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A Study on the Outdoor Thermal Comfort of Pedestrians in the Commercial Streets

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위 논문은 서울대학교 및 환경대학원 환경조경학과 학위논문 관련 규정에 의거하여 심사위원의 지도과정을 충실히 이수하였음을 확인합니다.

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Abstract

In response to the urban problems caused by sprawl, the development concept of Walkable City gradually become the trend of urban planning and development. Unfortunately, high-density development mode has led to problems in urban thermal environment. Though Seoul metropolitan city made a lot of efforts to improve walking environment, the quality of walking space is still varied.

The plan and design of the walking space should be focused on the human scale. So small scale as urban microclimate is more suitable for assessing pedestrians' thermal comfort. The improvement of outdoor thermal conditions is closely related to facing with global warming, improving the quality of life, the sustainable development of cities.

The purpose of this research is to explore the design strategies of vegetation and surface type that can improve the outdoor thermal comfort of streets in three typical blocks of commercial area under summer condition.

After classifying the commercial centers in Seoul metropolitan city according to urban form conditions, three typical blocks as compact low-rise, compact mid-rise, and open high-rise are selected as research areas. Then by idealizing the typical real sites, design scenarios about vegetation and surface type are set up to study the effect of different design strategies on alleviating the outdoor heat stress in commercial streets based on idealized models.

The main results of this study include:

In the three types of commercial blocks with different urban form features selected in this study, the compact low-rise type has little feedback on different landscape designs, but its urban form makes it a better outdoor thermal comfort. But the heat stress of compact mid-rise is the largest.

About landscape elements, the increase of green coverage has a positive effect on improving outdoor thermal comfort, which is the same as other research results. The effect of 25% green coverage, 5m of street tree interval and granite brick in compact low-rise and compact mid-rise; Asphalt in open high-rise is the best.

On the streets with different urban forms, the landscape design options for improving thermal comfort may also be different. In compact low-rise area such as model A, roadside trees with 5m spacing is the choice; In compact mid-rise area such as model B, changing all 3 landscape elements or only vegetation can work well; In open high-rise area such as model C, three landscape elements can be used, or just changing the pavement.

Therefore, the landscape reform of the pedestrian space needs to be based on different local forms.

Keywords: Outdoor Thermal Comfort; Landscape Design; Pedestrian; Commercial Street; ENVI-met; UTCI

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1.1 Research Background and Purpose

1.1.1 Research Background

Nowadays, more than half of the world's population lives in urban areas. This figure was only 30% in the 1950s, while in 2050s, the proportion of urban population in the world is expected to break through 2/3[1]. Since 2000, the proportion of urban population in South Korea has exceeded 80%, which is still on the rise. In 2050, there will be a population of 90% in urban areas[1].

The city has not only gathered the vast majority of the population, but also the high concentration of various elements. As a result, cities not only consume 60%-80%’s global energy but are vulnerable to extreme climate and climate change. Meanwhile, with the urban sprawl, urban problems such as traffic jam, environmental pollution, resource shortage and public health become more and more prominent. Therefore, in order to cope with the problems of climate change and inside the city, the development concept of Compact City is gradually promoted. This sustainable development concept put forward for the urban disorderly growth, which advocates the mixed use of land and intensive development. At the same time, it also emphasizes the reliance on cars and public transportation and walking. With the development of an evidence-based methodology, to achieve the shift from car-centric to human-scale cities is a shared global recognition that walkable environments can shape better cities. No matter how green and efficient, new technology and new energy are not as effective as walking. Consequently, Walkable City, Human-Centered City, Walkable Urbanism and so on gradually become the trend of urban planning and development.

As Jeff Speck said, “Get walkability right and so much of the rest will follow”[2], walking not only has the advantages including social benefits such as placemaking; Economical benefits including city attractiveness, cost savings and so on; Environmental benefits to do with ecosystem services, livability and so on; And political benefits associated with sustainable development and other else. Walking not only has the characteristics of Pro-environment, promoting social and economic benefits, community-based communication at the social level, but also has advantages in physical and mental health at the individual level. The choice of human behavior, such as walking, is affected by a variety of factors. Though in any case, human bodies will make the best choice for itself, the quality of the walking environment is the key to encourage people to choose more walking rather than driving[3]. However, there are few theories and methods to guide the planning and design of Walkable City in the field of transportation planning. Instead, urban designers and landscape architects get their focus on the improvement of walking

1 United Nations, "World Urbanization Prospects." 2017.

2 Speck Jeff, Walkable city (New York: Farrar, Straus and Giroux, 2012).

environment.

Seoul metropolitan city, the capital of South Korea, also began to focus on walking in the 90s of last century, and has made a positive effort to build a Walkable City in recent years. In 2013, the government of Seoul metropolitan city announced the human-centered Walkable City as a policy. After that, they planned “Walkable City, Seoul(걷는 도시, 서울)” in the year 2016. Four directions of the policy named “Possible to walk(걷을 수 있는 도시)”, “Easy to walk(걷기 쉬운 도시)”, “Want to walk(걷고 싶은 도시)”, “Walk together(함께 걷는 도시)”, containing 8 core practices and 35 detailed projects[4]. Except the 22 commercial centers mentioned in the “2030 Seoul Plan”, Seoul metropolitan city also added 53 living zone centers in the “2030 Seoul Living Zone Plan” in the year of 2018.

Unfortunately, like other megacities, urban development mode of high density and high volume has led to a series of climate problems such as poor ventilation, air pollution and urban heat island effect in Seoul. These climate problems, especially the urban thermal environment, have affected the urban outdoor comfort, and have also become the culprits to threaten the comfort of the walking environment. Following the policy of Walkable City, the government recently made a lot of efforts to improve the pedestrian environment in Seoul. A considerable number of

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3 Michael Southworth, "Designing the Walkable City." *Urban Planning International* (05), 2012, pp.54-64+95.

4 "Walkable City, Seoul." from http://english.seoul.go.kr/policy-information/urban-planning/walkable-city-seoul/. Retrieved 03/16, 2018.

pedestrianization and sidewalks have been implemented, and several “Pedestrian Friendly” districts across the city have been designated. Whereas the quality of the walking environment in Seoul is still varied[5]. Pedestrian areas such as commercial streets with much human flow will be focused on in this study.

The plan and design of the walking space should be focused on the human scale and embody the human-centered design. And human-centered design needs to be considered in two aspects: human needs and environmental comfort. While demand varies from person to person, environmental comfort can be improved by means of design. As far as pedestrian level is concerned, small-scale as urban microclimate is more suitable for assessing pedestrians’ thermal comfort than the overall urban climate or local climate change. Therefore, by studying the microclimate conditions at the pedestrian level, the condition of outdoor thermal comfort at the pedestrian level can be understood.

