be considered comfortable. However, when it is lower than 43%, it is not considered acceptable.

Meanwhile, the detailed relationships between CSV and microclimate out of the shade are plotted in Fig. 8. It can be found that all the measured elements cannot meet the comfort requirements except for the relative humidity. Parts of each microclimate element belong to the acceptable range ($CSV > -1$). The CSV increases with increasing wind speed and relative humidity and will decrease with the increasing temperature. When the temperature is lower than 30.7 °C, the comfortable level in acceptable. When the temperature is higher than 27 °C, the comfortable level decreases significantly. When the wind speed is faster than 1.25 m/s, the comfort is within the acceptable range. When the wind speed is close to 3 m/s, it is possible to obtain a comfortable level. For relative humidity, the situation can be considered comfortable when the relative humidity is higher than 78%. When the relative humidity is lower than 64.5%, the comfort is in an unacceptable range.

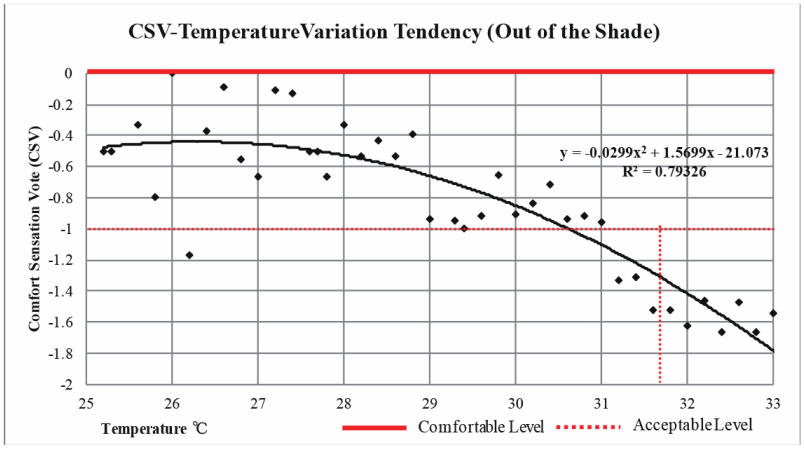
Additionally, the shade period before sunset at each measurement point is analyzed. Different colors represent different sunshine duration. Depending on the spatial arrangement, the positions are separated into the center line and edges. The center line is composed of east and west parts, in which the edge sides are composed of south and north parts. As shown in Fig. 9, the east side has more shade than the west side and the edge side has more shade than the center. Meanwhile, the south edge side has more shade than the north side. The corner (Nos. 7, 9, 11 and 13) and the under-roof locations (Nos. 8 and 12) also can provide more shade than the wide-open spaces such as Nos. 1, 2, 4, 6 and 15.

Based on the above results, the mean microclimate including T_a, WS and RH in different positions are also analyzed with the mean CSV. There are only slight differences in the mean temperature and humidity among the 15 points. However, the wind speeds vary for each point. As Fig. 10 shows, the center line has higher wind speed than the edges, especially at location Nos. 4, 6, 12 and 14, which are in the broad square and do not have any obstacles in the prevailing wind direction (east-west). Nevertheless, both ends of the center line (Nos. 1 and 15) have lower wind speeds than the other locations. Hence, uneven space edges, especially on the south side, can provide relatively favorable shade situations without higher wind speeds. The center line position can provide a favorable wind environment, but the broad square cannot provide a long period of shade. As shown by the mean CSV in each point, the comfortable position sequence from high to low is as follows: east center, south edge, north edge and west center. That is, the differences in shade and wind speed significantly influence the comfortable level.

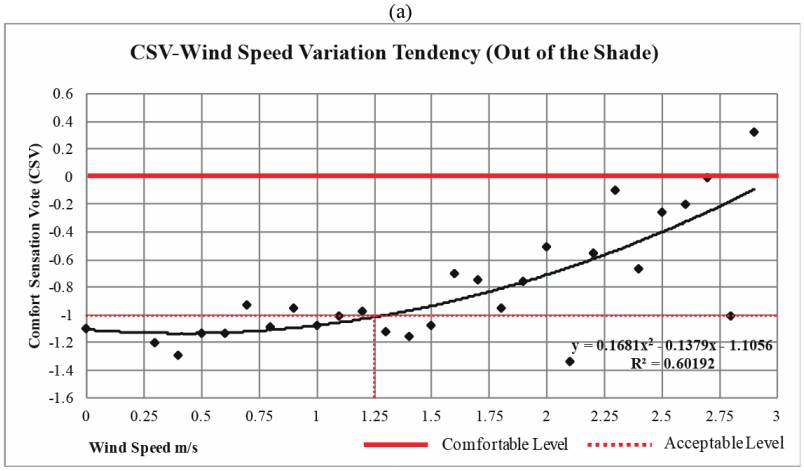
3.2 Behavior in Open Space

By using the panoramas, the position maps were analyzed in August 1st and 4th as a comparison of sunny and overcast day. As Fig. 11 shows, the study drew down the people's position for every 30 mins from 9:30 to 20:00, including the pedestrians and stationaries, and integrated them into one figure and counted the quantity of users (Fig. 12) by the separation of shade situation and behavior.

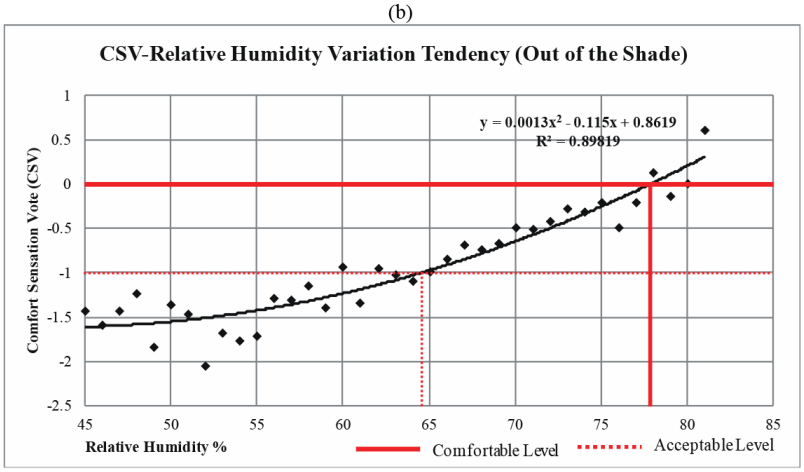
As shown in Fig. 11, on an overcast day, outdoor space can attract more people than clear day. On a clear day, the east side with long periods of shade, abundant



(a)



(b)



(c)

Fig. 8 CSV: (a) mean T_a (out of the shade); (b) mean V (out of the shade); (c) mean RH variation tendency (out of the shade).

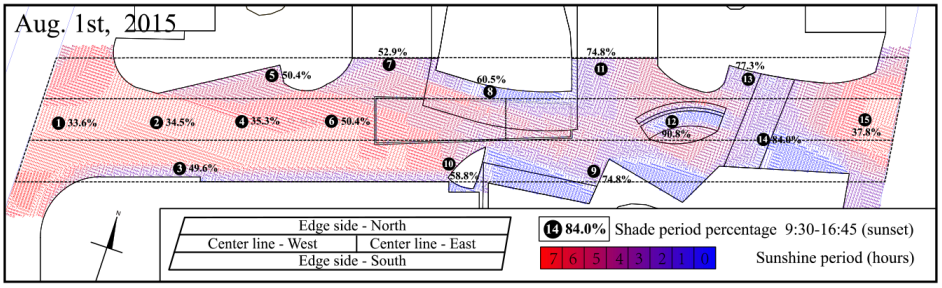


Fig. 9 Shadow situation before sunset.

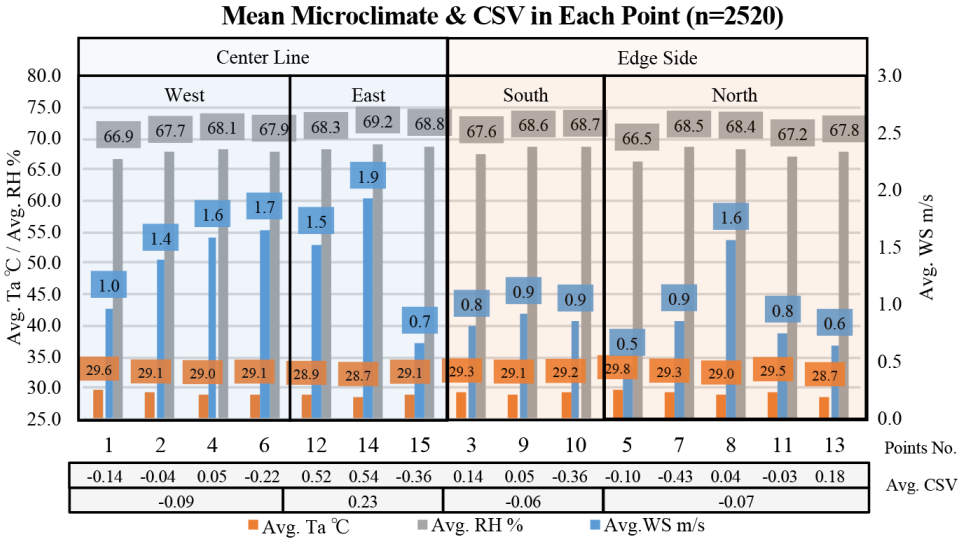


Fig. 10 Mean microclimate factors in each point with CSV.

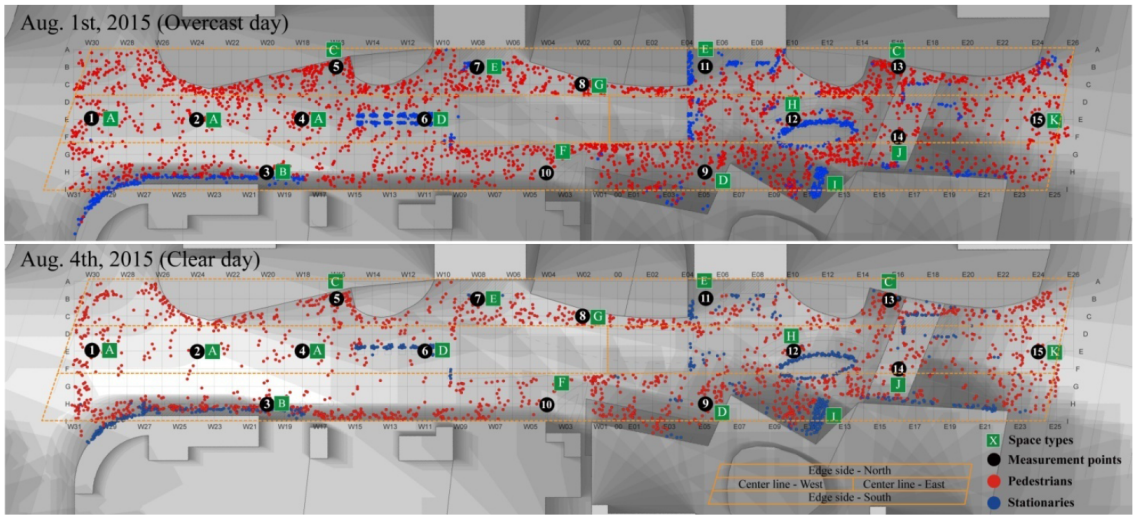


Fig. 11 The position relationship between clear day (August 1st) and overcast day (August 4th).

seats and other facilities (Nos. 9/Space Types I, 11/E, 12/H, 13/C and 14/J) can gather more people than the west side (Nos. 1, 2 and 4). The south side has more shade and can therefore gather more people than the north side, especially the area on the south side with seats or places to stay (e.g., Nos. 3/B and 9/I).

In these 2 days, the square type space A (Nos. 1, 2 and 4) and their south side square show low usage rates. People neither prefer to stay in or pass by the too-wide space that lacks any structures norspends long periods here. The activities tend to be irregular and fill the area on anovercast day. Many stationary people will choose to stay near the building edges (e.g., No. 3/B). Also, most of the pedestrians prefer to pass by the edge space (e.g., Nos. 5/C, 9/D, I and 13/C). The building corner (e.g., No. 9/I and 11/E) with seats and shade is suitable for long time stays. It can provide independent and quiet spaces that do not interfere with pedestrians. Space Type I can also provide a height difference to isolate two different types of space. Also, the under-roof space, such as Space Type H can provide thick shade all day. With the facilities such as seats, shrubs and fences, it is suitable for long stays.

Fig. 12 shows the number of people in these 2 days. The total number in overcast day before sunset is more than clear day in each measured time except 9:30. Both on an overcast day and a clear day, there are about 20%-30% of stationary people in the outdoor space. Before sunset, especially in overcast day, the number of the stationaries remained stable. During the survey, the static space is always full of people. To some degree, it can reflect the capacity of the static space. On a clear day, before sunset, about 60% of the people will stay in the shade. Combine with the former result, shade is an important element on the outdoor comfort.

The study also picked up the lunch time during these 2 days to draw down the pedestrian routes. The characteristicsof pedestrians were analyzed with the same quantity between different microclimate situations. As shown in Fig. 13, when the number of analyzed people is equal, the general routes are in the east-west direction (left-right direction). All the

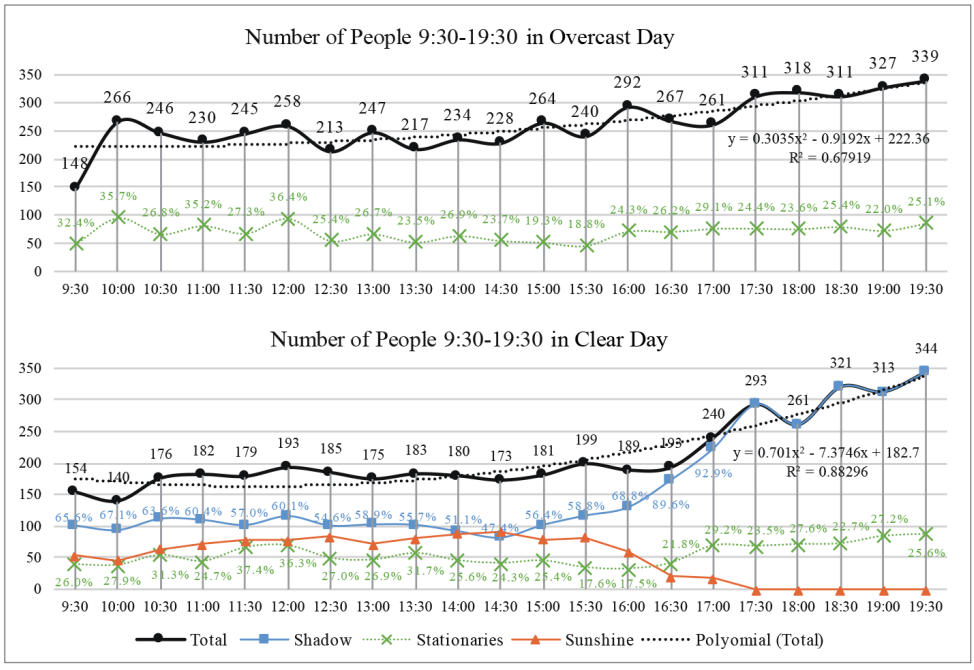


Fig. 12 Number of people comparison between clear day (August 1st) and overcast day (August 4th).

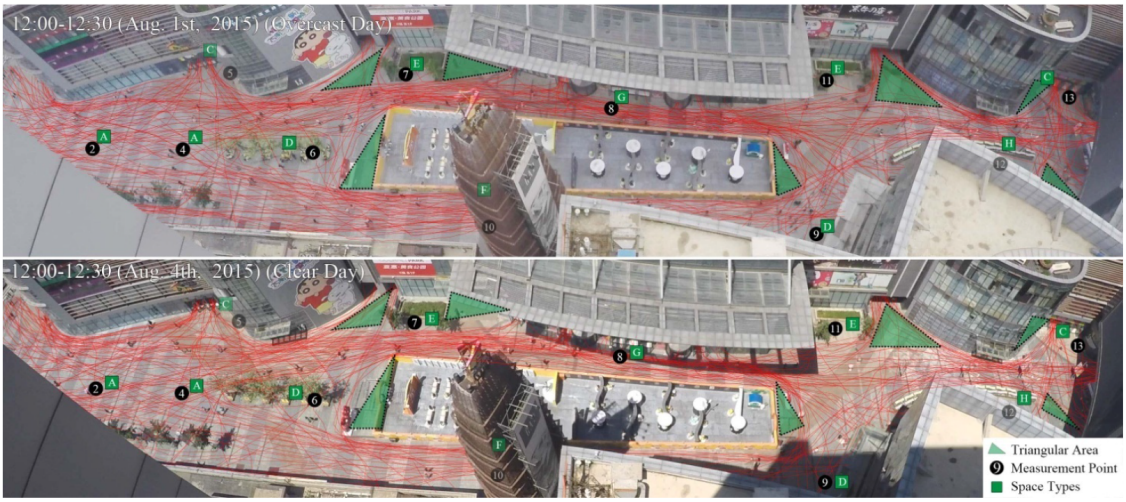


Fig. 13 Pedestrian routes comparison between clear day (August 1st) and overcast day (August 4th).

pedestrian routes are curved with almost no straight lines. In both cases, the pedestrian routes tend to be thicker at the edge of the buildings and the narrow spaces (Space Types F and G). When the space becomes wider, the routes tend to be laxer. Narrow canyon type spaces and the cross-flow are the space disadvantages for pedestrians. Pedestrians can choose any path in this case. It will create interferences between the pedestrians and stationary people, such as Space Types D (No. 6) and E (No. 7), because there are almost no boundaries or separations between the static space and dynamic space. However, a static place that has sufficient space in front does not cause as much interference with pedestrians, such as Space Types I and E (No. 11). Also, some triangular blank areas are formed by angular space edges and curved pedestrian routes. Both pedestrians and stationary people do not tend to choose this type of space that has the potential for interference.

4. Conclusion

This research focused on the relationship among open space design, people and microclimate. Through a field survey in a commercial open space, the study analyzed the microclimate elements that have a remarkable influence on behavior and feeling during the hottest summer in a northern China. The analyses and results led to the following conclusions:

4.1 Microclimate and Sensation

(1) In summer, shade plays a crucial role in the outdoor comfort. All the other objectively comfortable and acceptable microclimates show significant differences in different shade situations;

(2) In the shade, the comfortable temperature is ≤ 30.9 °C, the comfortable relative humidity is ≥ 57% and all the measured wind speeds (0-4.5 m/s) belong to the comfortable level. Meanwhile, a higher wind speed can increase the comfortable sensation. When the wind speed is in the range of 0~3.5 m/s, the comfortable level can expand. When the wind speed is over 3.5 m/s, the comfortable level decreases. When not in the shade, no measured temperature or wind speed can satisfy the comfortable requirements. The comfortable relative humidity is ≤ 78%. The acceptable temperature is ≤ 30.7 °C, humidity is ≥ 64.5%, and the wind speed is ≥ 1.25 m/s;

(3) In this canyon space, the mean temperature and humidity at each point are approximately the same; however, the wind speeds and shade that change CSV are distributed unevenly. The shade period sequence from long to short is as follows: south edge, north edge,

east center and west center. The wind speed in the center line is higher than on the edges. The CSV position sequence from high to low is as follows: east center, south edge, north edge and west center. That is, the difference in shade and wind speed significantly influences the comfort level.