The improvement of outdoor thermal conditions is closely related to increasing walking, promoting health and improving the utilization of outdoor public space. Without any shadow of a doubt, facing with global warming, improving the quality of life, the sustainable development of cities, and the outdoor thermal comfort of pedestrian level through design and planning is a worthwhile research topic.

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5 S. Kim, S. Park and J. S. Lee, "Meso- or micro-scale? Environmental factors influencing pedestrian satisfaction." *Transportation Research Part D-Transport and Environment*, 30, 2014, pp.10-20.

1.1.2 Research Purpose and Significance

The purpose of this research is to explore the design strategies of vegetation and surface type that can improve the outdoor thermal comfort of streets in three typical blocks of commercial area under summer condition.

This paper uses microclimate simulation tools to study the temporal and spatial distribution and variation of the outdoor thermal comfort of pedestrians in streets in three typical commercial blocks. Meanwhile, based on the analysis of influence factors, scenarios to improve outdoor thermal comfort are designed to explore the improvement suggestion of microclimate through landscape design.

Every activity of the human body in the outdoor begins with walking and on foot. Thus, it is of great significance to our current urban development to pay attention to the comfort of walking and walking environment. And one of the effective ways to solve urban problems is to create a more comfortable outdoor walking environment through the design.

The results of this study will provide a better refine solutions and support decision-making process. Which allows architects and designers to put forward more scientific and reasonable design proposal in renovation and regeneration process. This research will help improve the outdoor walking environment in urban areas, promote the construction of a more scientific and humane Walkable City, thereby increase walking behavior in the cities and promote green, sustainable urban development, at the same time as guaranteeing the rights of pedestrians.

1.2 Previous Research

1.2.1 Definition

(1) Compact City and Walkable City

The Compact City

The Compact City is an urban sustainable development concept which is proposed for urban sprawl. In recent years, with the increasing concern of global climate issues, Compact City has attracted worldwide attention and discussion as a sustainable development mode dealing with climate change and construction of the low-carbon city.

Compact City is not primary high-density development, but a compact and functional hybrid development model based on walking and public transportation[6]. It advocates intensive and adjacent development, the connection of public transport systems, local services and employment opportunities[7].

The concept of Compact City can be traced back to the medieval fortress city and even the ancient cities. Surely, these cities are only had the compact scale and their connotation is far from the Compact City talked today. Later, at the end of the 19 Century, Ebenezer Howard put forward the concept of ‘Garden City’, which was the first modern urban planning model, containing the concept of Compact City. As

6 Oliver Gillham, *The Limitless City: A Primer on the Urban Sprawl Debate* (Washington, DC: Island Press, 2002): 179.

7 OECD, *Compact City Policies: A Comparative Assessment (Chinese version)*: OECD Publishing, 2014): 12-13.

the ‘Green Belt’ incorporated into the British National Urban Policy in 1935, many cities also adopted this concept. Among them, in South Korea, the urban planning law was promulgated in 1971, following by the restricted development zones delimited in Seoul and another 13 cities[7].

The appearance of the Compact City was first put forward by George(1973)[8] in his published monograph. Then with the popularity of this concept in the western countries, the Commission of the European Communities(CEC)[9] once again put forward the concept of ‘Compact City’ and regarded it as a way to solve the problems of housing and environment, which is consistent with the requirements of sustainable development.

After that, because the Compact City concept can well cope with the challenges of urban sprawl, Urban Heat Island(UHI) and even urban economic sustainable growth in the process of green growth, more and more governments regard it as a development policy[7].

The Walkable City and Walkability

In fact, cities from the former industrialized cities to the 19th Century have maintained a suitable walking feature. But with the advent of automobile and Modernism in the 1920s, the modernist value led by cars was dominant in the

8 George Bernard Dantzig and Thomas L Saaty, *Compact city: a plan for a liveable urban environment*: WH Freeman, 1973).

design of urban form and transportation system, resulted in the disappearance of the walkable cites[3]. After the Second World War, the urban environment became a tough public health problem, and people began to reflect on the sedentary lifestyle that relied on cars[10]. The concept of ‘Walking Priority’ by Donald Appleyard has aroused attention to research on walking. And the Buchanan Report in the UK in 1963 clearly emphasized the importance of the walking environment and which affected the exploration of Walkable City by the UK and other countries. After that, the Transport Oriented Development(TOD) and the Traditional Neighborhood Development(TND) had been put forward, and a great deal of research has been carried out[11].

Despite the theory and research on the Walkable City are often touted, but their definition is less clear. Walkable City is a simple, practical-minded solution to a host of complex problems[2]. To discuss Walkable City, we have to probe into Walkability.

Walkability has health, environmental, and economic benefits. Which represents the level of how built environments support and encourage walking. And four conditions, useful, safe, comfortable and interesting are indispensable. One

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9 Commission of the European Communities, "Green Paper on the Urban Environment." Commission of the European Communities, 1990.

10 Tianyang Ge, Wenjun Hou and Jianqiang Yang, "Pedestrian-oriented City Centre Development in the UK." *Urban Planning International*, 2017, pp.1-19.

11 Shaohua Tan, Yingliang Wang and Jian Xiao, "A Study on Walkable City Strategies Based on Active Intervention." *Urban Planning International* (05), 2016, pp.61-67.

proposed definition[12] for Walkability and Walkable is:

> 'The extent to which the built environment is walking friendly.'

Additionally, the 'Wisconsin Pedestrian Policy Plan 2020' described the Walkable Community as[13]:

> 'A Walkable Community is thoughtfully planned, designed, or otherwise retrofitted to integrate pedestrian travel into the community's fabric. In a Walkable Community, walking is considered a normal transportation choice and is not a distraction or obstacle to motor vehicle traffic.'

(2) Thermal Comfort and Microclimate

Thermal Comfort

The study of thermal comfort starts with indoor thermal comfort. It is defined as 'that condition of mind which expresses satisfaction with the thermal environment'[14]. Its definition can be traced back to the 1970s, by the American Society of Heating, Refrigerating and Air-Conditioning Engineers[15]. According to this definition, the emergence of human thermal comfort is a process of cognition. Thus this process is not only affected by physical and physiological factors, but also related to psychological factors.

There are mainly two types of views on the definition of thermal comfort. One

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12 Stephen Abley, "Walkability Scoping Paper." 2005, pp.3.

13 Wisconsin Department of Transportation, "Wisconsin Pedestrian Policy Plan 2020." 2002, pp.24-25.

14 ISO, "International Standard 7730." ISO Geneva, 1990.

15 ASHRAE Fundamentals Handbook, "American society of heating, refrigerating and air-conditioning engineers." *Inc.: Atlanta, GA, USA*, 2009.

regards it as a thermal sensation, so as long as human beings in the thermal comfort zone, they can feel comfortable. The other insists that thermal comfort only exists in a dynamic process rather than a steady process, always accompanied by discomfort[16].

The evaluation of thermal comfort can be traced back to the effective temperature(ET) proposed by Houghten et al.(1923)[17]. Over the past 100 years, various indicators have been put forward. However, most indicators are based on indoor thermal environment, and there are few studying outdoor thermal environment. With more attention in the field of urban planning and urban greening recently, outdoor thermal comfort becoming an important basis for measuring the quality of outdoor thermal environment, has been earnestly studied as mitigating measures. Both modeling and empirical methods of outdoor thermal comfort studies have been attempted[18].

Five thermal conditions are commonly determined in empirical outdoor thermal comfort studies to understand human thermal perception: neutral temperature, preferred temperature, acceptable temperature range, comfortable temperature range, and neutral temperature range[18].

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16 Feng Xiwen, He Chunxia, Fang Zhaosong, et al., "Present Ｒesearch on Outdoor Thermal Comfort." *Building Science*, 33 (12), 2017, pp.152-158.

17 Chen Raochao, Studies on outdoor thermal environment indices and its application based on campus in Guangzhou, master's degree. (Guangzhou University, 2015), Pages.

Microclimate

On the other hand, as early as the 1920s, the German meteorologist Geiger observed that the air layer adjacent to the ground was different from that of other parts. In the publication in the 1940s, Geiger(1951)[19] first proposed the word ‘microclimate’ and he thought that microclimate was a combination of near ground environmental variables. Subsequently, a series of studies have been carried out in view of its definition and connotation. Baum(1949)[20] pointed out that regional microclimate changes seasonally with the elevation of altitude. Landsberg(1950)[21] believed that microclimate is the local change when the atmosphere encountered different terrain, vegetation and artificial facilities. Weller(1974)[22] clarified that microclimate refers to the atmosphere where occurs most biological activity near the ground. And Meerow(1988) [23] emphasized that the characteristics of microclimate are consistent and can be improved. Although the above scholars have different interpretations of microclimate, they all agree that microclimate has the characteristics of small-scale and variety.

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18 P. K. Cheung and C. Y. Jim, "Determination and application of outdoor thermal benchmarks." *Building and Environment*, 123, 2017, pp.333-350.

19 Geiger R, "Microclimates. (Book reviews: The climate near the ground)." *The Scientific Monthly*, 72 (2), 1951, pp.132.

20 Baum W A, "On the relation between mean temperature and height in the layer of air near the ground." *Ecology*, 30 (1), 1949, pp.104-107.

21 Landsberg H E, "Comfortable living depends on microclimate." *Weatherwise*, (1), 1950, pp.7-10.

22 Weller G and Holmgren B, "The microclimates of the Arctic Tundra." *Journal of Applied Meteorology*, 13 (8), 1974, pp.854-862.

23 Meerow A W and Black R J, *Landscaping to conserve energy: A guide to microclimate modification* (Florida: University of Florida, 1988): 8.

1.2.2 Research on Microclimate

(1) Research on Architecture and Microclimate

Outdoor comfort is strictly connected with the phenomenon of UHI and its impact on the sector of building energy demand. Due to the UHI of high-density cities, people tend to stay indoors with air conditioning instead of going out. Which has a significant impact on building energy consumption. Firstly, from the point of view of architecture, many studies are concerned with the influence of microclimate on building energy consumption(Ye et al., 2018)[24]. Except this, some scholars have also used the microclimate to predict the residential area future peak cooling energy demand(Yi et al., 2017)[25].

In order to have a better understanding of the outdoor microenvironment, which might help address mitigation strategies and design solutions for architects and designers, a lot of research described the relationship between energy use and microclimate as well as different influencing factors. Experts mainly aim to achieve energy saving by changing microclimate elements in this field.

Among which, analyses focused on the impact of green infrastructure on building energy consumption were paid a lot of attention. For example, green

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24 H. Ye, Q. Ren, L. Y. Shi, et al., "The role of climate, construction quality, microclimate, and socio-economic conditions on carbon emissions from office buildings in China." *Journal of Cleaner Production*, 171, 2018, pp.911-916.

25 C. Y. Yi and C. Z. Peng, "Correlating cooling energy use with urban microclimate data for projecting future peak cooling energy demands: Residential neighbourhoods in Seoul." *Sustainable Cities and Society*, 35, 2017, pp.645-659.

facades(Vox et al., 2017; Vox et al., 2018)[26, 27], tree shading(Hsieh et al., 2018)[28], and green roofs(Berardi, 2016)[29]. Additionally, the topic related to street canyon and energy saving has been studied by Huang et al.(2017)[30].

(2) Research on Urban Microclimate

In the field of microclimate research, the majority are studies on urban microclimate rather than other areas such as rural areas. Literature in this field can be divided into studies under different climate and regional conditions, and researches in specific areas of the city, including urban blocks, streets, parking lots, public green spaces such as parks and gardens, residential areas, green roofs, courtyards, water and so on.

Mazhar et al.(2015)[31] compared the garden containing green infrastructure and water with a hard-surfaced courtyard, in order to generate the design guidelines of thermally comfortable outdoor spaces, obtaining the result of solar radiation to

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26 G. Vox, I. Blanco, S. Fuina, et al., "Evaluation of wall surface temperatures in green facades." *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, 170 (6), 2017, pp.334-344.
27 G. Vox, I. Blanco and E. Schettini, "Green facades to control wall surface temperature in buildings." *Building and Environment*, 129, 2018, pp.154-166.
28 C. M. Hsieh, J. J. Li, L. M. Zhang, et al., "Effects of tree shading and transpiration on building cooling energy use." *Energy and Buildings*, 159, 2018, pp.382-397.
29 U. Berardi, "The outdoor microclimate benefits and energy saving resulting from green roofs retrofits." Ibid., 121, 2016, pp.217-229.
30 K. T. Huang and Y. J. Li, "Impact of street canyon typology on building's peak cooling energy demand: A parametric analysis using orthogonal experiment." Ibid., 154, 2017, pp.448-464.

be the main determinant of thermal discomfort. The research implemented by Mao et al.(2017)[32], the Urban Weather Generator(UWG) was used to analyze the current status of urban microclimate system on Abu Dhabi(UAE). The results showed that UWG is excellent as a simulator of the urban thermal environment of UAE. Significant factors identified by UWG will be the subject of future research on understanding the microclimatic effect on urban energy and environment. And Forouzandeh(2018)[33] conducted a study on the microclimate in a semi-closed courtyard space between buildings by the model ENVI-met as a simulator, which was evaluated with field data measured in different climate conditions in both summer and winter. By summarizing the relationship between microclimate with mountainous terrain environment and ecological environment, Yuhui et al.(2012)[34] used factors that restrict the microclimate of the mountain cities, put forward three models of the low-carbon and ecological planning of mountainous cities.