4.2 Open Space and Behavior

(1) Shade can encourage more people to use the space;

(2) People prefer to choose the place with higher wind speed, and thick shade for either staying or passing by;

(3) Seats, space edges, corner spaces, under the roof spaces, the space with abundant landscape facilities and the spaces with height differences are popular for stationary people, especially when the location can meet the comfortable conditions. Too-wide square spaces, narrow aisles and spaces without abundant facilities are unpopular;

(4) Curved pedestrian routes without boundaries and angular static spaces create interference between pedestrians and stationary people and create triangular blank areas that are wastes of traffic space.

5. Discussion and Design Optimization

For this case, shade is an essential requirement for the people who want to be active outside and should be given priority in design. Additionally, using the naturally longer shade on the east side, more static space can be designed. At the west side, more landscape structures should be designed to enlarge the shading area and increase the comfort level here.

Dynamic spaces and static spaces should be clearly separated to avoid the space use conflicts to improve space utilization. Avoiding too-wide spaces without facilities and too narrow space and creating more comfortable static spaces with enough facilities can improve the quality of a space. Reducing rectilinear spaces and making more rounded spaces without angular edges can provide a flowing space for pedestrians and can also decrease the interference between dynamic and static spaces.

For stationary people, corner spaces, building edges and the center line area with higher wind speed should be thoughtfully considered to attract more people to stay for longer times. Creating landscape structures that are open to the direction of the prevailing summer wind and providing shade, seats and spatial separations among the above-mentioned places are necessary for a high-quality static space.

Based on the above results and conclusions, designing a canyon open space as a sandwich structure can be realized as a solution for the comfortable sensation and spatial utilization. As Fig. 14 shows, the static space should be arranged in the middle side and at the edge of the buildings. The traffic space is placed between these two static spaces. This design can not only improve the space utilization and decrease interference between stationary people and pedestrians but also offer possibilities for creating a favorable microclimate environment. Because the wind environment

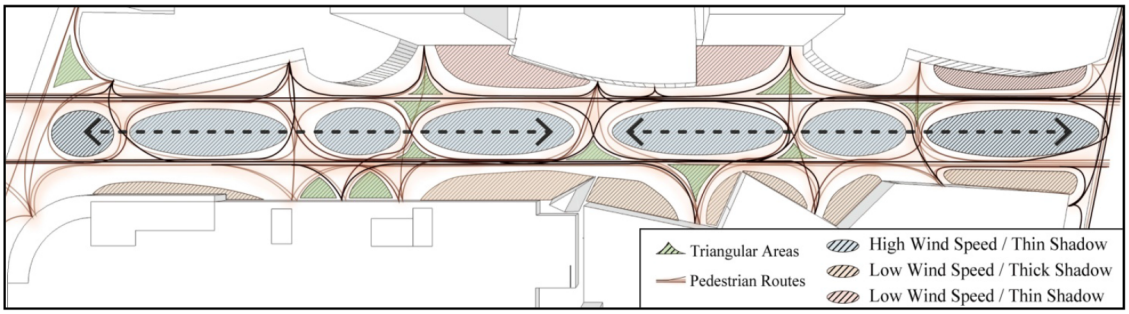


Fig. 14 Optimization design of canyon open space.

in the middle is better than that on the edges, designing the shading structures and humidifiers that are open to the wind direction can create a favorable environment based on the above-mentioned principle of a comfortable microclimate.

To create a suitable and high-quality open space that is comfortable for both pedestrians and stationary people, the following proposals should be considered:

(1) At the beginning of the open space design, understand the general microclimate situation and the comfortable threshold in the hottest day. Among all the microclimate elements, shade plays a crucial role and should be considered first. Roofs and plants, etc., that can provide thick enough shade. Based on theseparameters, different design methods will be separated by different microclimate situation (Fig. 15).

(2) Curved pedestrian routes should be planned with rounded space edges to enhance spatial utilization. The triangular blank area formed by a curved route and an angular boundary can be used for some functional landscape structures such as streamline leading or symbols (Fig. 16);

(3) Avoid too-wide square spaces without any facilities and too-narrow spaces. Provide abundant street facilities which can offer shade, resting areas and spatial separations at suitable places without spatial contradiction. By controlling the width of the traffic space with streamline leading structures, traffic efficiency can be improved by design. Additionally, depending on the shade distribution, setting landscape structures and plants that are open to the prevailing wind direction is necessary to ensure the spatial utilization (Fig. 17);

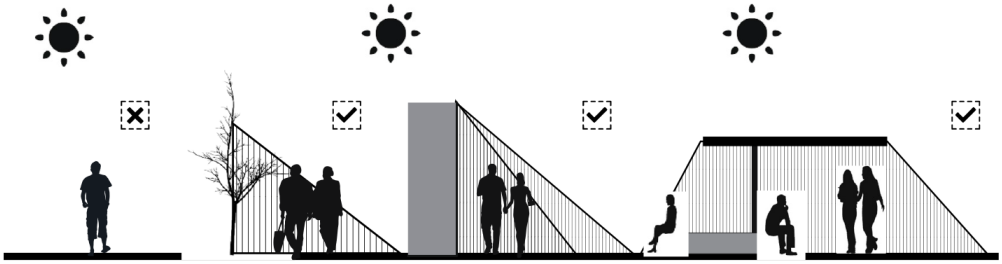


Fig. 15 Comfortable microclimate creation.

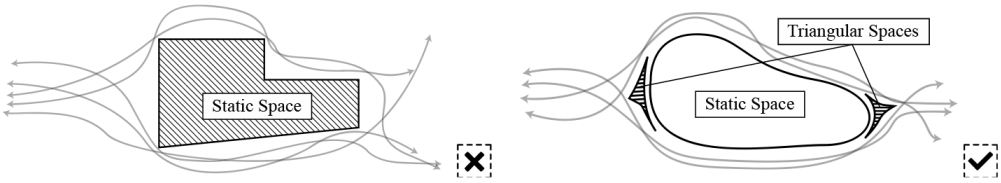


Fig. 16 Flowing route and curve space.

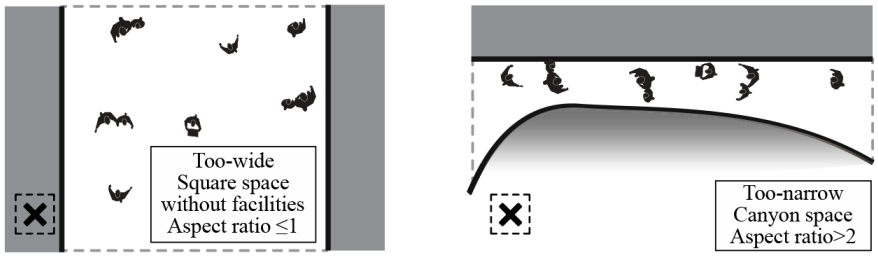


Fig. 17 Spatial scale.

Fig. 18 Space interference.

(4) By creating independent static spaces in the centerline area, edge side area and corners, interference between pedestrians and stationary people can be avoided. Meanwhile, spatial separations, such as fences, billboards, shrubs, height differences, are necessary in areas that could create conflicts. Providing sufficient functional facilities and structures are required to create an attractive place (Fig. 18).

6. Future Study

The microclimate in a northern city varies greatly between summer and winter. In Shenyang, China, the average annual temperature ranges from 1981 to 2010 is 35.8 °C [48]. Based on the summer study, the future research will focus on the cold winter situation. By analyzing both summer and winter, comprehensive and integrated proposals will be provided for the urban design of open space for northern cities with large temperature differences.

Acknowledgments

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References

[1] Bonan, G. B. 2000. "The Microclimates of a Suburban Colorado (USA) Landscape and Implications for Planning and Design." *Landscape and Urban Planning* 49 (3): 97-114.

[2] Hart, M. A., and Sailor, D. J. 2009. "Quantifying the Influence of Land-Use and Surface Characteristics on Spatial Variability in the Urban Heat Island." *Theoretical and Applied Climatology* 95 (3-4): 397-406.

[3] Stone, B., and Norman, J. M. 2006. "Land Use Planning and Surface Heat Island Formation: A Parcel-Based Radiation Flux Approach." *Atmospheric Environment* 40: 3561-73.

[4] De Schiller, S., and Evans, J. M. 1996. "Training Architects and Planners to Design with Urban Microclimates." *Atmospheric Environment* 30 (3): 449-54.

[5] Evans, J. M., and De Schiller, S. 1996. "Application of Microclimate Studies in Town Planning: A New Capital City, an Existing Urban District and Urban River Front Development." *Atmospheric Environment* 30 (3): 361-4.

[6] Eliasson, I. 2000. "The Use of Climate Knowledge in Urban Planning." *Landscape and Urban Planning* 48 (1): 31-44.

[7] Li, S. 1994. "User's Behaviour of Small Urban Spaces in Winter and Marginal Seasons." *Architecture and Behaviour* 10: 95-109.

[8] Nagara, K., Shimoda, Y., and Mizuno, M. 1996. "Evaluation of the Thermal Environment in an Outdoor Pedestrian Space." *Atmospheric Environment* 30 (3): 497-505.

[9] Nikolopoulou, M., Baker, N., and Steemers, K. 2001. "Thermal Comfort in Outdoor Urban Spaces: Understanding the Human Parameter." *Solar Energy* 70: 227-35.

[10] Shimazaki, Y., Yoshida, A., Suzuki, R., Kawabata, T., Imai, D., and Kinoshita, S. 2011. "Application of Human Thermal Load into Unsteady Condition for Improvement of Outdoor Thermal Comfort." *Building and Environment* 46 (8): 1716-24.

[11] Thorsson, S., Lindqvist, M., and Lindqvist, S. 2004. "Thermal Bioclimatic Conditions and Patterns of Behaviour in an Urban Park in Goteborg." *International Journal of Biometeorology* 48: 149-56.

[12] Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., and Lim, E.-M. 2007. "Thermal Comfort and Outdoor Activity in Japanese Urban Public Places." *Environment and Behavior* 39: 660-84.

[13] Nikolopoulou, M., and Lykoudis, S. 2007. "Use of Outdoor Spaces and Microclimate in a Mediterranean Urban Area." *Building and Environment* 42 (10): 3691-707.

[14] Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., and Lindberg, F. 2007. "Climate and Behavior in a Nordic City." *Landscape and Urban Planning* 82: 72-84.

[15] Chen, H., Ooka, R., Harayama, K., Kato, S., and Li, X. 2004. "Study on Outdoor Thermal Environment of Apartment Block in Shenzhen, China with Coupled Simulation of Convection, Radiation and Conduction." *Energy and Buildings* 36 (12): 1247-58.

[16] Ooka, R., Chen, H., and Kato, S. 2008. "Study on Optimum Arrangement of Trees for Design of Pleasant Outdoor Environment Using Multi-objective Genetic Algorithm and Coupled Simulation of Convection, Radiation and Conduction." *Journal of Wind Engineering and Industrial Aerodynamics* 96 (10): 1733-48.

[17] Shahidan, M. F., Jones, P. J., Gwilliam, J., and Salleh, E. 2012. "An Evaluation of Outdoor and Building Environment Cooling Achieved through Combination Modification of Trees with Ground Materials." *Building and Environment* 58: 245-57.

[18] Aspinall, P. A., Ward Thompson, C., Alves, S., Sugiyama, T., Brice, R., and Vickers, A. 2010. "Preference and Relative Importance for Environmental Attributes of Neighbourhood Open Space in Older People." *Environment and Planning B: Planning and Design* 37 (6): 1022-39.

[19] Coombes, E., Jones, A. P., and Hillsdon, M. 2010. "The Relationship of Physical Activity and Overweight to Objectively Measured Green Space Accessibility and Use." *Social Science & Medicine* 70 (6): 816-22.

[20] Giles-Corti, B., Broomhall, M. H., Knuiman, M., Collins, C., Douglas, K., Ng, K., et al. 2005. "Increasing Walking: How Important Is Distance to, Attractiveness, and Size of Public Open Space?." *American Journal of Preventive Medicine* 28 (2): 169-76.

[21] Hino, A. A. F., Reis, R. S., Ribeiro, I. C., Parra, D. C., Brownson, R. C., and Fermino, R. C. 2010. "Using Observational Methods to Evaluate Public Open Spaces and Physical Activity in Brazil." *J Phys Act Health*, 7 (Suppl 2): S146-S154.

[22] Kaczynski, A. T., and Havitz, M. E. 2009. "Examining the Relationship between Proximal Park Features and Residents' Physical Activity in Neighborhood Parks." *Journal of Park and Recreation Administration* 27 (3): 42-58.

[23] Sugiyama, T., and Thompson, C. W. 2008. "Associations between Characteristics of Neighbourhood Open Space and Older People's Walking." *Urban Forestry & Urban Greening* 7 (1): 41-51.

[24] Timperio, A., Giles-Corti, B., Crawford, D., Andrianopoulos, N., Ball, K., Salmon, J., and Hume, C. 2008. "Features of Public Open Spaces and Physical Activity among Children: Findings from the CLAN Study." *Preventive Medicine* 47 (5): 514-8.

[25] Givoni, B. 1998. *Climate Considerations in Building and Urban Design.* New York: John Wiley & Sons.

[26] Carr, S., Francis, M., Rivlin, L. G., and Stone, A. M. 1993. *Public Space.* Cambridge, New York: Cambridge University Press.

[27] Marcus, C. C., and Francis, C., eds. 1997. *People Places: Design Guidelines for Urban Open Space.* City: John Wiley & Sons.

[28] Gehl, J., and Gemzøe, L. 2004. *Public Spaces, Public Life.* Copenhagen: Danish Architectural Press and the Royal Danish Academy of Fine Arts, School of Architecture Publishers.

[29] Maruani, T., and Amit-Cohen, I. 2007. "Open Space Planning Models: A Review of Approaches and Methods." *Landscape and Urban Planning* 81 (1-2): 1-13.

[30] Nicholson, S. E. 1967. "A Pollution Model for Street-Level Air." *Atmospheric Environment* 9 (1): 19-31.

[31] Nakamura, Y., and Oke, T. R. 1988. "Wind, Temperature and Stability Conditions in an East-West Oriented Urban Canyon." *Atmospheric Environment* 22 (12): 2691-700.

[32] Oke, T. R. 1981. "Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observations." *Journal of Climatology* 1 (3): 237-54.

[33] Johnson, G. T., and Watson, I. D. 1984. "The Determination of View-Factors in Urban Canyons." *Journal of Climate and Applied Meteorology* 23 (2): 329-35.

[34] Vardoulakis, S., Fisher, B. E., Pericleous, K., and Gonzalez-Flesca, N. 2003. "Modelling Air Quality in Street Canyons: A Review." *Atmospheric Environment* 37 (2): 155-82.

[35] Spagnolo, J., and De Dear, R. 2003. "A Field Study of Thermal Comfort in Outdoor and Semi-outdoor Environments in Subtropical Sydney Australia." *Building and Environment* 38 (5): 721-38.

[36] Erell, E., Pearlmutter, D., and Williamson, T. 2012. *Urban Microclimate: Designing the Spaces between Buildings.* New York: Routledge.

[37] China Meteorological Administration, National Meteorological Information Center. n.d. *The Database of Climate Standard Daily Value in Chinese International Ground Switching Center*. Beijing (China): China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. 1971-2014. Accessed August 28, 2012. http://data.cma.cn/data/detail/dataCode/A.0029.0001.html. (in Chinese)

[38] ASHRAE (American Society of Heating Refrigerating and Airconditioning Engineer). 2001. *ASHRAE Handbook of Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

[39] Thorsson, S., Lindberg, F., Eliasson, I., and Holmer, B. 2007. "Different Methods for Estimating the Mean Radiant Temperature in an Outdoor Urban Setting." *International Journal of Climatology* 27: 1983-93.

[40] S. Tanabe. 1988. "Thermal Comfort Requirements in Japan." Ph.D. thesis, Waseda University, Tokyo, Japan.

[41] China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. 2005. *China Standard Weather Data for Analyzing Building Thermal Conditions.* Beijing: China Building Publishing House.

[42] Ministry of Housing and Urban-Rural Development of the PRC(MOHURD). 1994. *Chinese Standard for Assessment Parameters of Sunlight on Building (GB/T50947-2014).* Beijing: Standard Press of China; 1994. (in Chinese)

[43] Blalock, H. M. Jr. 1972. *Social Statistics.* New York: McGraw-Hill.

[44] Johansson, E., and Emmanuel, R. 2006. "The Influence of Urban Design on Outdoor Thermal Comfort in the Hot, Humid City of Colombo, Sri Lanka." *International journal of biometeorology* 51 (2): 119-33.

[45] Cheng, V., Ng, E., Chan, C., and Givoni, B. 2012. "Outdoor Thermal Comfort Study in a Sub-tropical Climate: A Longitudinal Study Based in Hong Kong." *International Journal of Biometeorology* 56 (1): 43-56.

[46] Hwang, R. L., Lin, T. P., and Matzarakis, A. 2011. "Seasonal Effects of Urban Street Shading on Long-Term Outdoor Thermal Comfort." *Building and Environment* 46 (4): 863-70.

[47] Shimazaki, Y., Yoshida, A., Suzuki, R., Kawabata, T., Imai, D., and Kinoshita, S. 2011. "Application of Human Thermal Load into Unsteady Condition for Improvement of Outdoor Thermal Comfort." *Building and Environment* 46 (8): 1716-24.

[48] Website of Chinese Meteorological Data. n.d. *The Database of Climate Standard Daily Value in Chinese International Ground Switching Center.* Beijing (China): China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. 1981-2010. Accessed August 28, 2012. http://data.cma.cn/data/detail/dataCode/A.0029.0005.html. (in Chinese)

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Public Open Space Design Study on the Basis of Microclimate and Spatial Behavior in Hot and Cold Weather Conditions in Downtown Area

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Abstract

Microclimate in open space affected by the urban layouts and spatial forms plays an important role in the outdoor comfort, thus the outdoor activities based on the comfort sensation will directly affected by the microclimate. An outstanding open space should satisfy different requirements of outdoor activities and create relatively comfortable sensation.