Besides, the changes of microclimate after the development of urban parks were quantitatively analyzed by the microclimate analysis program ENVI-met. And

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31 N. Mazhar, R. D. Brown, N. Kenny, et al., "Thermal comfort of outdoor spaces in Lahore, Pakistan: Lessons for bioclimatic urban design in the context of global climate change." *Landscape and Urban Planning*, 138, 2015, pp.110-117.

32 J. C. Mao, J. H. Yang, A. Afshari, et al., "Global sensitivity analysis of an urban microclimate system under uncertainty: Design and case study." *Building and Environment*, 124, 2017, pp.153-170.

33 A. Forouzandeh, "Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings." *Sustainable Cities and Society*, 36, 2018, pp.327-345.

34 Xu Yuhui, Zhang Wentao and Dong Shiyong, "Research on the Adaptability Planning Model of Low-carbon and Ecological Residential Areas in Chongqing under the Urban Microclimate Environment." *Research Journal of Chemistry and Environment*, 16, 2012, pp.62-68.

this study proposed a way to evaluate the benefit of the urban park from the perspective of microclimate control(Kim et al., 2010)[35]. In thousands of papers, there appeared studies using Energy Integrated urban planning Support System(EnerISS), to predict urban microclimate(Seo, 2011; Cho et al., 2013a; Cho et al., 2013b; Kim, 2013) [36, 37, 38, 39].

Influence of Different Factors on Microclimate

Influence of Urban Form

The research on the impact of urban form on microclimate has attracted much attention not only in the field of urban planning, urban design, landscape design, urban geography, but also in urban sociology, even urban history and archaeology. Middel et al.(2014)[40] studied the effects of five urban forms and three landscape

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35 Dae Wuk Kim, Jung Kwon Kim and Eung Ho Jung, "An Analysis of Micro-climate Environmental Changes Followed by Establishment of an Urban Park- Focused on the Junggu in Daegu City." *Journal of the Urban Design Institute of Korea Urban Design*, 11 (2), 2010, pp.77-94.
36 Ji Eun Seo, A Study on the Development of Statistical Model for the Prediction of Microclimate Changes according to Regional Characteristics of Seoul, Master's degree. (Yonsei University 2011), Pages.
37 Tae Geun Cho and Jurng Jae Yee, "Urban Climate Prediction by EnerISS and an Applicability Study." *Journal of the Korea Institute for Sustainable Building*, 7 (4), 2013, pp.281-288.
38 Tae Geun Cho, Hyun Soo Kim and Jurng Jae Yee, "A Study on the Urban Micro Climate Prediction using EnerISS and Verification with Measured Temperature." *Journal of Architectural Institute of South Korea*, 15 (3), 2013, pp.231-237.
39 Hyun Soo Kim, A Study on the Urban Energy Demand Prediction Using the Energy Integrated Urban Planning Support System, Master's degree. (Dong-A University 2013), Pages.
40 A. Middel, K. Hab, A. J. Brazel, et al., "Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones." *Landscape and Urban Planning*, 122, 2014, pp.16-28.

types on microclimate in semi-arid areas in the afternoon. The result showed that density can create urban cool islands. The thermal comfort of five urban forms in the Netherlands was calculated by Physiological Equivalent Temperature(PET) in the research by Taleghani et al.(2015)[41], noting that the courtyard provides the most comfortable microclimate in the hottest days. The research conducted by Jeong et al.(2017)[42] aimed at reducing the UHI phenomenon by complex types. The result of which, all 3 representative complexes, detached house complex, apartment complex and commercial complex, the reduction of building roofs' temperature is better than adjusting the reflectivity.

At present, the study of urban form is very diverse. Because of the comprehension diversity of different scholars from the multifarious point of view, many related concepts have also been derived. For an example, urban morphology, urban typology, urban geometry, urban landscape, townscape and so on, which have greatly enriched the application field.

There is a great number of interdisciplinary researches focusing on the influence of urban form, including land use intensity, built form, canyon geometry, space enclosure and so on, on the urban thermal environment. Such as research by

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41 M. Taleghani, L. Kleerekoper, M. Tenpierik, et al., "Outdoor thermal comfort within five different urban forms in the Netherlands." *Building and Environment*, 83, 2015, pp.65-78.

42 Juri Jeong and Min Hee Chung, "The Planning of Micro-climate Control by Complex Types." *Journal of Ecological Architecture*, 17 (1), 2017, pp.49-54.

Sharmin et al.(2017)[43] that detected the microclimate simulation tool ENVI-met in the research, and achieved effective results when identifying the variation of microclimate in urban geometry. But it was found that it cannot identify the exact details of urban geometric features, and which may make a significant difference in the microclimate in the actual situation. Also, more and more experts are studying on the effect of urban morphology on urban microclimate(Tong et al., 2017; Merlier et al., 2018)[44, 45]. Among them, Wei et al.(2016)[46] studied the influence of urban morphological parameters on urban microclimate, and provided a suitable parameter range, in order to benefit the thermal comfort of pedestrians.

Concretely, there are some researches about urban microclimate focus on the impact of land use. Such as in the area with high thermal sensitivity in Seoul, the influence of the area of urban infrastructure in land use on road microclimate was studied through field measurement by Lim et al.(2012)[47].

There is also some literature focus on the effect of built form on the outdoor thermal environment. By analyzing the temporal and spatial relationship between

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43 T. Sharmin, K. Steemers and A. Matzarakis, "Microclimatic modelling in assessing the impact of urban geometry on urban thermal environment." *Sustainable Cities and Society*, 34, 2017, pp.293-308.

44 S. S. Tong, N. H. Wong, C. L. Tan, et al., "Impact of urban morphology on microclimate and thermal comfort in northern China." *Solar Energy*, 155, 2017, pp.212-223.

45 L. Merlier, F. Kuznik, G. Rusaouen, et al., "Derivation of generic typologies for microscale urban airflow studies." *Sustainable Cities and Society*, 36, 2018, pp.71-80.