Most studies have been conducted on these relationships only above 0 Celsius degree. However, only few have focused on extreme situations in both hot and cold seasons. Therefore, from microclimate perspective, taking people's comfort and spatial behaviors as criterions, this research discussed how the open space forms affect microclimate, thus affect comfort sensation and spatial behaviors. The outcomes may provide some useful insights for planners and architects to understand the relationship among microclimate, open space and people.

Results showed that microclimate obviously affected people's comfort. In hot season, shade and air-flow played crucial roles in outdoor comfort. People tend to stay outside in the shade and the area with higher air velocity. After sunset is popular period for outdoor activities. In cold season, at the same ambient temperature, lower air velocity raised the comfort level. Shade also had influences on comfort sensation but do not affect spatial behaviors significantly.

This paper also proposes optimization design proposals of densely populated open space based on extreme microclimate and spatial behaviour.

Keywords: outdoor comfort, urban design, street canyon, activities, optimization design

1. Introduction

Open space that accommodate daily social activities plays an important role in cities. One of open space design targets is attracting more people to enjoy the outdoor environment (Carr, 1993; Marcus, 1997; Gehl, 2011; Maruani, 2007). Most open spaces are based on a type of open space formed by streets and buildings. One of the main types of open space is urban canyon that defined as the space composed of the street and its flanking buildings (Nunez, 1977). The city commercial zones are mostly planned in downtown urban canyons which are densely populated, and convenient for traffic. These properties lead to crucial status of urban canyon. For field surveys of urban canyon space, researching the commercial open space has obvious typicality and research value than any other types of urban space (Spagnolo, 2003).

On the basis of spatial types in the urban canyon, the microclimate undergoes complex changes, thus affecting outdoor activities dramatically. Many studies have researched outdoor thermal comfort and outdoor activities influenced by microclimate (Nikolopoulou, 2007; Shimazaki, 2011; Thorsson, 2007; Eliasson, 2007). An increasing number of researchers have focused on the relationship between the microclimate and urban forms.

Several studies have proved that shade and exposure to sunlight greatly influence ambient temperature in urban canyon, thus affecting users' feelings of comfort (Bourbia, 2010; Hwang, 2011; Andreou, 2012; Andreou, 2013, 2014; Shahrestani, 2015). Erell et al. (2012) have provided new perspective on interaction between microclimate and urban landscape for architects and urban designers. Among them, however, few studies have researched regions that suffer wide differences in temperature between summer and winter.

The relationship between microclimate and people's reactions, including comfort sensation and spatial behaviors in urban canyon should be paid more attention, especially in extreme weather. Li (1994) researched on small urban spaces in New York in winter to study the spatial behaviour influenced by climatic conditions. By using microclimate monitoring and interviews, Lai (2014) conducted a field survey at a park in northern China revealed the relationship between human comfort and each parameter of boreal climate. Furthermore, this research estimated northerners' comfort level and cold-resistant level by multimethod. Baruch (1998) discussed the relationship among building, design, and climate, introducing design principles in different climate regions, broadly including cold regions. Using wind and snow tunnel simulation and evaluation, Setoguchi et al. (2004, 2007, 2008, 2009) and Watanabe et al. (2016) discussed design procedures for winter cities, especially those suffering heavy snow. They discussed urban structures and building forms which are suitable for outdoor activities in cold season. Meng (2010) provided open space design guidelines for downtown areas suffering strong winds and low winter temperatures by simulating various types of downtown, high-rise buildings in a wind tunnel.

An outstanding open space should satisfy different requirements of outdoor comfort in different climate conditions. Other than the indoor space which can be created to satisfy the needs of the occupants, the outdoor space which affected by urban microclimate should be built by understanding the microclimate and should responds to them in appropriate ways (Erell et al.,2012). By researching the extreme urban microclimate situation, this study may provide useful insights for planner, architects and environment engineers to demonstrate the microclimate factors affected outdoor comfort significantly. Through microclimate measurement with public feedback in a central open space in northern China, this research discusses important elements that significantly affect people's sensations and behaviors, especially, how to optimize the open space design to prevent poor situations in hot summer and cold winter.

2. Method

2.1 Study Area

The study case is a canyon type open space located in the central area of Shenyang in northern China (41°48′01.11″N, 123°27′49.33″E), which has long, severely cold winter and relatively short summer (Chinese State Bureau of Technology Supervision (CSBTS), 1994). The annual temperature range which undergoes over approximately 60°C (China Meteorological Administration, 2014) is relatively larger than that of other areas; however, several weeks in summer also suffer high temperatures.

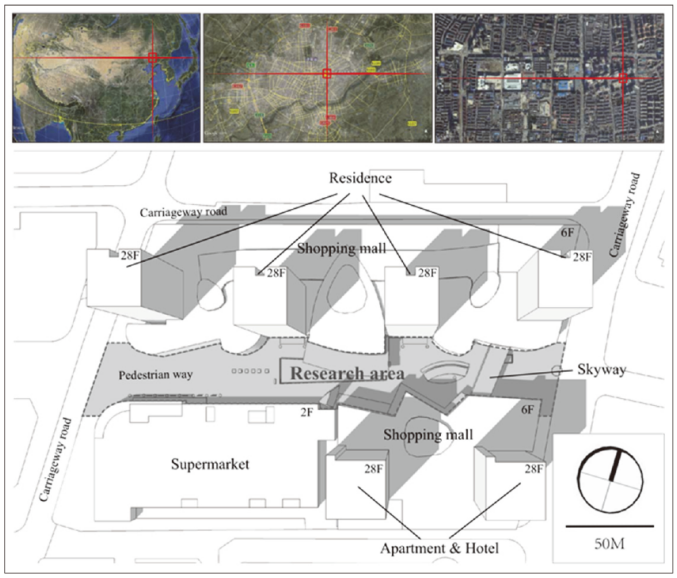

Figure 1. Research area in Shenyang, northern China

The study area is located at the mid-street in Shenhe district, Shenyang with approximately 400–600 thousands of tourists per day (ZHANG, 2008), named as one of the most popular public spaces in the downtown area. There are resourceful public facilities with building area of about 282,700 m^2 like shopping malls, supermarkets, residences, hotels, and apartments. The subway station is located at the second underground floor of a shopping mall. As Fig.1 shows, this place is a pedestrian street canyon (approximately 35×280 m^2). The area is mostly covered with hard materials with several tree pools. There are more than 20 entrances of the buildings opening to the pedestrian street. As an integrated public area, many and various subjects can be found to participate as references in the research.

2.1 Field Survey

The hottest period in summer and coldest period in winter were chosen to research the extreme climate situation on the basis of 5 years (2009–2014) daily maximum and minimum temperatures from July to September in summer and December to February in winter (Fig. 2). Jul. 28–Aug.9, 2015 (12 days in summer) and Jan. 15–29 (15days in winter), 2016 were chosen as the survey periods.

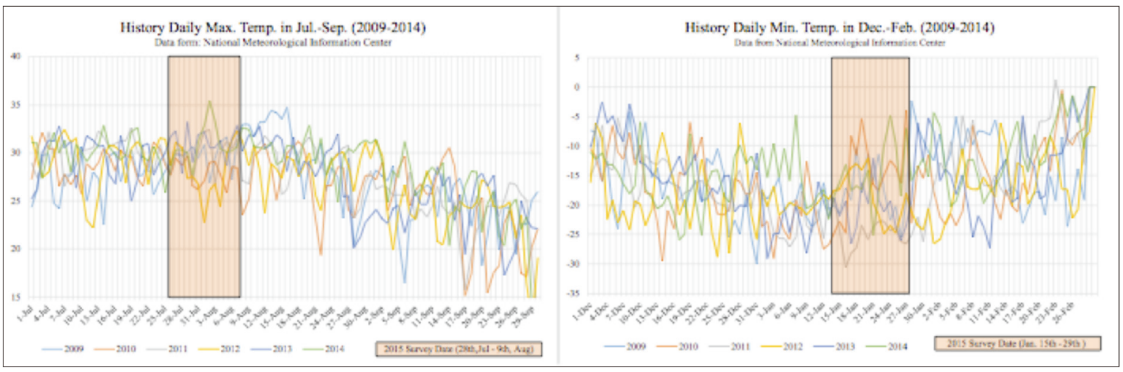

Figure 2. Historical daily maximum and minimum temperatures from July to September and December to February 2009–2014 (China Meteorological Administration, 2014)

In the research area, 4 areas named west center line, east center line, north edge side and south edge side, including 15 measurement points were separated depending on space characteristics (see Fig. 3). As shown in Table 1, the microclimate parameters were recorded at each point every 15 minutes from 9:30 to 20:00, including ambient temperature (T_a), air velocity (V), relative humidity (RH), globe temperature (T_g) and shade situation. The wind chill (WC) will be recorded during the winter survey day.

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 actual non-uniform enclosure" (ASHRAE, 2001). It is based on the conversion of radiative energy between the absorbing and the emitting of two objects. In this study, the T_{mrt} is estimated using the globe temperature method. Depending on the previous study, there are relatively small differences between the globe temperature methods and other complicated methods (Thorsson, 2007). Tmrt is calculated based on the following formula (ASHRAE, 2001):

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.10\times10^8 V^{0.6}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)\right]^{\frac{1}{4}} - 273 \quad (1)$$

where T_{mrt} is mean radiant temperature (°C), T_g is globe temperature (°C), T_a is air temperature, V is air velocity (m/s), D is globe diameter (m) (in this study D=0.075m), ε is emissivity (0.95 for black-colored globe).

The Physiological Equivalent Temperature (PET) (Mayer, 1987) was employed in this research as a reference of the objective thermal comfort level. It can be defined as a temperature dimension index in degrees Celsius (°C) based on the Munich Energy-balance model for Individuals (MEMI) (Höppe, 1999). The PET can be calculated by using the software (e.g., RayMan) (Matzarakis, 2007) with inputting parameters of positional information, basic human factors, T_a, V, RH and T_{mrt}. It is also used by the human bio-meteorological evaluation of climate in urban and regional planning in German (VDI 3787) (VDI, 1998).

The environmental comfort sensation votes (CSV) which can be defined as subjectively integrated reactions of local people to the environment were also collected at the same time with recording the microclimate data (see Table 2) (Tanabe, 1988).

Panoramic images and the time-lapse videos were taken during the survey for analyzing the people presents and their position relations (Fig. 3). As a comparison research of people present in and out of shade in summer and winter, two clear days, Aug.4, 2015 (summer) and Jan. 22, 2016 (winter) were chosen to analyze the spatial positions by counting and drawing down the people's position according to the panoramas and videos every 30 minutes. Besides the real shade situation recording, this study also simulated the shade in Aug. 4th and Jan. 22nd as references of the behaviour analyses depending on the solar incident angle (China Meteorological Bureau, 2005; MOHURD, 1994).

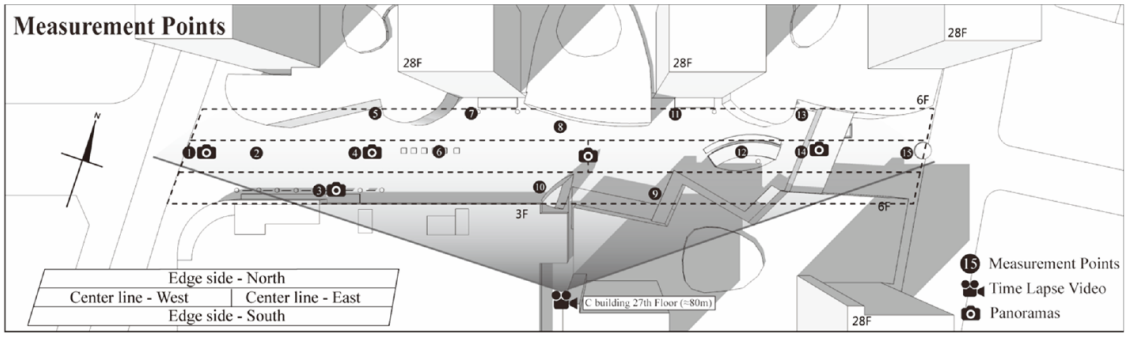

Figure 3. Space types, position information, and measurement methods of central open space, Shenyang, Northern China

Table 1. Sensor specifications and measurement height

Sensor	Parameter	Accuracy	Resolution	Range	Setting place
Kestrel 4500	V	3%	0.1 m/s	0.6 to 40.0 m/s	From point No. 1 to No. 15, 1.5m as the average height of the head.
	T_a	0.5 °C	0.1 °C	−29.0 to 70.0 °C	
	RH	3.0 %	0.1 %	5 to 95% non-condensing	
	WC (winter)	0.9°C	0.1°C	Refer to Ranges for the V and T_a Sensors	
TR-71Ui	T_g	0.3°C	0.1 °C	-40 to 110 °C	

Note. Wind chill temperature (WC) results from combining the effect of air velocity and ambient temperature. Calculated based on the NWS Wind Chill Temperature Index (The National Weather Service (NWS), 2011).

Table 2. The scale used by participants for subjective responses about comfort sensation during field surveys

Value	Comfort sensation vote
−3	Very uncomfortable
−2	Uncomfortable and unacceptable
−1	Uncomfortable, but acceptable
0	Neutral
1	Slightly comfortable
2	Comfortable
3	Very comfortable

3. Results

3.1 Sensation Analysis with Microclimate Parameters

During the survey, 2489 groups of microclimate data and the corresponding CSV in summer and 2501 groups in winter were collected. The measured T_a range were 24.4–35.9°C in summer, −21.6–2.2°C in winter. The maximum temperature range between summer and winter was 57.5°C. The measured air velocity range were 0–7.1 m/s in summer and 0–4.8 m/s in winter. The mean air velocity in summer was 1.2m/s higher than in winter (1m/s). The RH range were 36–100% in summer (mean RH was 38.8%) and 20–56.2% in winter (mean RH was 20%).

Table 3 displays the correlations (Blalock, 1972) between CSV and microclimate data by using the software IBM SPSS Statistics (Version 20.0.0) (N_{summer}=2489, N_{winter}=2501). It can be used to evaluate the microclimate elements which will affect the comfort level greater. The higher the correlation coefficient, the greater influence

on comfortable level. A measure of linear correlation between the two variables X and Y, a value is given between +1 and −1, inclusively, with 1 indicating total positive correlation, 0 indicating no correlation, and −1 indicating total negative correlation.

The results indicated that in summer (Table 3a), all measured factors affected CSV significantly. Among them, shade had the highest correlation (r=−0.464) with CSV, followed by RH (r=0.449). T_a was third, with a coefficient of −0.421, follow by the T_{mrt} (r=−0.234). The weakest correlation with CSV was air velocity, with a coefficient of 0.222. More shade, lower T_a, higher air velocity, and higher RH improved sensations of comfort.

In winter (Table 3b), wind chill is employed as an important part for comfort evaluation. There are significant correlations between CSV and all measured factors. T_{mrt} affected CSV most with a coefficient of 0.336, followed by wind chill (r=0.310). Correlation coefficients decreased gradually from T_a (r=0.298) and shade (r=0.236) to air velocity (−0.074). Higher wind chill, less shade, higher T_a, and lower air velocity improve comfort sensations.

Consequently, all the parameters mentioned in this part will affect the CSV. However, there is no correlation coefficients above 0.5, that is, no single parameter will affect the CSV as a leading role. All the factors have come together on the comfort level.

Table 3a. Correlations between comfort sensation votes (CSV) and microclimates in summer

		CSV	Shade	T_a	Tmrt	V	RH
summer	CSV	1					
	Shade	-.464**	1				
	T_a	-.421**	.288**	1			
	T_{mrt}	-.234**	.250**	.215**	1		
	V	.222**	-.080**	-.157**	.216**	1	
	RH	.449**	-.287**	-.685**	-.283**	.165**	1

** *Correlation is significant at the 0.01 level (2-tailed).*

Table 3b. Correlations between comfort sensation votes (CSV) and microclimates in winter

		CSV	Shade	Ta	Tmrt	V	WC
winter	CSV	1					
	Shade	.236**	1				
	T_a	.298**	.036**	1			
	T_{mrt}	.336**	.157**	.461**	1		
	V	-.074**	-0.008	.124**	.260**	1	
	WC	.310**	.038*	.894**	.321**	-.290**	1

** *Correlation is significant at the 0.01 level (2-tailed).*

Note. CSV – comfort sensation votes, T_a – air temperature, T_{mrt} – mean temperature radiant, V – air velocity, RH – relative humidity.

In Fig.4, for every 0.5°C of PET interval, the mean CSV was calculated in both summer and winter as suggested by Ref. (Lin, 2008). The PET ranges were −31.7 to 3.1°C (cold season) and 21 to 40.9°C (hot season). Linear regression was conducted as follows:

Cold season:

$$y=0.0497x-1.1394 \ (R^2=0.86436) \quad (2)$$

Hot season:

$$y=-0.1043+3.1178 \ (R^2=0.71803) \quad (3)$$

The correlation between mean CSV and PET in both summer and winter were higher than 0.7 (R^2=0.86 in winter, R^2=0.72 in summer). The regression coefficients were 0.0497 in winter and −0.1043 in summer. The results indicate that comparing with the cold season, the residents in Shenyang were more sensitive to hot season. With the scale for subjective responses about comfort sensation in Table 2, the unacceptable PET range is lower than −17.32°C in winter. The neutral PET is 29.89°C in summer.

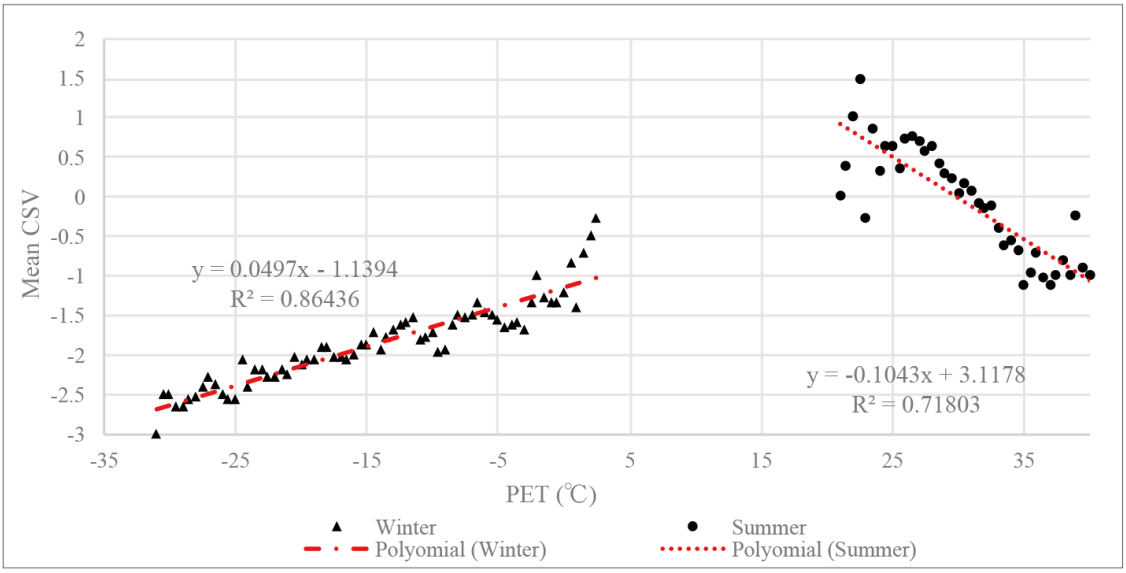

Figure 4. Relationship between mean CSV and PET

Studies had been conducted that residents in different areas shows environmental adaptability and individual differences (Nikolopoulou, 2001; Oliveira, 2007). In this research, the comfort sensation of residents in Shenyang was collected with corresponding microclimate data. Considering about the regional and individual differences, more than 2400 groups of data were employed for the sensation tendency research.

By analyzing the relation between mean CSV and each microclimate factor in summer, the variation tendencies were found: as Fig. 5 shows, CSV decreased with increasing ambient temperature, decreasing air velocity, and rose in relative humidity. Among these meteorological parameters, 29.6°C of T_a, 1.1 m/s of air velocity, and 67% of RH were threshold values for whether the environment was comfortable or not. When the T_a is higher than 31.9°C and the RH is lower than 52%, it can be seen to be uncomfortable situation. To sum up, in summer, lower ambient temperature, higher air velocity and relative humidity are more comfortable.

In winter, all the CSV was below 0°C, that is, all the measured microclimate cannot satisfy people's comfort level. CSV decreased with increasing air velocity and decreasing ambient temperature and wind chill (Fig. 6). Among them, −14.4°C of T_a, −16.5°C of WC, and 1.6 m/s of air velocity were environmental threshold values that can be accepted or not. Consequently, in winter, lower air velocity, higher ambient temperature and wind chill will make the outdoor environment more comfortable.

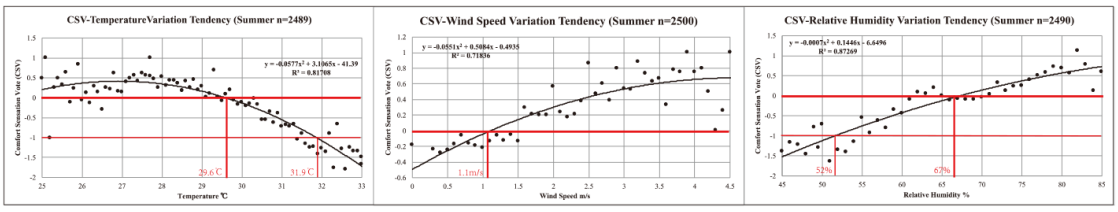

Figure 5. CSV- ambient temperature, air velocity, and relative humidity variation tendency (Summer)

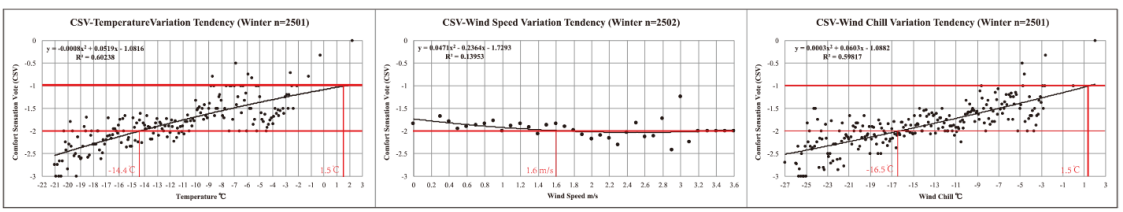

Figure 6. CSV- ambient temperature, air velocity, and wind chill variation tendency (Winter)

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3.2 Relationships between Comfort Sensations Votes (CSV), Microclimate, and Time

Previous studies had demonstrated that shade affect the solar radiation, thus affect the thermal sensation greatly (Lin, 2010; Hwang, 2011). Among the microclimate parameters, shade situation is easy to be distinguished and calculated. Therefore, separating the shade situation to analyze the relationship among mean CSV, microclimate factors and time may provide some distinct insights on the outdoor environment research.

Fig. 7 shows the relations among microclimate factors and CSV as a function of time in different shade situations, the following results were obtained:

In summer, CSV curves in and out of shade are obviously separate. In the morning (before 11:00 a.m.) and evening (after 17:00 p.m.), the CSV was higher than other periods, most people feel comfortable. T_a and RH change with time gradually. From morning, Ta increase gradually until 14:30 p.m. After 14:30 p.m., the Ta started to decrease gradually. The RH was opposite to the Ta with higher rate of change. Air velocity was not about time but significantly affects instantaneous CSV.

In winter, all the measured CSV was below 0 Celsius temperature. From morning, CSV curving in and out of shade separated gradually. From 13:00 p.m. to 15:00 p.m., higher CSV can be measured especially out of the shade. Ta and RH changed gradually with time, however, wind chill changed with air velocity, significantly affected instantaneous CSV.

Consequently, the RH and T_a will change with time. It can be suggesting that according to the solar radiation and spatial characteristics, some of the microclimate factors will change gradually with time. Meanwhile, the air velocity which is not related to time will also affect the CSV significantly. By according to the ruler guide in Fig.7, almost all the instantaneous change was due with the air-flow.

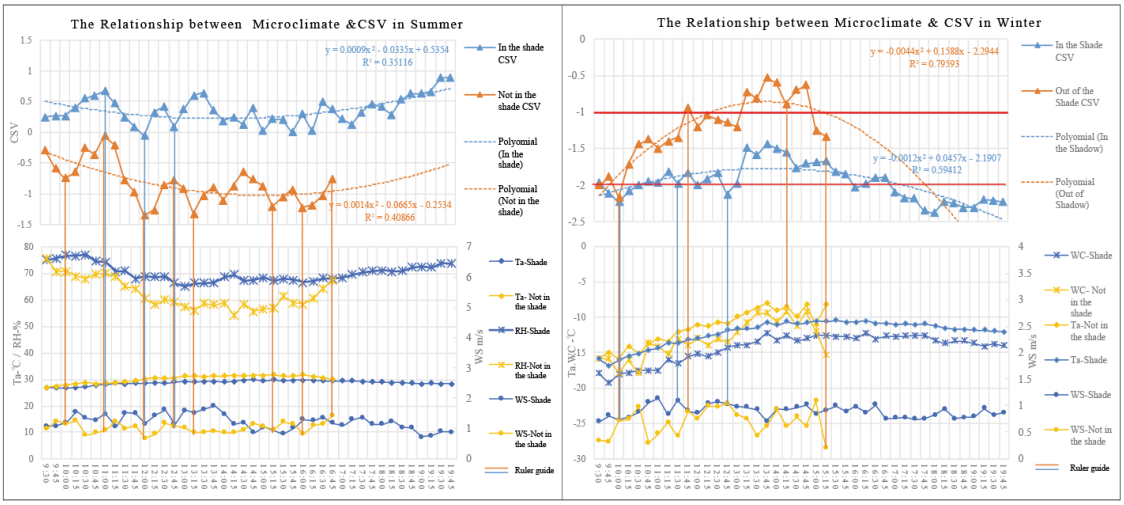

Figure 7. Relationships among mean CSV, microclimate factors with time in different shade situations

The analysis of people present is an effective way to evaluate the period people chose to stay outside. By Two days (Aug. 4, 2015 in summer and Jan. 22, 2016 in winter) were chosen to compare the differences between summer and winter by the following reasons: First, two days were all clear days. There were no influences by cloud. Secondly, these two days were all workdays and there were no commercial events during the survey periods. The pedestrian volume can be seen as normal levels. As Fig. 8 shows, both in summer and winter, total numbers relate to the time of day. The average total number of people in summer (212.10) was twice than that in winter (99.76). The least number of people were recorded during the morning (9:30−10:30) in both summer and winter. Since all the shopping malls open at 10:00, it can be speculated that the number of people affected by the function of open space.

In summer, the total number was least at 14:30, but after sunset (no direct sunlight in the study area) at about 16:30, numbers of people increased substantially. In the outdoor space, approximately 30% of people were stationary. Before sunset, the number of stationary people remained stable, and approximately 60% of them stayed in the shade. Hence, afternoon before sunset was the most unpopular time in summer, but after sunset, more people came outside.

In winter, the biggest number of people were recorded around 3 o'clock p.m. People not in the shade related significantly to time change, and there were almost no stationary people outside. In summary, from lunchtime (12:00−13:00) to sunset at about 16:30 was the most attractive period for people in winter.

Consequently, there is a clear difference in the suitable time distribution for outdoor activities in summer and winter, that is to say, the same outdoor space should be treated differently under different outdoor environment conditions.

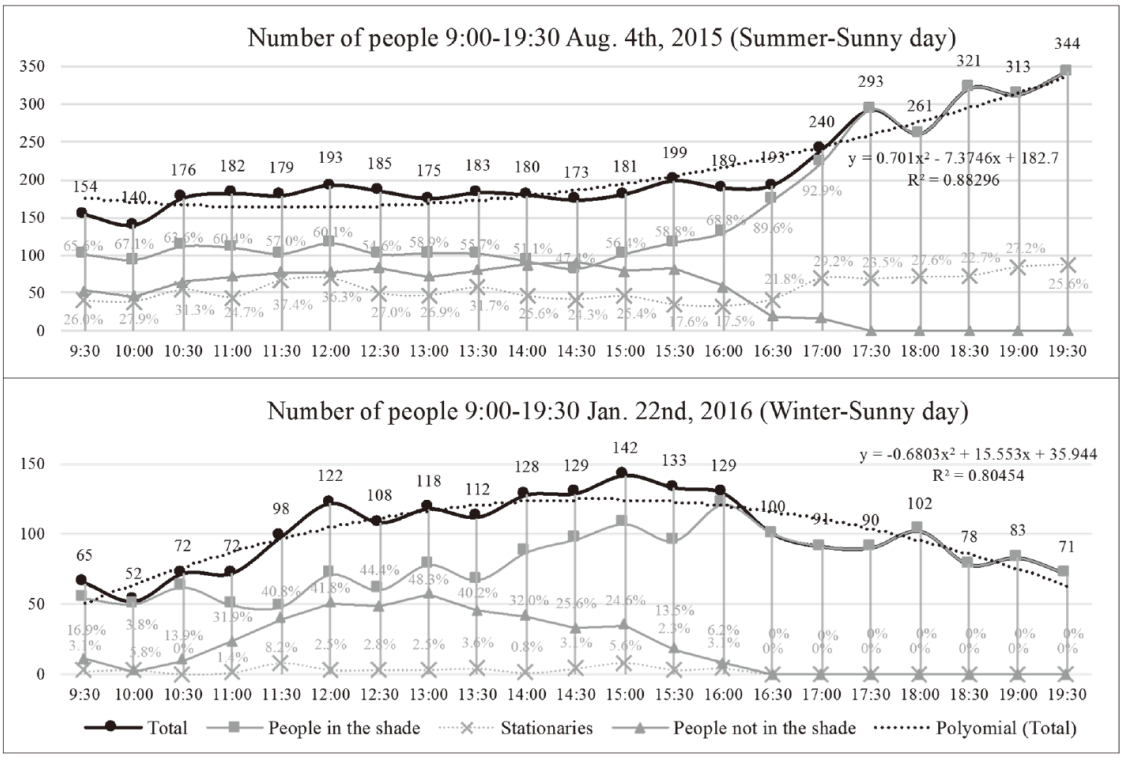

Figure 8. Number of people present in sunny day at research site (Aug. 4, 2015 and Jan. 22, 2016)

3.3 Microclimate Analysis at Each Measurement Point

Microclimate comparison among different areas and points were conducted. Based on different spatial characteristics, the results of microclimate are as the Fig.9. In summer and winter, the ambient temperature and humidity did not show large differences among each point. However, the relative humidity at north side where can get more sunlight was lower than other areas. Direct sunlight has the function of reducing humidity. Air-flow at center line was affected by the spatial forms more than edge sides. The highest mean air velocity in both summer and winter were found at the point No.14, where located at the narrowest place in canyon. The lowest mean air velocity was in No.5 located at building corner which can be realized as shelter from the wind.

Furthermore, the mean CSV show regularity as different microclimate. In summer and winter, the mean CSV distributions are just opposite to each other. In summer, the highest mean CSV was found at the east center line where located at the long shade and relatively narrow space with high air-flow. The lowest mean CSV was located at west center line named as unshaded and wide area where suffered relatively low air velocity. In winter, the north edge space with relatively lower air velocity and short shade got the highest mean CSV. The east center line with higher air velocity and longer shade got the lowest mean CSV. Consequently, different spatial forms will cause different microclimate conditions, thus affect the comfort level. The air velocity and shade situation are the two factors that easy to be affected by spatial form.

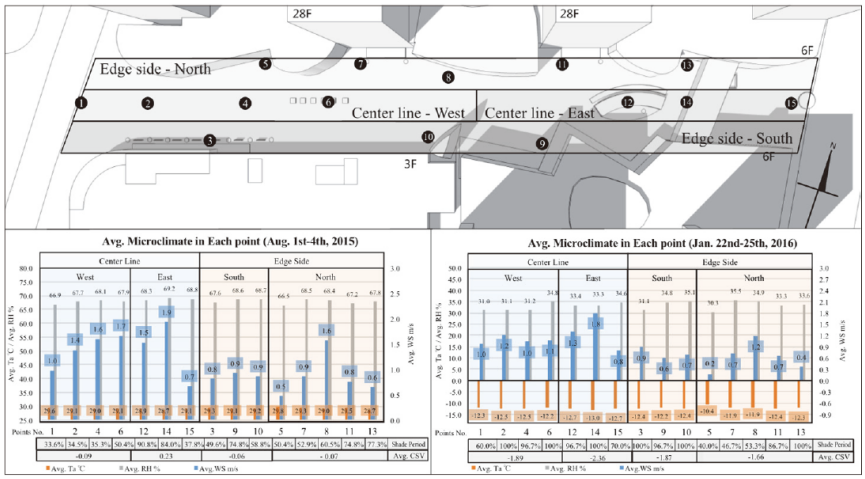

Figure 9. Mean microclimate data at each point with mean CSV for Shenyang, northern China

Two special points (Nos.5 and 14) with extreme microclimate were chosen to evaluate the microclimate factors difference during a continuous period (Aug. 1st-4th, 2015 in summer, Jan. 22nd-25th, 2016 in winter). These two points also had relatively exceptional Ta and RH. In Fig. 10, there are huge difference in air velocity and temperature between No.5 and No.14. Air velocity at No. 14 which is located at canyon "entrances" was higher than at Nos. 5 located at building corner. According to the previous study by H. Wu (1994), the skyway above the point No.14 can be seen as a diverter of air-flow. The wind pass through the skyway was separated into two parts. The area of air duct was decreased by the skyway. The air volume per unit area was increased. That caused the air velocity under the skyway to increase. The building corner at No.5 can resist the air-flow from the vertical direction. At the same time, it can also lead the air-flow from parallel direction to skim over the corner.

Differences in T_a between the highest point (No. 5) and lowest point (No. 14) vary with shade situations. The difference in temperature between these two points can reach 6.4°C in summer and 9.5°C in winter. In terms of their spatial characteristics, No. 5 is located at the north edge of the building and is exposed to sunlight and solar reflection from the glass building. On the contrary, No. 14 is under the skyway with almost no sunlight all day long; it is also far from the building's reflection. Therefore, people can feel higher CSV at No. 14 in summer, with lower ambient temperature, and lower CSV at No. 5 in winter.

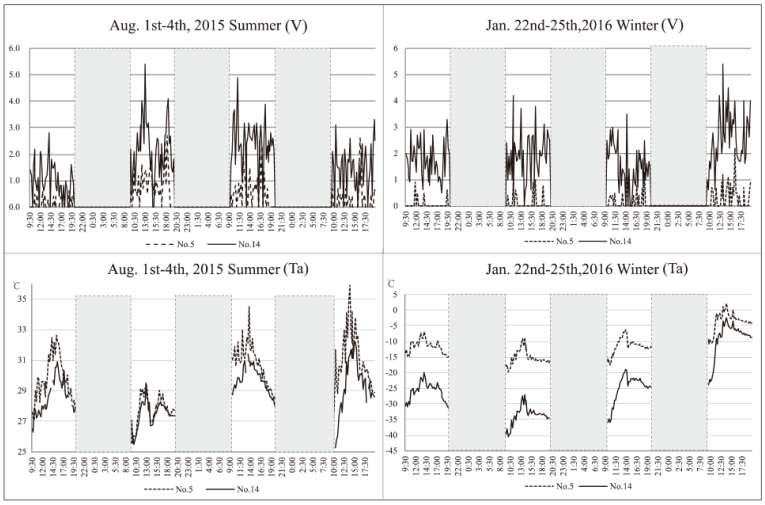

Figure 10. Air velocity and ambient temperature distributions at measurement points Nos. 5 and 14 in summer and winter

Consequently, because of the different spatial forms, there are huge differences on microclimate in the same place to affect comfort sensation.

Outdoor distributions of people influenced by shade and spatial forms was conducted in two clear days (Aug. 4, 2015 and Jan. 22, 2016) between summer and winter. On the basis of solar simulation and high-resolution photographs, the position of people was recorded every 30 minutes. Figs. 11 and 12 shows the analyses of position relationships with shade simulation results.

In summer, according to the results 3.3, the south side suffer higher CSV than north. The area in west centre line is not popular by pedestrians. Instead, as Fig.11 shows, the east side with long periods of shade, abundant seats and other facilities can gather more people than the west side. There are sufficient seats inside the shade at the Nos. 3, 9, 11 and 12, and there are also seats under vegetation which can provide shade at No. 6. Most of the stationaries will choose these places to stay. From the above, the necessary factors for the people who stay outside in summer are shade and rest facilities.

In winter, as shown in Fig.12, people distribute evenly. Shade and rest facilities do not affect the position distribution seriously. Meanwhile, a few of people who stay outside will choose sunlight place or the place related to their destinations, for example: the entrance of the supermarket or the shopping mall or the subway station. The rest facilities and shade are not the necessary factors of attracting people to stay or sit outside in winter.

Consequently, in summer, shade influences the overall distributions of people obviously. Rest facilities with sufficient shade also attract people. In winter, no strong relations were found between shade situation and distributions of people.