46 Ruihan Wei, Dexuan Song, Nyuk Hien Wong, et al., "Impact of Urban Morphology Parameters on Microclimate." *Procedia Engineering*, 169, 2016, pp.142-149.

the building structure and urban environment, Peng et al.(2017)[48] studies microclimate in Compact City, and put forward some suggestions for sustainable development. Rojas-Fernandez et al.(2017)[49] did a research on the relationship between the urban building densification and the climatic factors. There also has quite a lot of studies concerned about the impact of building layout on outdoor wind(Yoon, 2006; Seo, 2009; Ryu et al., 2010; Jin et al.2017)[50, 51, 52, 53].

In addition, after Oke(1981)[54] introduced that neighborhood's microclimate is strongly influenced by street geometry, research on canyon geometry began to emerge in an endless stream. These studies have been conducted from the

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47 Ji Hyu Lim and Yu Hwa Lee, "The Effect of Urban Landuse on Road Microclimate - A Case Study on the Seoul of Road Sensible Temperature." *Civil Engineering Association*, 2012 (10), 2012, pp.1557-1560.

48 F. Peng, M. S. Wong, H. C. Ho, et al., "Reconstruction of historical datasets for analyzing spatiotemporal influence of built environment on urban microclimates across a compact city." *Building and Environment*, 123, 2017, pp.649-660.

49 J. Rojas-Fernandez, C. Galan-Marin, J. Roa-Fernandez, et al., "Correlations between GIS-Based Urban Building Densification Analysis and Climate Guidelines for Mediterranean Courtyards." *Sustainability*, 9 (12), 2017, pp.26.

50 Young In Yoon, A Study on the Micro-climate of the City to Construct Wind Ways, Master's degree. (Gwangju University 2006), Pages.

51 An Seon Seo, Planning Apartment Complexes to Preserve Wind Corridor, Master's degree. (Hanyang University, 2009), Pages.

52 Byong Ro Ryu and Eun Ah Ko, "Wind Simulation and Optimal Building Allocation using Envi-met 3-D Model." *Journal of Environmental Technology*, 11 (4), 2010, pp.207-215.

53 H. Jin, Z. M. Liu, Y. M. Jin, et al., "The Effects of Residential Area Building Layout on Outdoor Wind Environment at the Pedestrian Level in Severe Cold Regions of China." *Sustainability*, 9 (12), 2017, pp.18.

54 T. R. Oke, "Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations." *Journal of Climatology*, 1 (3), 1981, pp.237.

viewpoint of urban ventilation or sun-shading[55]. And indicators proposed to quantify canyon geometry including aspect ratio, street orientation and building density. The first two are most commonly used when investigating the effects of canyon geometry on microclimate. ENVI-met and PET were used to evaluate thermal comfort in the street canyons in the daytime, dealing with the dependence of thermal comfort on urban street design(Ali-Toudert et al., 2007)[56]. The microclimatic changes in three different urban canyons from three areas were investigated in the research by Kakon et al.(2009)[57], showing that the study sites are thermally uncomfortable and the new building construction rules are invalid.

Research related with SVF and thermal environment has been launched in many countries such as Hong Kong, Taiwan, Japan, Sweden and other European areas(Giridharan et al., 2007; Hwang et al., 2011; Yamashita et al., 1986; Bärring et al., 1985)[58, 59, 60, 61]. However, there is no universal standard of SVF threshold at

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55 Yingli Xuan, Guang Yang, Qiong Li, et al., "Outdoor thermal environment for different urban forms under summer conditions." *Building Simulation*, 9 (3), 2016, pp.281-296.

56 F. Ali-Toudert and H. Mayer, "Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons." *Solar Energy*, 81 (6), 2007, pp.742-754.

57 A. N. Kakon, N. Mishima and S. Kojima, "Simulation of the urban thermal comfort in a high density tropical city: Analysis of the proposed urban construction rules for Dhaka, Bangladesh." *Building Simulation*, 2 (4), 2009, pp.291-305.

58 Renganathan Giridharan, SSY Lau, S Ganesan, et al., "Urban design factors influencing heat island intensity in high-rise high-density environments of Hong Kong." *Building and Environment*, 42 (10), 2007, pp.3669-3684.

59 Ruey Lung Hwang, Tzu Ping Lin and Andreas Matzarakis, "Seasonal effects of urban street shading on long-term outdoor thermal comfort." Ibid., 46 (4), 2011, pp.863-870.

present. The optimal range of SVF needs to take local condition into account.

Influence of Landscape

Landscape elements such as surface type, vegetation and water, have been proposed as one of principal approach for improving urban microclimate.

Tsoka et al.(2017)[62] implemented a survey on the influence of different surfaces on microclimate and proposed a combination of strategies such as replacing the concrete pavement and asphalt streets with similar cool materials, increasing tree planting and so on. Followed by Hardin et al.(2018)[63], who both studied the surface types and the influence of the changes in the radiation absorbed by human on thermal comfort.

The impact of land cover on microclimate is also discussed in some papers as well(Shojaei et al.,2017; Lin et al., 2018)[64, 65]. Furthermore, some studies have

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60 Shuji Yamashita, Kiyoshi Sekine, Masahiro Shoda, et al., "On relationships between heat island and sky view factor in the cities of Tama River basin, Japan." *Atmospheric Environment (1967)*, 20 (4), 1986, pp.681-686.

61 Renganathan Giridharan, SSY Lau, S Ganesan, et al., "Urban design factors influencing heat island intensity in high-rise high-density environments of Hong Kong." *Building and Environment*, 42 (10), 2007, pp.3669-3684.

62 S. Tsoka, K. Tsikaloudaki and T. Theodosiou, "Urban space's morphology and microclimatic analysis: A study for a typical urban district in the Mediterranean city of Thessaloniki, Greece." *Energy and Buildings*, 156, 2017, pp.96-108.

63 A. W. Hardin and J. K. Vanos, "The influence of surface type on the absorbed radiation by a human under hot, dry conditions." *International Journal of Biometeorology*, 62 (1), 2018, pp.43-56.

64 P. Shojaei, M. Gheysari, B. Myers, et al., "Effect of different land cover/use types on canopy layer air temperature in an urban area with a dry climate." *Building and Environment*, 125, 2017, pp.451-463.

focused on the impact of imperviousness on microclimate(Yeo et al., 2017; Morabito et al., 2018)[66, 67].

The view[68] that urban climate is highly related to the quantity and type of vegetation is widely accepted and recognized. Based on the result that increasing green coverage can effectively reduce the heat island effect by providing shadow and reducing surface temperature[69, 70], many designers tried to mitigate the urban thermal environment with outdoor greening.