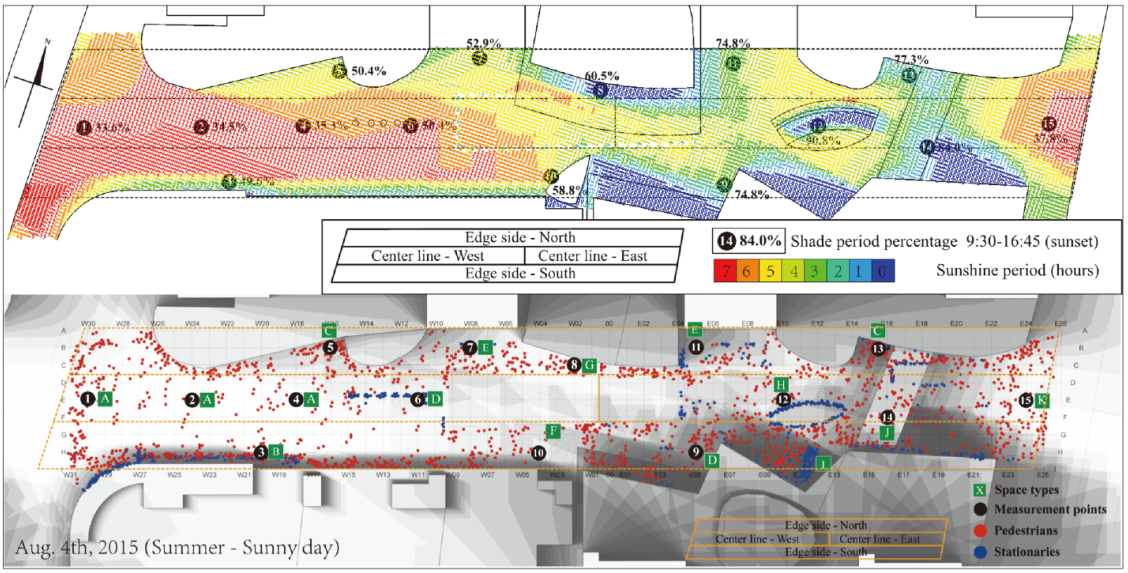

Figure 11. The position relationship with shade situation in summer

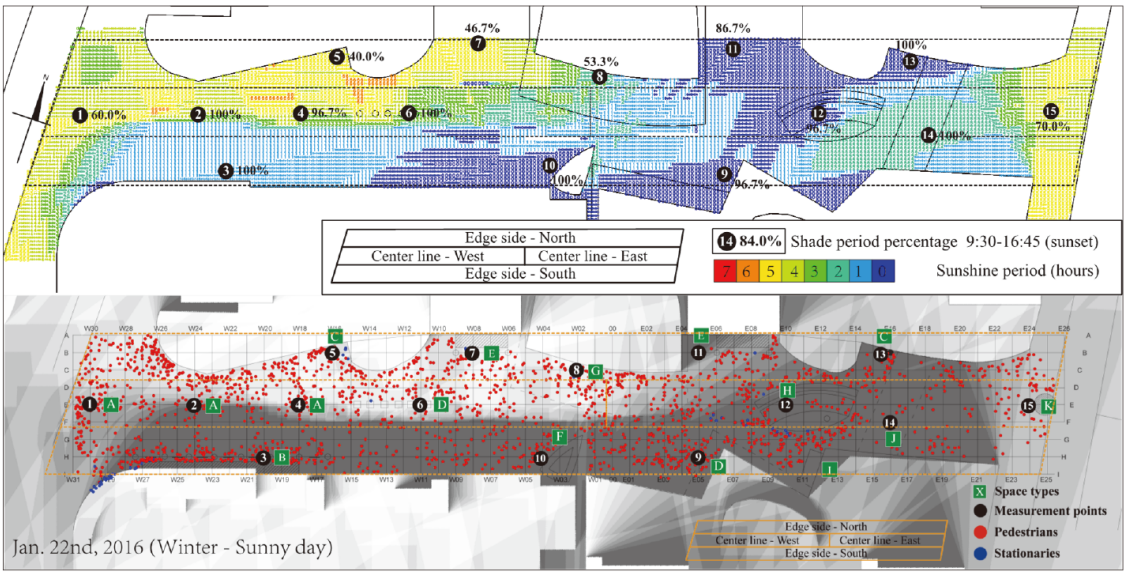

Figure 12. The position relationship with shade situation in winter

4. Conclusions

By using microclimate and human comfort as standards for environmental evaluation, this research conducted a field survey at a downtown pedestrian street both in hot summer and cold winter which have not been studied in the past. By analyzing how extreme weather situations influenced human behaviour and comfort, the study aimed to discover the microclimate associated with open space use, to support further open space design. The survey has demonstrated the following:

• Microclimate obviously affected people's comfort. In addition, the influence effect in summer and winter were distinct. No single parameter will affect the spatial comfort as a leading role. All the factors have come together on the comfort sensation.

• In summer, lower T_a, higher air velocity, RH and more shade brought higher CSV. 29.6°C of T_a, 1.1 m/s of air velocity, and 67% of RH were threshold values for whether the environment was comfortable or not. In winter, higher T_a, lower air velocity and less shade, caused higher CSV. −14.4°C of T_a, −16.5°C of WC, and 1.6 m/s of air velocity were environmental threshold values that can be accepted or not.

• The residents in Shenyang were more sensitive to hot season than cold season.

• Among all meteorological factors, change of T_a, RH, and shade situation were closely related to time and changed evenly. However, air velocity changed unevenly and significantly affected instantaneous comfort.

• Spatial form affected the shade situation and air velocity, and further affected comfort sensation.

• The human present is related to microclimate that change along with time, that is, in summer, afternoon before sunset (at about 16:30) was the most unpopular time, but after sunset, more people came outside. From lunchtime (12:00−13:00) to sunset at about 16:30 was the most attractive period for people in winter.

• Different spatial forms cause the differences of microclimate, thus affect comfort sensation. In summer, shade influences the overall distributions of people obviously. Rest facilities with sufficient shade also attract people. In winter, no strong relations were found between shade situation and distributions of people.

In such kind of city central open space suffering hot summer and cold winter, grasping the rules of the microclimate which affect the people's sensation and spatial behaviors can help the designers and planners to create more comfortable open space. By optimizing the spatial form, it is possible to change the wind environment and shade situation better. Meanwhile, understanding the time-microclimate rules, arranging the open space facilities in suitable time and season are important to raise the space utilization. From the conclusions above, densely populated open space design guidelines based on extreme microclimate and spatial behaviour are proposed:

• In hot season, attractive open space design should focus on rest facilities with shade and ventilation. In the

daytime, setting the broad-leaved vegetation and roofs on the widely open space can raise the comfort level. Adding rest facilities at the well-ventilated areas also can raise the environment comfort. Meanwhile, nightscape design should be especially considered.

• In cold season, the rest area should be arranged to combine well with relative behaviours around the buildings. Meanwhile, shelter from wind is a key point for a better winter environment. The design of the daytime environment, especially from noon to sunset, should be properly addressed.

Acknowledgments

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References

Andreou, E. (2013). Thermal comfort in outdoor spaces and urban canyon microclimate. *Renewable Energy, 55,* 182-188. https://doi.org/10.1016/j.renene.2012.12.040

Andreou, E. (2014). The effect of urban layout, street geometry and orientation on shading conditions in urban canyons in the Mediterranean. *Renewable Energy, 63,* 587-596. https://doi.org/10.1016/j.renene.2013.09.051

Andreou, E., & Axarli, K. (2012). Investigation of urban canyon microclimate in traditional and contemporary environment. Experimental investigation and parametric analysis. *Renewable Energy, 43,* 354-363. https://doi.org/10.1016/j.renene.2011.11.038

Blalock, H. M. (1972). *Social statistics.* New York: McGraw-Hill.

Bourbia, F., & Boucheriba, F. (2010). Impact of street design on urban microclimate for semi-arid climate (Constantine). *Renewable Energy, 35*(2), 343-347. https://doi.org/10.1016/j.renene.2009.07.017

Carr, S., Francis, M., Rivlin, L. G., & Stone, A. M. (1993). *Public space.* Cambridge, New York: Cambridge University Press.

China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. (1971-2014). *The database of climate standard daily value in Chinese international ground switching center* (cited 2009-2014 Jul., Aug., Dec., Jan., Feb.) [database on the Internet]. Retrieved from http://data.cma.cn/data/detail/dataCode/A.0029.0001.html

China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. (2005). *China Standard Weather Data for Analyzing Building Thermal Conditions.* Beijing: China Building Publishing House.

Chinese State Bureau of Technology Supervision (CSBTS) & Chinese Ministry of Construction. (1994). *GB50178 Standard of Climate Regionalization for Architecture.* Beijing: Standard Press of China.

Eliasson, I., Knez, I., Westerberg, U., Thorsson, S., & Lindberg, F. (2007). Climate and behavior in a Nordic city. *Landscape and Urban Planning, 82,* 72-84. http://dx.doi.org/10.1016/j.landurbplan.2007.01.020

Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate: designing the spaces between buildings.* New York: Routledge.

Gehl, J. (2011). *Life between buildings: using public space.* Washington, DC: Island Press.

Givoni, B. (1998). *Climate considerations in building and urban design.* New York: John Wiley & Sons.

Handbook, A. S. H. R. A. E. (2001). Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 111.*

Hoppe, P. (1999). The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology, 43*(2), 71-75. https://doi.org/10.1007/s004840050118

Hwang, R. L., Lin, T. P., & Matzarakis, A. (2011). Seasonal effects of urban street shading on long-term outdoor thermal comfort. *Building and Environment, 46*(4), 863-870. https://doi.org/10.1016/j.buildenv.2010.10.017

Lai, D., Guo, D., Hou, Y., Lin, C., & Chen, Q. (2014). Studies of outdoor thermal comfort in northern China. *Building and Environment, 77,* 110-118. https://doi.org/10.1016/j.buildenv.2014.03.026

Li, S. (1994). User's behaviour of small urban spaces in winter and marginal seasons. *Architecture and Behaviour, 10,* 95-109.

Lin, T. P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology, 52*(4), 281-290. https://doi.org/10.1007/s00484-007-0122-7

Lin, T. P., Matzarakis, A., & Hwang, R. L. (2010). Shading effect on long-term outdoor thermal comfort. *Building and Environment, 45*(1), 213-221. https://doi.org/10.1016/j.buildenv.2009.06.002

Marcus, C. C., & Francis, C. (Eds.). (1997). *People places: Design guidelines for urban open space.* New York: John Wiley & Sons.

Maruani, T., & Amit-Cohen, I. (2007). Open space planning models: A review of approaches and methods. *Landscape and urban planning, 81*(1), 1-13. http://dx.doi.org/10.1016/j.landurbplan.2007.01.003

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International journal of biometeorology, 51*(4), 323-334. https://doi.org/10.1007/s00484-006-0061-8

Mayer, H., & Hoppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and applied climatology, 38*(1), 43-49. https://doi.org/10.1007/BF00866252

Meng, X. W., & Setoguchi, T. (2010). Development of Urban Design Guidelines with Wind Tunnel Simulations for Downtown Districts in Winter Cities. *Journal of Asian Architecture and Building Engineering, 9*(2), 355-362. https://doi.org/10.3130/jaabe.9.355

Ministry of Housing and Urban-Rural Development of the PRC(MOHURD). (1994) *Chinese standard for assessment parameters of sunlight on building GB/T50947- 2014.* Beijing: Standard Press of China.

Nikolopoulou, M., & Lykoudis, S. (2007). Use of outdoor spaces and microclimate in a Mediterranean urban area. *Building and Environment, 42*(10), 3691-3707. http://dx.doi.org/10.1016/j.buildenv.2006.09.008

Nikolopoulou, M., Baker, N., & Steemers, K. (2001). Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar energy, 70*(3), 227-235. https://doi.org/10.1016/S0038-092X(00)00093-1

Nunez, M., & Oke, T. R. (1977) The energy balance of an urban canyon. *Journal of Applied Meteorology, 16*, 11-19. https://doi.org/10.1175/1520-0450(1977)016<0011:TEBOAU>2.0.CO;2

Oliveira, S., & Andrade, H. (2007). An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon. *International Journal of Biometeorology, 52*(1), 69-84. https://doi.org/10.1007/s00484-007-0100-0

Setoguchi, T. (2004). Efficiencies of infill developments against snow problem in winter cities-the snow simulations for desirable block designs using wind tunnel. *Journal of Asian Architecture and Building Engineering, 3*(2), 335-340. https://doi.org/10.3130/jaabe.3.335

Setoguchi, T. (2008). New urban design approaches with snow simulations for cold and snowy cities. *Journal of Asian Architecture and Building Engineering, 7*(1), 93-99. https://doi.org/10.3130/jaabe.7.93

Setoguchi, T. (2009) The development of urban design planning process linking with snow and wind environmental assessments on the urban complex redevelopment project in snowy and cold cities, *J. Archit. plan., AIJ, 74*(642), 1777-1786.

Setoguchi, T., & Tsutsumi, T. (2007). Snow and wind environmental assessment on the public space comparing high-rise and medium-rise building blocks using the wind tunnel simulation. *Journal of Architecture and Planning (Transactions of AIJ),* (614), 167-174.

Shahrestani, M., Yao, R., Luo, Z., Turkbeyler, E., & Davies, H. (2015). A field study of urban microclimates in London. *Renewable Energy, 73,* 3-9. https://doi.org/10.1016/j.renene.2014.05.061

Shimazaki, Y., Yoshida, A., Suzuki, R., Kawabata, T., Imai, D., & Kinoshita, S. (2011). Application of human thermal load into unsteady condition for improvement of outdoor thermal comfort. *Building and Environment, 46*(8), 1716-1724. http://dx.doi.org/10.1016/j.buildenv.2011.02.013

Spagnolo, J., & De Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and environment, 38*(5), 721-738. http://dx.doi.org/10.1016/S0360-1323(02)00209-3

Tanabe, S. I. (1988). *Thermal Comfort Requirements in Japan* (Doctoral dissertation) Waseda University, Tokyo, Japan.

The National Weather Service (NWS). (2011). *The NWS Wind Chill Temperature (WCT) index* [database on the Internet]. MD (US). Retrieved from http://www.nws.noaa.gov/om/cold/wind-chill.shtml

Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., & Lim, E.-M. (2007). Thermal comfort and outdoor activity in Japanese urban public places. *Environment and Behavior, 39,* 660_684. http://dx.doi.org/10.1177/0013916506294937

Thorsson, S., Lindberg, F., Eliasson, I., & Holmer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International journal of climatology, 27*(14), 1983-1993. http://dx.doi.org/10.1002/joc.1537

VDI. (1998). Methods for human biometeorological evaluation of climate and air quality for the urban and regional planning. Part I: Climate. *VDI guideline 3787, Part 2,* Beuth, Berlin, Germany.

Watanabe, N., Setoguchi, T., Sato, K., & Tsutsumi, T. (2016). New city block design approaches incorporating environmental assessment for downtown districts in cities with severe winter climates. *Journal of Asian Architecture and Building Engineering, 15*(3), 455-462. https://doi.org/10.3130/jaabe.15.455

Wu, H. (1994). *Pedestrian-level wind environment around buildings* (Doctoral dissertation). Concordia University, Montreal, Quebec, Canada

Zhang, H. Ch., & Peng, X. L. (2008). Mold Vigor Block: Shenyang Zhongjie Commercial Pedestrian Street User-friendly Research Analysis. *Modern Urban Research, 23*(12), 29-37.

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Optimization Design of Open Spaces Based on Wind Tunnel and CFD Simulation: Case Study of a Street Canyon in Northern China

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Abstract: Airflow in open spaces can significantly affect spatial quality. Therefore, according to the type of building structures, the airflow also has different forms. Studies have been conducted on the relation between airflow and pedestrian comfort; however, only few of them have focused on comprehensive urban planning that considers different weather conditions and people's ability to adapt. This research focuses on the differences in wind conditions caused by different spatial forms in different seasons. On the basis of a field survey in both summer and winter in a public open space, evaluation standards developed from environmental meteorological data and public feedback were used to evaluate simulation results. Next, several assumptions about canyon orientation and building types were proposed. Wind tunnel and CFD (computational fluid dynamics) simulations were conducted to evaluate the assumptions. The results showed that the canyon orientation significantly affected overall wind conditions and different building structures affected airflow. This research also provides a method to evaluate urban areas that have complicated wind environments.

Key words: Urban form, outdoor comfort, open space, wind tunnel simulation, optimization design.

1. Introduction

Public open spaces are important in cities [1], the environmental characteristics of which are determined by the climatic conditions. Therefore, to ensure practicable and usable public open spaces, designs must be based on the climate in order to reduce climatic effects and improve and enhance comfort [2].

Research on open spaces in seasonal cities requires a consideration of the temperature differences between summer and winter. In particular, as cities in colder regions have longer winters and shorter summers, the people in these climates, such as Northern China, Russia, Sweden, and southern Argentina, are better able to cope with the cold than people from other temperate regions; consequently, the environmental evaluation standards need to be suited to the region under investigation.

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Most wind comfort environmental research to date has been based on discrete points rather than spatial dimensions [3]. On the basis of research by Verkaik, Willemsen and Wisse, NEN8100 and NPR 6097 were developed as standards and guidelines for measuring wind comfort [4-11]. From research into pedestrian wind comfort, standards were established for threshold values based on hourly average wind speed (*UTHR* = 5 m/s). Isyumov and Davenport, Lawson, and Melbournealso designed wind comfort criteria on the basis of wind flow patterns [12-14]. However, these have generally referred to the mechanical effect of wind on pedestrian wind comfort and have seldom included spatial considerations [7]. Janssen compared the above four criteria types using a specific campus case and found that when used in complicated urban areas, there were large differences in the results, indicating that they were not useful as design guidelines [15]. Some qualitative research has focused on the wind effect on people or buildings; however,

these did not consider other factors such as air temperature, relative humidity, solar radiation, individual differences [15], specific environmental, or climatic characteristics, or any spatial details.

Other applied research has focused on thermal comfort and urban forms [16-22]; however, few considered wind speed as a high priority factor for thermal comfort or focused specifically on cold regions or low temperature environments. From the characteristics of the outdoor environment, the main factors affecting people's comfort have been identified as air temperature, solar radiation, relative humidity, air velocity, activities, clothing, and individual differences [23]. In a man-made environment, the following factors can be used to control comfort: solar radiation, which is affected by building shade [24, 17], ventilation caused by the differences in spatial forms, and the adaptability and differences in the people using the public space [25].

According to a field survey in both summer and winter in a specific public open space as well as environmental meteorological data, this research focuses, in particular, on the environmental wind effects of different spatial forms. Evaluation standards developed from meteorological data and feedback analysis were used for the simulation research.

On the basis of the prevailing air velocity and directions in both summer and winter in this area, a wind tunnel simulation was conducted, the results from which informed a proposal for optimum street alignments and building types. By analyzing the results, the reasons for the wind changes in the area were found.

CFD (computational fluid dynamics) simulation was also used for the wind tunnel simulation to check the wind paths; however, as the reliability and accuracy of CFD simulation have been questioned [26], in this study, the CFD simulation was set with the same conditions as the wind tunnel simulation only to check the wind path as a reference for the wind tunnel simulation. Using the above research design, this paper developed design guidelines and research methods for public spaces in colder climates.

2. Methods and Materials

A field survey that analyzed the relation between air velocity and wind comfort level was conducted to determine the comfort air velocity threshold. Depending on the average annual air velocity and the prevailing wind directions during the survey period, a wind tunnel simulation was then conducted using different urban street alignments and building types with the aim of improving the wind environment. A CFD simulation was also used to check the details.

2.1 Area Description

The pedestrian street in this study was in the downtown area of Shenyang, China (41°48′01.11″ N, 123°27′49.33″ E), a winter city in northeastern China. The general climate in Shenyang is temperate monsoon, with four distinct seasons (2009-2004). Depending on the climate data from China Meteorological Administration, the annual average temperature change from 2009 to 2014 is about 60 °C. Because of these climatic characteristics, there are different wind conditions in summer and winter, with the prevailing wind direction and the annual average air velocity in summer being SSW and 2.5 m/s, and in winter being ENE and 2.0 m/s [27].

The research area, which is located between high, density commercial buildings, is one of the most popular public open spaces in the city center (Fig. 1). However, because of the complicated building structures, this area suffers from varying microclimates throughout the day. A target area model at a scale of 1:500, which included pedestrian streets and surrounding buildings, was developed for both the wind tunnel and the CFD simulations.

2.2 Field Survey

The field survey was carried out during extreme temperatures in summer and winter. The microclimate

Fig. 1 Target area and surrounding buildings.

situation and the corresponding CSV (comfort sensation votes), which were the integrated reactions of pedestrians to the microclimates [28] (see Table 1), were analyzed to determine the acceptable air velocity level and threshold.

Five years (2009-2014) of climate data were analyzed (Fig. 2) [29]; summer from July to September and winter from December to February, with Jul. 28-Aug. 9, 2015 (12 days in summer) and Jan. 15-29 (15 days in winter), 2016 being chosen as representative data periods for the hottest part of summer and coldest part of winter.

Table 1 Scale used by participants for subjective responses regarding comfort during field surveys.

Value	Comfort sensation vote
-3	Very uncomfortable
-2	Uncomfortable andunacceptable
-1	Uncomfortable, but acceptable
0	Neutral
1	Slightly comfortable
2	Comfortable
3	Very comfortable

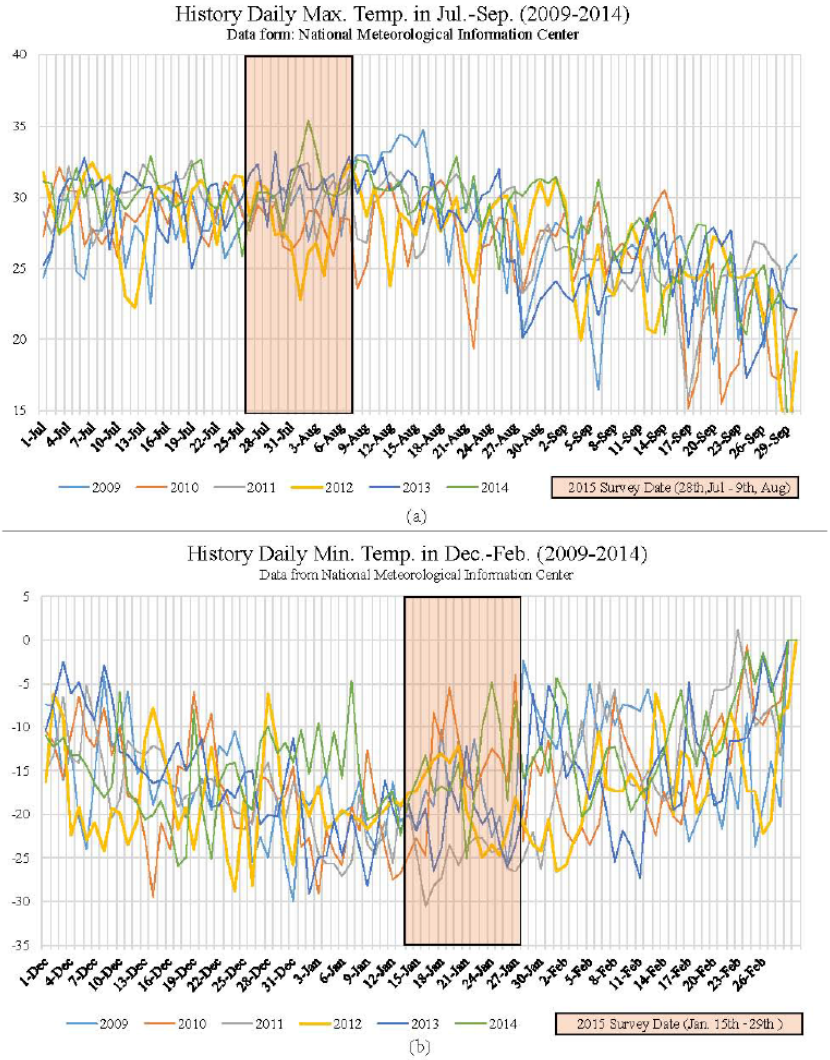


Fig. 2 Historical daily maximum and minimum temperatures from: (a) July to September (summer); and (b) December to February (winter) 2009-2014.

Note: Weather station No. 54342 Coordinates: 41°44 N, 123°31 E, altitude = 49 m.

On the basis of position and space, 15 sampling points were chosen for the collection of microclimate and comfort data every 15 minutes from 9:30 to 20:00 on the survey days (see Fig. 3). The microclimate data included ambient temperature (*Ta*) and air velocity (*v*). (see Table 2).

2.3 Wind Tunnel Simulation

Wind tunnel simulations were conducted several times for the original case and the redesigned cases for both summer and winter. The research area model and its surrounding buildings were built of Styrofoam at a scale of 1 to 500. The research area comprised a circle with a diameter of 900 m (Fig. 4). An atmospheric boundary layer wind tunnelwith a 1.8 m by 1.8 m cross section and a 20 m/s maximum air velocity was used for this research, as shown in Fig. 5.

Depending on the relations between the positions, 93 measurement points were determined, as shown in Fig. 3, at which 93 thermistor anemometers (Kanomax Climomaster model 0965-03) were set at the height of 3 mm on the model to measure the air velocity every second, which was calculated at 1.5 m, which was determined as the average head height of Chinese in a real situation [30]. A reference anemometer (Kanomax Climomaster model 0965-21) (Fig. 4) was set in front of the model at the height of 0.4 m, which was equal to 200 m, so as not to affect the surrounding buildings, to calculate the real air velocity from the vertical air velocity profiles, which could be calculated using the power-law at an exponent of 0.27 [31] (Fig. 6). Depending on the annual mean air velocity, the air velocity at each measurement points was calculated, as follows [32]:

$$\frac{V_w}{V_r} = \left(\frac{H_w}{H_R}\right)^{\alpha} \quad (1)$$

where:

V_w = air velocity in wind tunnel at the height of the weather station;

V_R = air velocity at the height of the reference anemometer;

H_w = height of the weather station (No. 54342 41°44′ N, 123°27′ E, H_w = 44.7 m [27]);

H_R = height of the reference anemometer (200 m);

α = exponential coefficient (0.27).

$$\frac{V_{1.5}}{V_w} = \frac{V_{r1.5}}{V_{rw}} \quad (2)$$

where:

$V_{1.5}$ = air velocity at a height of 1.5 m in the wind tunnel;

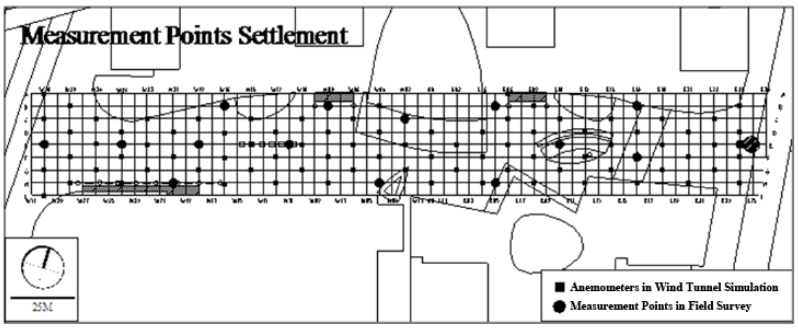


Fig. 3 Anemometers in wind tunnel and measurement points in field survey.

Table 2 Measurement factors for micrometeorological parameters, Shenyang, Northern China.

Parameter	Accuracy	Resolution	Range	Setting place
Air velocity (*v*)	Larger than 3% of reading, least significant digit	0.1 m/s	0.6-40.0 m/s	1.5 m as the average height of the head
Ambient temperature (*Ta*)	0.5 °C	0.1 °C	(-)29.0-70.0 °C	

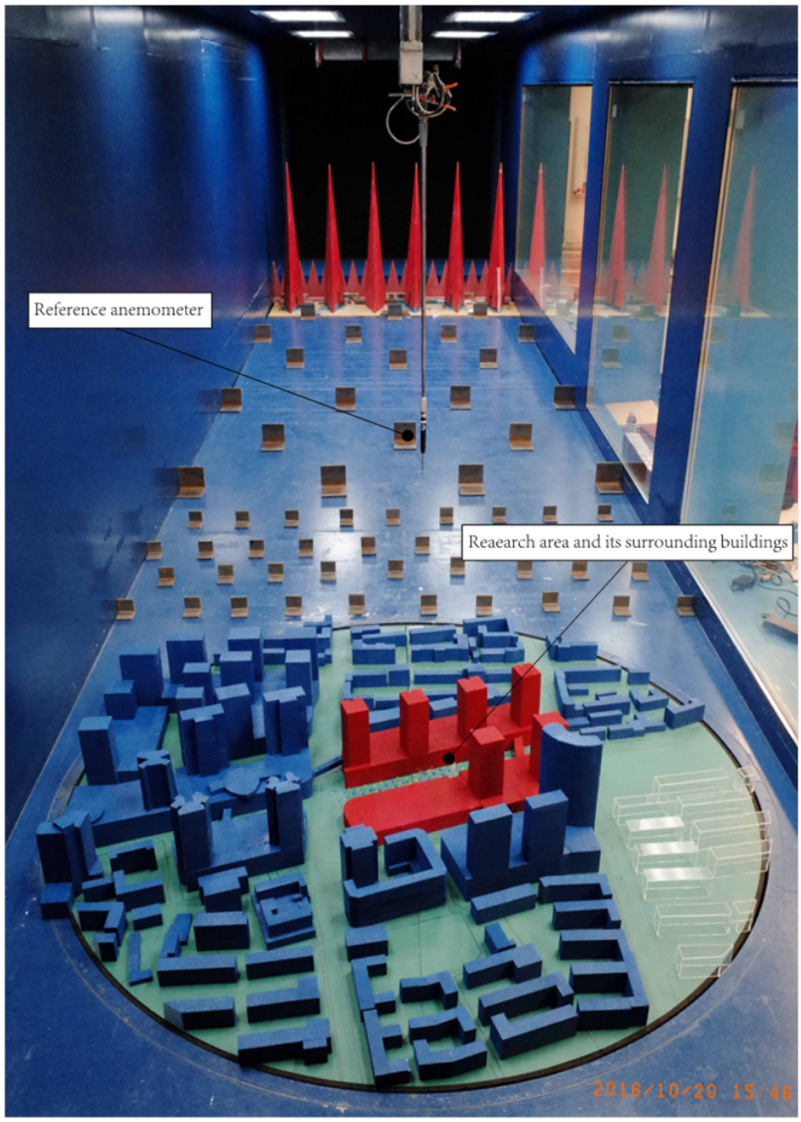


Fig. 4 Research model in the wind tunnel.

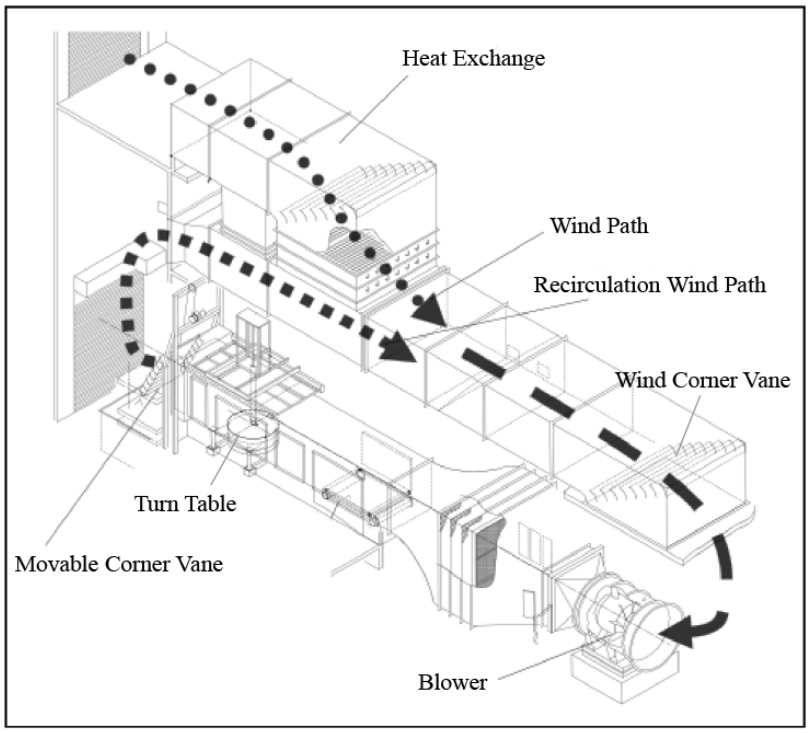


Fig. 5 Environmental wind tunnel used in this research [33].

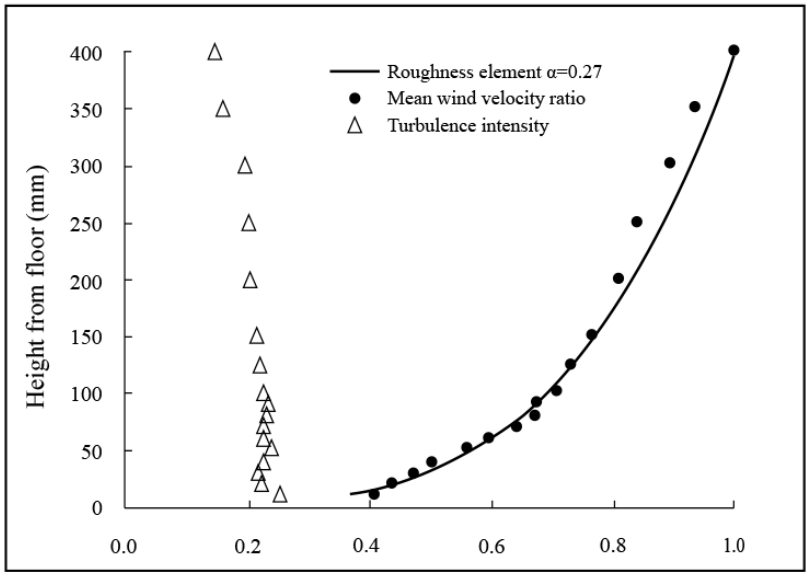


Fig. 6 Vertical air velocity profiles [34].

V_w = air velocity at the height of the weather station in the wind tunnel;

$V_{r1.5}$ = air velocity at a height of 1.5 m in the real situation;

V_{rw} = annual average air velocity from the weather station (summer 2.5 m/s SSW, winter 2.0 m/s ENE)

[27].

2.4 CFD Simulation

The CFD simulation was conducted using the software PHOENICS developed by Cham Ltd. to simulate the airflow under the same situations with the wind tunnel. Using the CFD simulation, the detailed wind pressure and air flow path distributions were detected.

A Cartesian grid system across the whole zone was used to divide the research area and surrounding area in consideration of the research area boundaries. The dimensions 900 (x) × 900 (y) × 900 (z) m were adopted with 233 (x-direction) × 225 (y-direction) × 250 (z-direction) cells at each axis. The grids were changed gradually from fine close the central area to coarse nearer the outer boundary. A 1.2 expansion rate was maintained for the grid adjustment. The standard k-ε turbulent model with 5,000 iterations were applied for the CFD simulation.

3. Results

3.1 Wind Comfort in Summer and Winter

The field survey results gave general information for the measured ambient temperature and air velocity, as shown in Table 3; the temperature range was 24.4-35.9 °C (summer) and (-)21.6-2.2 °C (winter), and the air velocity range was 0-7.1 m/s (summer) and 0-4.8 m/s (winter).

Acceptable airflow and thresholds were analyzed by calculating the mean CSV of pedestrians for every 0.1 unit of air velocity. During the survey days in summer and winter, more than 2,500 groups of effective data were recorded. As Fig. 7 shows, the CSV increased with an increasing air velocity in summer and decreased with an increasing air velocity in winter. Linear regression was conducted as follows:

Summer:

$$y = 0.2459x - 0.275 \quad (R^2 = 0.67066) \tag{3}$$

Winter:

$$y = -0.1346x - 1.7746 \quad (R^2 = 0.37224) \tag{4}$$

The regression coefficients were 0.2459 in summer and -0.1346 in winter that indicated that the residents in Shenyang were more sensitive to the summer wind. With the scale for subjective responses about comfort sensation in Table 1, the neutral air velocity in summer is 1.12m/s; however, in winter, all CSVs were below -1, indicating that the microclimate air velocity was unable to satisfy the neutral level. When the air velocity was higher than 1.67 m/s, it was found to be unacceptable.

The above results indicated that a higher air velocity in summer and taking shelter from the wind in winter would improve comfort levels.