Great amount of literatures has followed the topic of vegetation's effect on microclimate(Kim et al., 2002; Ahn et al., 2006; Lee et al., 2016; Fahmy et al., 2017; Fabbri et al., 2017)[71, 72, 73, 74, 75]. A study to reveal the influence of vegetation

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65 B. B. Lin, M. H. Egerer, H. Liere, et al., "Local- and landscape-scale land cover affects microclimate andwater use in urban gardens." *Science of the Total Environment*, 610, 2018, pp.570-575.

66 Chang Hwan Yeo, Jae Ik Kim and Jun Yong Hyun, "Comparison of effectiveness among indexes of urban expansion: surface temperature, vegetation and impervious surface area." *Journal of Intelligence*, 33 (3), 2017, pp.145-154.

67 M. Morabito, A. Crisci, T. Georgiadis, et al., "Urban Imperviousness Effects on Summer Surface Temperatures Nearby Residential Buildings in Different Urban Zones of Parma." *Remote Sensing*, 10 (1), 2018, pp.17.

68 M. E. Baris, S. Sahin and M. E. Yazgan, "The contribution of trees and green spaces to the urban climate: The case of Ankara." *African Journal of Agricultural Research*, 4 (9), 2009, pp.791-800.

69 Argiro Dimoudi and Marialena Nikolopoulou, "Vegetation in the urban environment: microclimatic analysis and benefits." *Energy and Buildings*, 35 (1), 2003, pp.69-76.

70 Feng Yang, Stephen SY Lau and Feng Qian, "Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate." *Architectural Science Review*, 54 (4), 2011, pp.285-304.

71 Hae Dong Kim and Hyun Suk Goo, "Assessment on the Function of Microclimate Amelioration by Urban Trees - Observational Study." *A collection of Environmental Science Papers*, 7 (1), 2002, pp.189-198.

and canyon aspect ratio on the thermal environment in street canyons in particular(Lee et al., 2016)[76].

Some studies have shown that the distribution and species of vegetation have an important impact on the outdoor environment(Wu et al., 2017; Zhang et al., 2018)[77, 78]. Besides, Li et al.(2018a)[79] conducted a research on the spatiotemporal dynamic impact of tree canopy on temperature, with the result showing that neighborhood differences might affect, and impervious surfaces have an influence on the temperature. This paper pointed to the importance of scale in importance

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72 Tae Won Ahn and Hyun Kil Jo, "Exploring Relationships between Urban Tree Plantings and Microclimate Amelioration." *Journal of the Korean Institute of Landscape Architecture*, 34 (5), 2006, pp.70-75.

73 Lee Jae Yoon and Ki Kyong Seok, "Correlation Between the Microclimate and the Crown of Platanus orientalis and Ulmus davidiana." *Journal of Environmental Ecological*, 30 (4), 2016, pp.793-799.

74 M. Fahmy, H. El-Hady, M. Mandy, et al., "On the green adaptation of urban developments in Egypt; predicting community future energy efficiency using coupled outdoor-indoor simulations." *Energy and Buildings*, 153, 2017, pp.241-261.

75 K. Fabbri, G. Canuti and A. Ugolini, "A methodology to evaluate outdoor microclimate of the archaeological site and vegetation role: A case study of the Roman Villa in Russi (Italy)." *Sustainable Cities and Society*, 35, 2017, pp.107-133.

76 S. H. Lee, H. Lee, S. B. Park, et al., "Impacts of in-canyon vegetation and canyon aspect ratio on the thermal environment of street canyons: numerical investigation using a coupled WRF-VUCM model." *Quarterly Journal of the Royal Meteorological Society*, 142 (699), 2016, pp.2562-2578.

77 Z. F. Wu and L. D. Chen, "Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: Integrating modeling with in-situ measurements." *Landscape and Urban Planning*, 167, 2017, pp.463-472.

78 L. Zhang, Q. M. Zhan and Y. L. Lan, "Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters." *Building and Environment*, 130, 2018, pp.27-39.

79 Y. Li, W. Kang, Y. Han, et al., "Spatial and temporal patterns of microclimates at an urban forest edge and their management implications." *Environmental Monitoring and Assessment*, 190 (2), 2018, pp.13.

microclimate assessments. And they also explored the marginal effects of vegetation[80].

What's more, urban vegetation, in the form of green spaces, parks, street trees, green roofs, has always been a focus of research(Jo et al., 1999; Jo et al., 2000; Park, 2013; Moon et al., 2015; Lee et al., 2016; Kim et al., 2017; Santamouris et al., 2014)[81, 82, 83, 84, 85, 86, 87].

Influence of Microclimate on Other Factors

As the fog and haze become increasingly known as the challenges faced by

80 Li Y., W. Kang, Y. Han, et al. (2018). "Spatial and temporal patterns of microclimates at an urban forest edge and their management implications." Environmental Monitoring and Assessment, 190(2): 13.

81 Hyun Kil Jo and Tae Won Ahn, "Function of Microclimate Amelioration by Urban Greenspace " *Journal of the Korean Institute of Landscape Architecture*, 27 (4), 1999, pp.23-28.

82 Hyun Kil Jo and Yoshiteru Nojimal, "Effects of Urban Greenspace on Microclimate Amelioration, CO_2 Sequestration and Fire Obstruction." *Journal of the Korean Institute of Plant Resources*, 13 (3), 2000, pp.162-170.

83 Jong Hoon Park, Air temperature reduction effects of small green spaces in urban blocks of Seoul, Korea, Doctor's degree. (Seoul National University, 2013), Pages.

84 Jooyeon Moon, Chul Hee Lim, Cholho Song, et al., "Climate Impact of Urban Forest near Urban Communities in Seoul, Dongdaemun-gu, Baebong Mountain." *Journal of Korean Society for Geo-Spatial Information System*, 2015 (5), 2015, pp.121-124.

85 Jae Yoon Lee, Kyong Seok Ki, Bo Hyun Kim, et al., "Microclimate Impacts by Highlands Large Facilities of Mudeungsan Nationalpark." *Journal of Korean Institute of Environmental ecology*, 2016 (2), 2016, pp.131-131.

86 Jeong Ho Kim, Won Jun Choi and Yong Han Yoon, "A Study on the Temperature Reduction Effect of Street Green Area." *Journal of Korean Society for Environmental Science*, 26 (12), 2017, pp.1363-1374.