3.2 Wind Situation for the Original Survey Area from the Wind Tunnel Simulation

The wind tunnel simulation results are shown in Fig. 8, from which it can be seen that the distribution of air velocity in both summer and winter were roughly the same. Airflow in the western area was lower than in the central and eastern areas. In summer, there was a dark red area in the center and an orange area in the west. The CSV analysis showed that the comfort level in this area was higher than in the green and blue areas in which the air velocity was lower than 1.12 m/s. In winter, there were three parts showing orange, which were considered to be unacceptable areas. The green and blue areas were better than the yellow and orange

Table 3 General information for the microclimate data in the central open space, Shenyang, Northern China

Season	Data		Avg.	Max.	Min.
Summer	Jul.-Aug., 2015	*Ta* (°C)	29	35.9	24.7
	(*n* = 2,520)	*V* (m/s)	1.2	7.1	0
Winter	Jan., 2016	*Ta* (°C)	–21.6	2.2	–21.6
	(*n* = 2,520)	*V* (m/s)	1	4.8	0

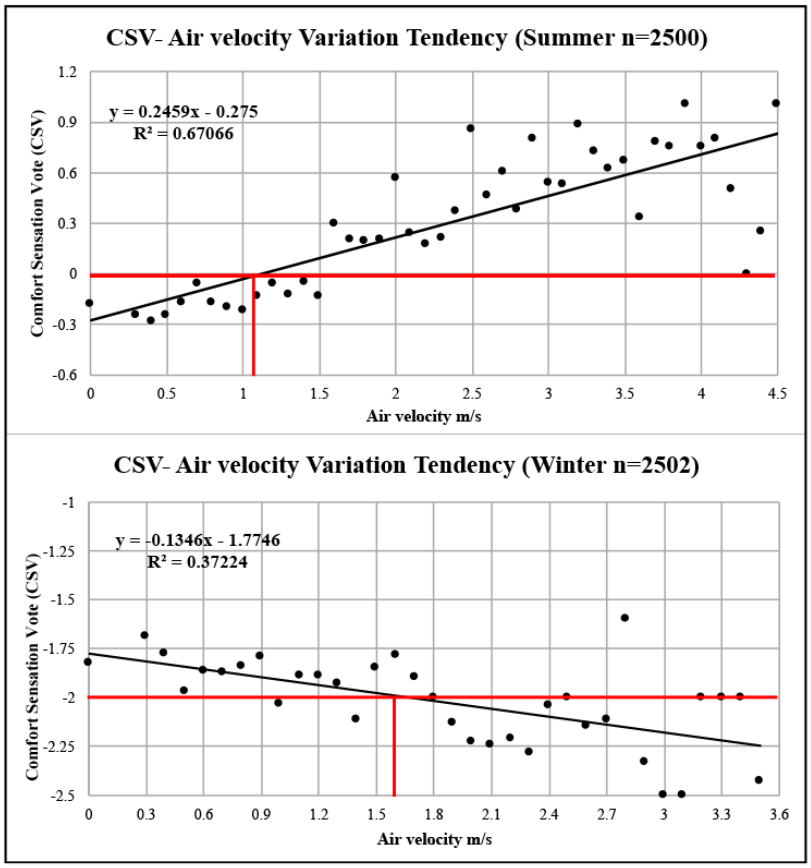


Fig. 7 CSV—air velocity variation tendency.

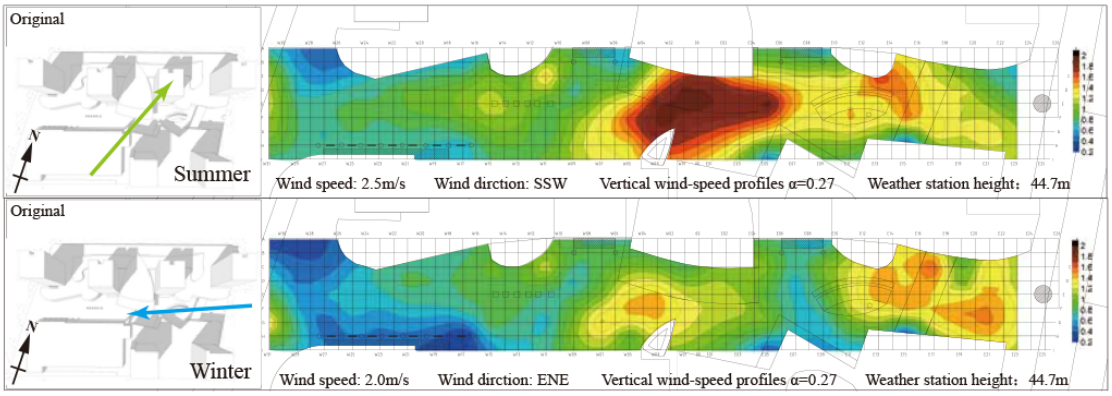


Fig. 8 Wind situation of the original survey area by wind tunnel simulation.

area for people outside.

3.3 Wind Situation Affected by Canyon Orientation

Previous research has found that the wind attenuation of an individual space is affected by canyon aspect ratios and orientations [35]. Fig. 9 shows that when the airflow was parallel, the attenuation factors for the four cases with different aspect ratios were higher than when the airflow was perpendicular.

As the prevailing wind directions were different between summer and winter, there were also fixed angles between the wind direction and the street alignment. Two assumptions are proposed for changing the canyon orientation to satisfy the following situations:

Streets aligned parallel to the summer wind direction have a higher air velocity in summer.

Streets aligned perpendicular to the winter wind direction have less strong wind in winter.

As shown in Fig. 10, rotating the street counterclockwise (CCW) 22.5° would make the summer wind parallel to the street. Rotating the street clockwise 90° would make the winter wind perpendicular to the street.

As Fig. 11 shows, the wind in the rotated streets changed significantly. This illustrates that changing the angles between the streets and the prevailing wind direction can radically change the wind situation. However, the CCW 22.5° could decrease the air velocity area in summer and increase the air velocity in the central and western areas in the winter, which, based on the results, would not meet the requirements for a comfortable wind environment.

In Fig. 12, when the street was rotated clockwise (CW) 90°, the wind situation in both summer and winter obviously changed. The street had higher air velocity in summer and lower air velocity in winter, thereby satisfying the requirements for a comfortable wind environment in both seasons; however, for a northern city such as Shenyang, because of its extreme winter temperatures, reducing the wind in winter would be more important than increasing the air velocity in summer. Therefore, prioritizing the long winter period by making the winter wind direction perpendicular to the main street would significantly improve wind comfort.

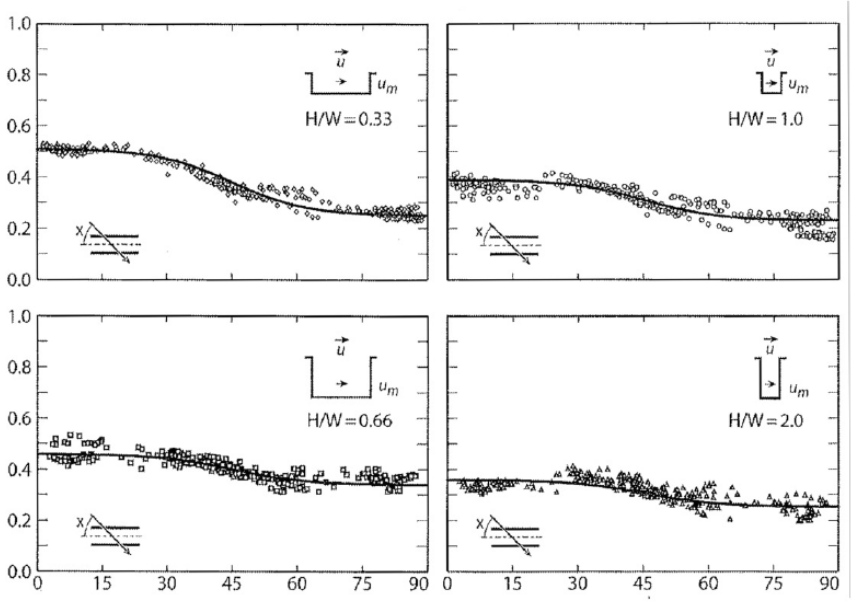
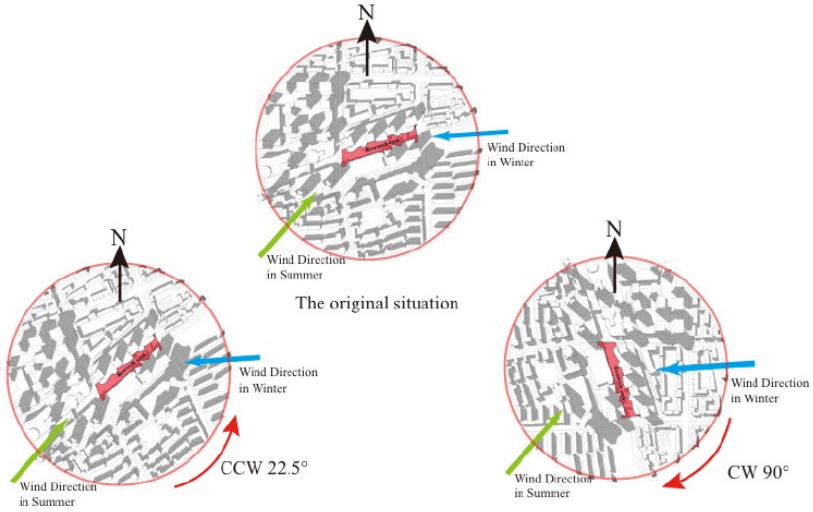


Fig. 9 Correlation between wind attenuation and angle of attack for street canyons of varying aspect ratios [35].



a. The street papallel to summer wind by rotating the street on CCW 22.5°

b. The street perpendicular to winter wind by rotating the street on CW 90°.

Fig. 10 Changing the canyon orientation.

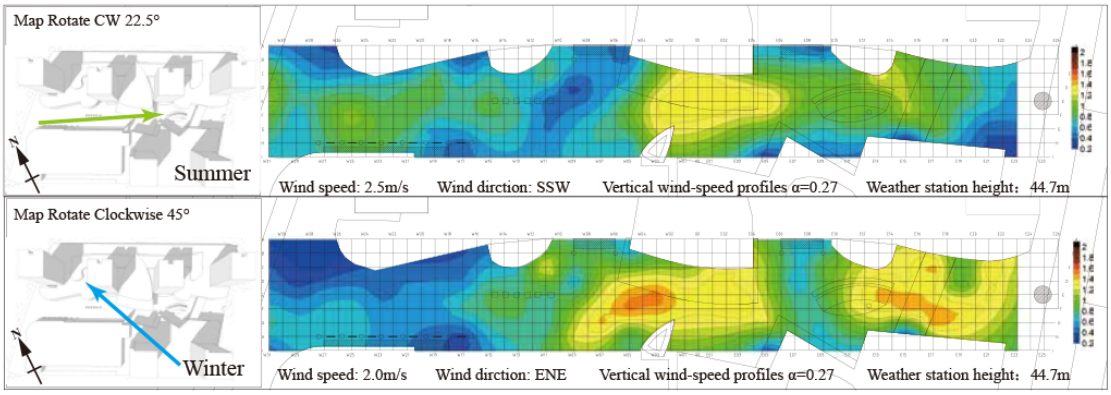


Fig. 11 Wind situation of the survey area by rotating CCW 22.5°.

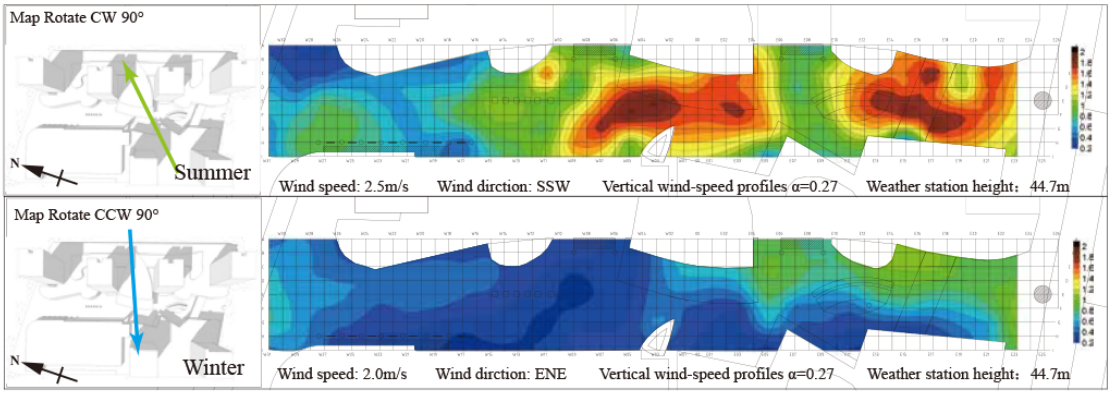


Fig. 12 Wind situation in the survey area by rotating CW 90°.

3.3 Wind Situation by Changing Building Types

On the basis of the simulation results from the original street, several hypotheses were made for the different building types without changing the building floor area ratio. Wind tunnel simulations were conducted on these cases to determine the impact of building type change on wind flow.

As shown in Fig. 13, high-rise buildings, podium buildings, and building details' propositions were considered. A1-3 were for high-rise buildings: in A1, two high-rise buildings were set back to determine the impact of the high-rise building position on wind flow; in A2, the high-rise buildings were changed to a plate type to determine the impact of building shape on wind flow; and in A3, the high-rise buildings were shortened and compacted while meeting the same sunshine conditions to determine the impact of building density on wind flow at the pedestrian level.

B1 and B2 were used for podium buildings to determine whether special building shapes or building structures affected wind flow: in B1, the skyway connecting the two main podium buildings was removed to determine whether the skyway affected the wind flow at the street entrance; and in B2, two-side street entrances were broadened by smoothing the irregular building edges, and the alleyway on the south side between the two main buildings was closed off, from which B2-1 was proposed, in which all irregular podium buildings were smoothed and the two podium buildings on the south side were set at the same height. As Fig. 14 shows, comparisons of wind tunnel simulation results between the original situation and each proposed building type were conducted.

In summer, the general wind flow distributions in A1-3, B1, and B2 did not change from the original layout. However, in B2-1, a high air velocity area was found in the central and eastern areas and at the same time, there was a higher air velocity on the west side. Therefore, it was concluded that regular building edges force the wind to blow rapidly and consistently. In detail, in A3, the eastern area had lower air velocity and the central area had higher air velocity than the original. In B1, when the skyway was removed, the high wind area in the east was smaller and more separated.

In winter, the general distributions for the wind in A1, A3, B1, and B2 did not change from the original. In B2-1, as with summer, the air velocity in all areas was higher; however, the highest air velocity was lower

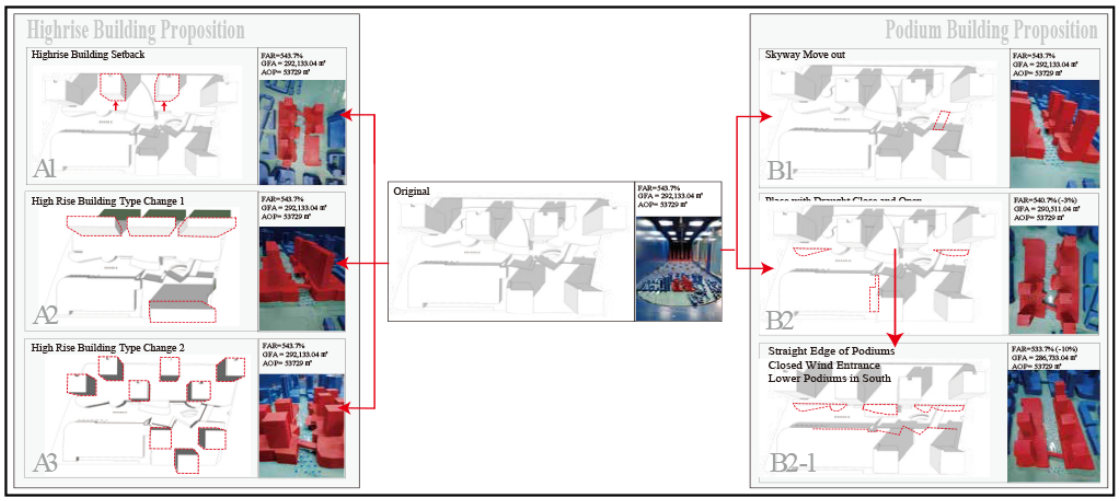


Fig. 13 Building type propositions.

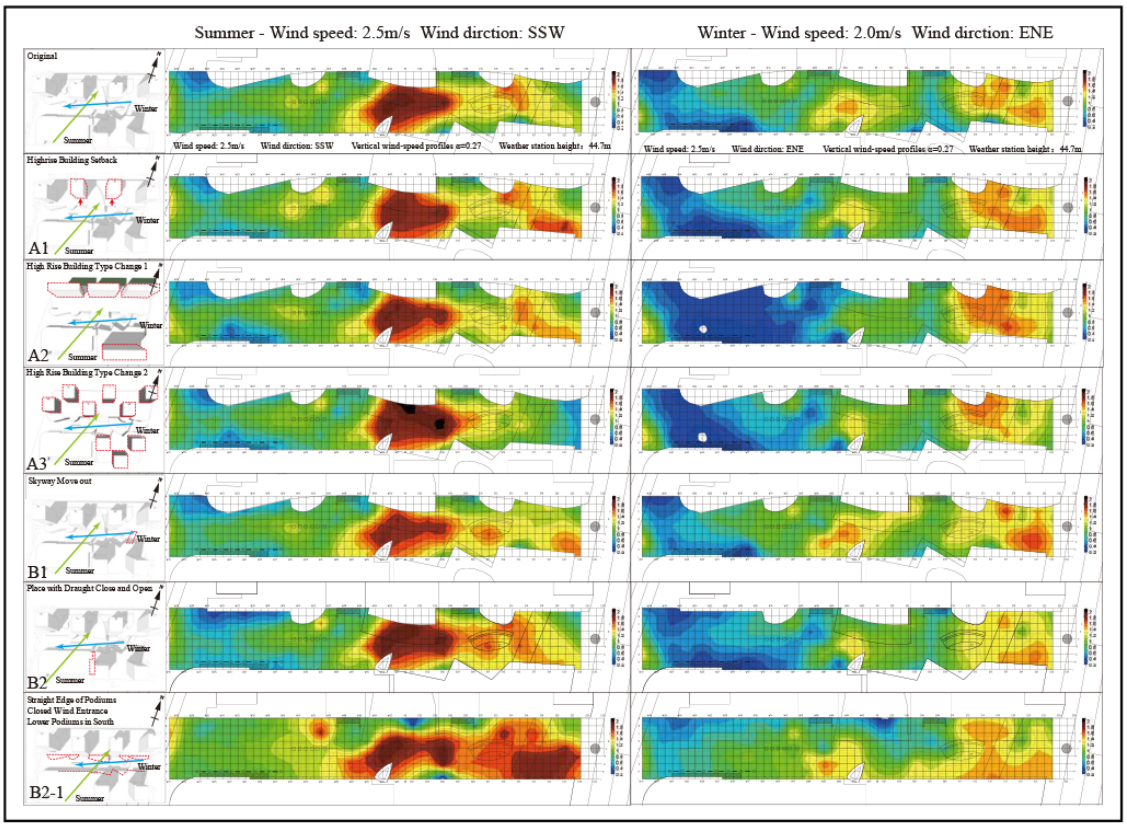


Fig. 14 Wind flow at the survey area when changing building types.

than in other cases. In A-2, there was no higher air velocity in the central area and the western area had a lower air velocity than the original. In detail, in B-2, the eastern area had a lower air velocity than the original case and in A-3, the air velocity in the central and western areas were lower than the original.