87 Mattheos Santamouris, "Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments." *Solar Energy*, 103, 2014, pp.682-703.

many cities, the quantitative study of the influence of air quality on microclimate is also emerging(Kim et al., 2012; Mei et al., 2017; Ostovic et al., 2017)[88, 89, 90].

As high ambient temperature and air pollution might have a negative impact on health, experts began to study the subject of microclimate and health(Evans et al., 2017; Schinasi et al., 2018)[91, 92].

(3) Methodology of Microclimate

The earliest research methods of microclimate are ground observation and field measurement. Later, large-scale monitoring based on satellite remote sensing technology emerged gradually. Due to the shortcomings of traditional field measurement, such as high cost, low mobility and weather constraint, and high accuracy requirement in remote sensing, environmental simulation has become the first choice of many types of research.

The application of simulation models is mainly divided into two categories:

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88 Dong Min Kim and Myeong In Lee, "Influences of the Urban Microclimate Structure on the Air Pollutant Dispersion over the Ulsan Metropolitan Area." *Journal of Korean Society for Atmospheric Environment*, 2012 (5), 2012, pp.26-26.

89 D. Mei, Y. Wang and Q. H. Deng, "Modeling the Airflow and Particle Dispersion in Street Canyons under Unsteady Thermal Environment with Sinusoidal Variation." *Aerosol and Air Quality Research*, 17 (4), 2017, pp.1021-1032.

90 M. Ostovic, S. Mencik, I. Ravic, et al., "Relation between microclimate and air quality in the extensively reared turkey house." *Macedonian Veterinary Review*, 40 (1), 2017, pp.83-90.

91 M. V. Evans and C. C. Murdock, "Urban microclimate and dengue vector competence of the invasive asian tiger mosquito, aedes albopictus." *American Journal of Tropical Medicine and Hygiene*, 95 (5), 2017, pp.60-60.

models based on energy balance model or computational fluid dynamics. Models based on energy balance include Monolayer Model, Multi-layer model, Cluster Thermal Time Constant(CTTC), a design tool for urban microclimate thermal environment named DUTE and so on[93].

And the Computational Fluid Dynamics(CFD) model is a representative of the computational fluid dynamics model. This model based on the Navier-Stokes control equations has been designed at micro-scale by Oke(1988)[94]. At present, the CFD model has been widely used in the analysis of the wind and thermal environment of urban microclimate at the human body scale, in particular in wind environment(Kim, 2014; Antoniou et al., 2017; Shirzadi et al., 2017; Toparlar et al., 2017) [95, 96, 97, 98].

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92 L. H. Schinasi, T. Benmarhnia and A. J. De Roos, "Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis." *Environmental Research*, 161, 2018, pp.168-180.

93 Zong Hua, Zhou Ye and Li Junqiang, "The Current Situation, Characteristics and Prospects of Microclimate Research of Outdoor Habitat Environment in Urban and Rural Area." *Ecological Economy* (01), 2018, pp.145-152.

94 T. R. Oke, *Boundary layer climates (2nd ed.)L* (London: Routledge, 1988).

95 Jae Kwon Kim, The Comparisons of the Field Measurement and CFD Simulation Results in Outside City hall of Thermal and Wind Environment, Master's degree. (Hoseo University, 2014), Pages.

96 N. Antoniou, H. Montazeri, H. Wigo, et al., "CFD and wind-tunnel analysis of outdoor ventilation in a real compact heterogeneous urban area: Evaluation using "air delay"." *Building and Environment*, 126, 2017, pp.355-372.

97 M. Shirzadi, P. A. Mirzaei and M. Naghashzadegan, "Improvement of k-epsilon turbulence model for CFD simulation of atmospheric boundary layer around a high-rise building using stochastic optimization and Monte Carlo Sampling technique." *Journal of Wind Engineering and Industrial Aerodynamics*, 171, 2017, pp.366-379.

After Bruce et al.(1998)[99] developed the non-static software ENVI-met based on CFD and thermodynamic theory, this tool has been widely applied, and considered to be the best 3D microclimate simulation program.

Duarte et al.(2015)[100] used ENVI-met to analyze the cooling effect of vegetation in the urban environment. Tseliou et al.(2016)[101] calculated the daily microclimate changes in the city area by ENVI-met. The purpose of Sharmin(2017)[102]'s study was to make a specific comparison of how measured data and the simulated data by the microclimate simulation tool ENVI-met worked in complex geometry. It tried to demonstrate how to use the correct inputs as a boundary condition to make better outputs.

Based on the above models and theories, some of the simulation tools are shown in Table 1-1.

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98 Y. Toparlar, B. Blocken, B. Maiheu, et al., "A review on the CFD analysis of urban microclimate." *Renewable & Sustainable Energy Reviews*, 80, 2017, pp.1613-1640.

99 Bruse M and Fleer H, "Simulating surface plant-air interactions inside urban environments with a three dimensional numerical model." *Environmental Modeling & Software*, 13 (4), 1998, pp.373-384.

100 Duarte D H S, Shinzato P, Gusson C D S, et al., "The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate." *Urban Climate*, 14, 2015, pp.224-239.

101 Tseliou A and Tsiros I X, "Modeling urban microclimate to ameliorate thermal sensation conditions in outdoor areas in Athens (Greece)." *Building Simulation*, 9 (3), 2016, pp.251-267.

102 T. Sharmin, K. Steemers and A. Matzarakis, "Microclimatic modelling in assessing the impact of urban geometry on urban thermal environment." *Sustainable Cities and Society*, 34, 2017, pp.293-308.

[Table 1-1] Simulation tools and contents[103]

Tool	Type	Content
ENVI-met	Microclimate	Thermal environment, Wind, Pollutant, Vegetation effect
Flunet	Residential area	Thermal environment, Wind, Pollutant
RayMan	Urban climate	Thermal environment
CFX		Thermal environment, Wind
AUSSSMTOOL	UHI	Thermal environment
DUTE	Residential area	Thermal environment
PHOENICS	Building	Thermal environment, Wind, Pollutant, Vegetation effect
Autodesk Ecotect Analysis	Building CFD	Thermal environment, Wind, Sunlight simulation
IESve	Building CFD	Thermal environment, Wind, Sunlight simulation
PKPM Sunlight	Building sunlight	Sunlight simulation
CFD2000	CFD	Thermal environment, Wind
FastSUN	Building sunlight	Sunlight simulation

On the other hand, the development of simulation models at the urban level is emerging in an endless stream. Among them, there is a lot of research on urban energy simulation models(Afshari, 2017; Afshari et al., 2017; Martin et al., 2017; Frayssinet et al., 2018)[104, 105, 106, 107]. There has also studied on Integrated

103 Zhang Jun, ENVI-met Simulation of Summer Microclimate in Xi'an Hanguang Street Canyondegree. (Xi'an University of Architecture and Technology, 2017), Pages.
104 A. Afshari, "A new model of urban cooling demand and heat island application to vertical greenery systems (VGS)." *Energy and Buildings*, 157, 2017, pp.204-217.