In summary, it was concluded that changing the building type affected wind flows. For lower air velocity in winter and higher air velocity in summer, A2 and B2-1 proved to be the most effective.

3.4 Wind Situation by Changing Building Type and Rotating the Urban Street

Further hypotheses were proposed to clarify the optimal case. By rotating A2 and B2-1 CW 90°, wind tunnel simulations were again conducted.

As shown in Fig. 15, in summer, for A2, the high air velocity areas on the eastern and western sides increased. The high air velocity area on the eastern side was larger than in the original case and the highest air velocity area was also larger; however, the central area air velocity was lower than in the original case. In B2-1, the air velocity distribution was almost the same as the original case and the overall air velocity was higher than the original case. The highest air velocity area in both the central and eastern areas increased.

In winter, the wind flow distribution in A2 was similar to the original case, but the air velocity in the eastern and western entrances to the square significantly increased. In B2-1, the low air velocity area was larger than in the original case, but there was no high air velocity area. In summary, by changing the building types and rotating the urban street, B2-1 achieved an optimum result.

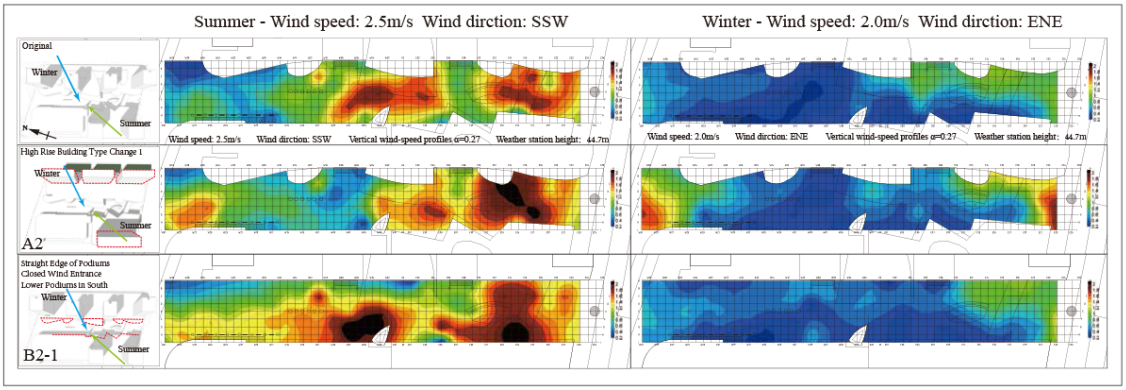


Fig. 15 Wind situation by changing the building types and changing the canyon orientation.

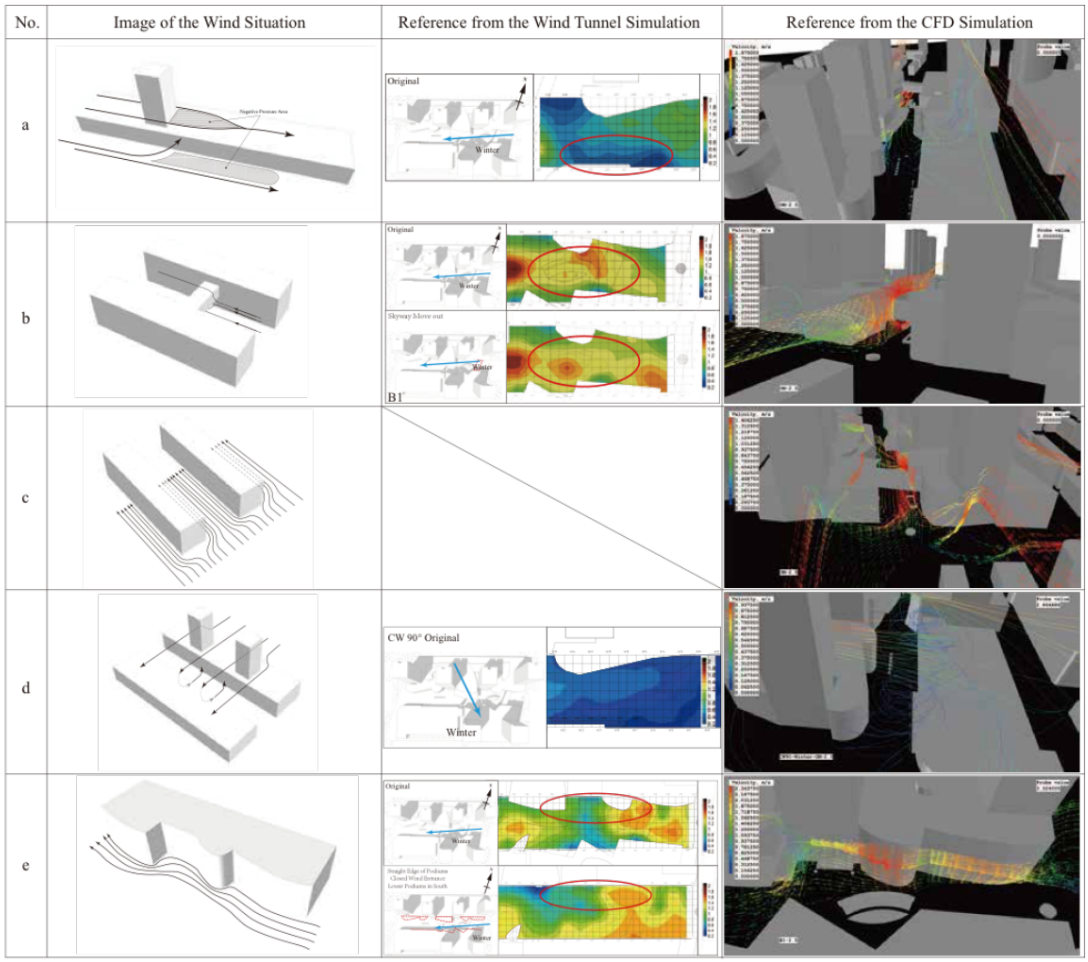


Fig. 16 Schematic of wind flow.

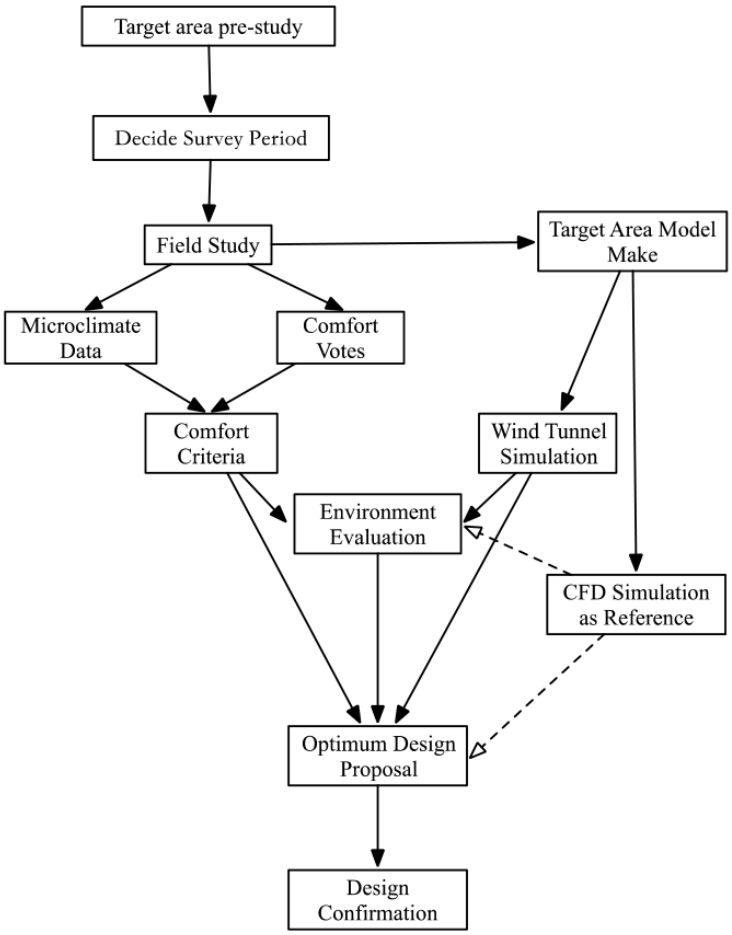


Fig. 17 Schematic representation for the optimization of public open space design.

3.5 Aerodynamic Flow Effect

From the above simulation results, several conclusions were made. Fig. 16 gives the schematics from the results of the wind tunnel and CFD simulations.

Fig. 16a shows that the wind shadow area formed a native pressure zone. The pedestrian-level wind in the lower position moved to a higher native pressure zone, which caused lower air velocity at the pedestrian-level. This principle can be used to create a low air velocity area.

Fig. 16b shows that the skyway acted as a wind diverter. The wind passing through the skyway was separated into two parts and the air area was decreased by the skyway; however, the air volume per unit area increased, which caused the air velocity under the skyway to increase.

As Fig. 16c shows, the wind flow went through the air duct formed by the urban canyon and the air velocity increased because of the increase in air volume per unit area. This is called a funnel effect, which occurs when narrow building structures cause accelerated air velocity [36].

As Fig. 16d shows, the airflow coming from the back side of the building crossed the podium from the roof. Parts of the airflow were obstructed by the podium opposite, and went down in a reverse direction, causing a lower pedestrian-level wind.

As Fig. 16e shows, streamlining the building edges also changed the air duct area, causing a higher airflow at the narrow section.

4. Conclusion

In this case study, by collecting microclimate and corresponding comfort data for summer and winter, wind comfort criteria were developed to be used as standards for a wind simulation, the results from which were applied to improve wind comfort. While these research methods cannot provide a uniform approach for wind comfort, they give guidance on dealing with wind in special urban areas that have complicated wind environments and individual differences.

A higher air velocity in summer and taking shelter from the wind in winter would improve comfort levels. The residents in Shenyang were more sensation to the wind in summer. The air velocity of 1.12 m/s in summer is the threshold of neutral air velocity. When the air velocity was higher than 1.67 m/s in winter, it was found to be unacceptable.

The prevailing wind directions during hot and cold periods in a monsoon climate city should be used to decide on urban layout as suitable street orientation can control wind attenuation.

Airflow in open spaces can affect spatial quality, and building structures can affect airflow. Building structures were found to cause five types of airflow found in this research, knowledge that can be used to improve pedestrian comfort.

5. Discussion

This research provided a method to evaluate special urban areas with complicated wind environments and individual differences.

As Fig. 17 shows, first, pre-research such as basic geographic information and historical climate information is needed on the target area, from which periods of extreme weather that significantly affect human comfort are identified.

Second, field surveys are conducted during the extreme weather periods to collect sufficient microclimate and comfort data. By analyzing the relation between the microclimate data and average comfort, the comfort variation trends corresponding to the microclimate can be identified and threshold comfort values estimated.

Third, using wind tunnel and CFD simulations to evaluate the current environmental situation, the disadvantages of the current situation can be identified.

Fourth, new designs or reconstruction designs can be proposed to improve wind comfort. The wind tunnel and CFD simulations are conducted again to check the new area and evaluate the new environment.

The fourth step is conducted several times until an optimum design is determined.

For new projects, a neighboring urban area or a space with similar functions not far away from the target area should be chosen to conduct the same work.

Acknowledgments

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References

[1] Mohit, M. A. 2013. "Quality of Life in Natural and Built Environment—An Introductory Analysis." *Procedia-Social and Behavioral Sciences* 101: 33-43.

[2] Gehl, J. 2011. *Life between Buildings: Using Public Space.* Washington, DC: Island Press.

[3] Zhu, Y., Shen, Y., Li, Y., and Shi, X. 2014. "A Comprehensive Pedestrian Wind Environment Assessment System for High Density Cities." Presented at the 9th International Symposium on City Planning and Environment Management in Asian Country, Oita, 2014: 171-6.

[4] Verkaik, J. W. 2000. "Evaluation of Two Gustiness Models for Exposure Correction Calculations." *J Appl Meteorol.* 39 (9): 1613-26.

[5] Verkaik, J. W. 2007. "On Wind and Roughness over Land." Ph.D. thesis, Wageningen University. The Netherlands. P.123.

[6] Willemsen, E., and Wisse, J. A. 2002. "Accuracy of Assessment of Wind Speed in the Built Environment." *J Wind Eng Ind Aerodyn.* 90: 1183-90.

[7] Willemsen E, and Wisse, J. A. 2007. "Design for Wind Comfort in The Netherlands: Procedures, Criteria and Open Research Issues." *J Wind Eng Ind Aerodyn.* 95 (9-11): 1541-50.

[8] Wisse, J. A., and Willemsen, E. 2003. "Standardization of Wind Comfort Evaluation in the Netherlands." Presented at 11th Int. Conf. Wind Eng. (11ICWE), Lubbock, Texas.

[9] Wisse, J. A., Verkaik, J. W., and Willemsen, E. 2007. "Climatology Aspects of a Wind Comfort Code." Presented at 12th Int. Conf. Wind Eng. (12ICWE), Cairns, Australia.

[10] NEN (Nederlands Normalisatie Instituut). 2006. *Wind Comfort and Wind Danger in the Built Environment.* NEN 8100 Dutch standard. (in Dutch)

[11] NEN. 2006. *Application of Mean Hourly Wind Speed Statistics for the Netherlands.* NPR 6097:2006 (in Dutch). Dutch practice guideline.

[12] Isyumov, N., and Davenport, A. G. 1975. "The Ground Level Wind Environment in Built-up Areas." In *Proceedings of fourth international conference on wind effects on buildings and structures,* Heathrow, UK: Cambridge University Press, 403-22.

[13] Lawson, T. V. 1978. "The Wind Content of the Built Environment." *J Ind Aerodyn.* 3: 93-105.

[14] Melbourne, W. H. 1978. "Criteria for Environmental Wind Conditions." *J Ind Aerodyn.* 3: 241-9.

[15] Janssen, W. D., Blocken, B., and Van Hooff, T. 2013. "Pedestrian Wind Comfort around Buildings: Comparison of Wind Comfort Criteria Based on Whole-Flow Field Data for a Complex Case Study." *Building and Environment* 59: 547-62.

[16] Ali-Toudert, F., and Mayer, H. 2006. "Numerical Study on the Effects of Aspect Ratio and Orientation of an Urban Street Canyon on Outdoor Thermal Comfort in Hot and Dry Climate." *Building and Environment* 41 (2): 94-108.

[17] Lin, T. P., Matzarakis, A., and Hwang, R. L. 2010. "Shading Effect on Long-Term Outdoor Thermal Comfort." *Building and Environment* 45 (1): 213-21.

[18] Johansson, E., and Emmanuel, R. 2006. "The Influence of Urban Design on Outdoor Thermal Comfort in the Hot, Humid City of Colombo, Sri Lanka." *International journal of biometeorology* 51 (2): 119-33.

[19] Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., and Lim, E. M. 2007. "Thermal Comfort and Outdoor Activity in Japanese Urban Public Places." *Environment and Behavior* 39 (5): 660-84.

[20] Nikolopoulou, M., and Steemers, K. 2003. "Thermal Comfort and Psychological Adaptation as a Guide for Designing Urban Spaces." *Energy and Building* 35 (1): 95-101.

[21] Nikolopoulou, M., and Lykoudis, S. 2006. "Thermal Comfort in Outdoor Urban Spaces: Analysis across Different European Countries." *Building and Environment* 41 (11): 1455-70.

[22] Ahmed, K. S. 2003. "Comfort in Urban Spaces: Defining the Boundaries of Outdoor Thermal Comfort for the Tropical Urban Environments." *Energy and Buildings* 35 (1): 103-10.

[23] Höppe, P. 1984. *Die Energiebilanz des Menschen.* Vol. 49. Munchen: Universitat Munchen, Meteorologisches Institut. (in German)

[24] Fazia, A., and Helmut, M. 2006. "Numerical Study on the Effects of Aspect Ratio and Orientation of an Urban Street Canyon on Outdoor Thermal Comfort in Hot and Dry Climate." *Int. J Building and Environment* 41: 94-108.

[25] Brown, R., and Gillespie, T. 1986. "Estimating Outdoor Thermal Comfort Using a Cylindrical Radiation: The Mometer and an Energy Budget Model." *Int. J Biometeor.* 30: 43-52.

[26] Blocken, B. J. E., Stathopoulos, T., and Van Beeck, J. P. A. J. 2016. "Pedestrian-Level Wind Conditions around Buildings." *Building and Environment* 100 (1): 50-81.

[27] China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. 2005. *China Standard Weather Data for Analyzing Building Thermal Conditions.* China Building Publishing House, China.

[28] Tanabe, S. I. 1988. *Thermal Comfort Requirements in Japan.* Doctoral dissertation, Waseda University, Tokyo, Japan.

[29] China Meteorological Administration, National Meteorological Information Center. n.d. "The Database of Climate Standard Daily Value in Chinese International Ground Switching Center." Beijing (China): China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. Accessed August 4, 2012. http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html. (in Chinese)

[30] General Administration of Sport of China. 2014. "Communiqué of Nationals' Physique." Accessed November 25, 2015. http://www.sport.gov.cn/n16/n1077/n1422/7331093.html. (in Chinese)

[31] Kaltschmitt, M., Streicher, W., and Wiese, A., eds. 2007. *Renewable Energy: Technology, Economics and*

Environment. New York: Springer Science & Business Media.

[32] Heier, S. 2005. *Grid Integration of Wind Energy Conversion Systems*. Chichester: John Wiley & Sons. p. 45. ISBN: 0-470-86899-6.

[33] Tsutsumi, T. 2009. "Snowdrift Wind Tunnel." *Wind Engineers* 34 (1): 36-41.

[34] Meng, X. W., and Setoguchi, T. 2010. "Development of Urban Design Guidelines with Wind Tunnel Simulations for Downtown Districts in Winter Cities." *Journal of Asian Architecture and Building Engineering* 9 (2): 355-62.

[35] Erell, E., Pearlmutter, D., and Williamson, T. 2012. *Urban Microclimate: Designing the Spaces between Buildings*. New York: Routledge.

[36] Wu, H. 1994. "Pedestrian-Level Wind Environment around Buildings." Doctoral dissertation, Concordia University.