Multi-scale Environmental Urban Model(IMEUM)(Lim et al., 2017)[108].

(4) Evaluation of Microclimate Comfort

Microclimate comfort is the perception of human on environmental microclimate. And temperature is one of the most important factors. At present, thermal comfort is commonly regarded as an evaluation benchmark for microclimate perception. While researches on indoor environment comfort are more mature, the study of outdoor comfort is still in its infancy. For the reason of more complex outdoor environment, indoor comfort indexes such as PMV, ASHRAE, WBGT, PSI, HI, are widely used in the field of outdoor microclimate comfort, also constantly revised as well.

1.2.3 Research on Outdoor Thermal Comfort

As the case stands, except the research of the outdoor thermal comfort that focus on the analysis or evaluation of the characteristics and changes of urban outdoor thermal environment by methods of measurement and simulation(Kim,

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105 A. Afshari and N. B. Liu, "Inverse modeling of the urban energy system using hourly electricity demand and weather measurements, Part 2: Gray-box model." Ibid., pp.139-156.

106 M. Martin, N. H. Wong, D. J. C. Hii, et al., "Comparison between simplified and detailed EnergyPlus models coupled with an urban canopy model." Ibid., pp.116-125.

107 L. Frayssinet, L. Merlier, F. Kuznik, et al., "Modeling the heating and cooling energy demand of urban buildings at city scale." *Renewable & Sustainable Energy Reviews*, 81, 2018, pp.2318-2327.

108 T. K. Lim, M. Ignatius, M. Martin, et al., "Multi-scale urban system modeling for sustainable planning and design." *Energy and Buildings*, 157, 2017, pp.78-91.

2014; Ryu et al., 2016; Kim et al., 2016a; Kim et al., 2016b; Eum, 2016)[109, 110, 111, 112, 113], not a few have also discussed the impact of landscape elements on the thermal environment.

Such as Sun et al.(2017)[114] studied the thermal comfort potential of a park in Beijing and the effect of the numerical simulation of the landscape parameters. Research on the influence of landscape parameters on human thermal sensation by Park(2013)[115]. The influence of the landscape elements as water, river for example(Jung, 2012)[116]. And additionally many research concerned about vegetation, especially the impact of trees on thermal comfort launched by landscape architects in South Korea(Ryu et al., 2015; Wesam et al., 2015; Park et al., 2016; Jo

109 Yoon Ha Kim, Analysis of Thermal Environment over a Small Scale Landscape using ENVI-met Model, Master's degree. (Konkuk University, 2014), Pages.

110 Nam Hyong Ryu and Chun Seok Lee, "Thermal Environments of Children's Parks during Heat Wave Period." *Journal of the Korean Institute of Landscape Architecture*, 44 (6), 2016, pp.84-97.

111 Jeong Ho Kim, Hak Gi Kim, Yong Han Yoon, et al., "Thermal Environment Transition of Response Climate Change and Heat Wave Application Evaporative Cooling System." *Journal of Korean Society for Environmental Science*, 25 (9), 2016, pp.1269-1281.

112 Jeong Ho Kim, Won Jun Choi and Yong Han Yoon, "A Study on Verifying the Effect of Thermal Environment Control of Street Canyons based on Application of Green Wall System." *Journal of Korea Society for Environmental Science*, 25 (2), 2016, pp.311-322.

113 Jeong Hee Eum, "Vulnerability Assessment to Urban Thermal Environment for Spatial Planning - A Case Study of Seoul, Korea - " *Journal of the Korean Institute of Landscape Architecture*, 44 (4), 2016, pp.109-120.

114 S. B. Sun, X. Y. Xu, Z. M. Lao, et al., "Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation." *Building and Environment*, 123, 2017, pp.277-288.

115 Soo Kuk Park, "Landscape Planning and Design Methods with Human Thermal Sensation." *Journal of the Korean Institute of Landscape Architecture*, 40 (1), 2012, pp.1-11.

et al., 2017)[117, 118, 119, 120].

What's more, in the field of urban design and landscape design, more discussions are made on how to improve thermal comfort through design. And most of them tried to improve outdoor thermal comfort by adjusting microclimate.

For instance, Barakat et al.(2017)[121] intended to improve the design of thermal comfort by simulating the microclimate. Du et al.(2017)[122] proposed a kind of design named Lift-up Design and analyzed its influence on thermal comfort. A complete design method of urban open space considering microclimate was

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116 Yong Hoon Jung, A Study on the Impact on Thermal Environments around Urban River Restorations : Focused on Beomeo Stream of Daegu City, Master's degree. (Keimyung University, 2012), Pages.

117 Nam Hyong Ryu and Chun Seok Lee, "The Gradient Variation of Thermal Environments on the Park Woodland Edge in Summer -A Study of Hadongsongrim and Hamyangsangrim- " *Journal of the Korean Institute of Landscape Architecture*, 43 (6), 2015, pp.73-85.

118 Wesam M El-Bardisy, Mohammad Fahmy and Germeen F El-Gohary, "Climatic Sensitive Landscape Design: Towards a Better Microclimate through Plantation in Public Schools, Cairo, Egypt." *Procedia-Social and Behavioral Sciences*, 216, 2016, pp.206-216.

119 Jong Hwa Park, Jeongseob Kim, Dong Keun Yoon, et al., "The influence of Korea's green parking project on the thermal environment of a residential street." *Habitat International*, 56, 2016, pp.181-190.

120 Sang Man Jo, Cheol Ji Hyun and Soo Kuk Park, "Analysis of the Influence of Street Trees on Human Thermal Sensation in Summer " *Journal of the Korean Institute of Landscape Architecture*, 45 (5), 2017, pp.105-112.

121 A. Barakat, H. Ayad and Z. El-Sayed, "Urban design in favor of human thermal comfort for hot arid climate using advanced simulation methods." *Alexandria Engineering Journal*, 56 (4), 2017, pp.533-543.

122 Y. X. Du, C. M. Mak, T. Y. Huang, et al., "Towards an integrated method to assess effects of lift-up design on outdoor thermal comfort in Hong Kong." *Building and Environment*, 125, 2017, pp.261-272.

proposed by Marianna et al.(2017)[123], that can provide necessary information for designers to help them make decisions. Or to determine the order of the design, Nouri et al.(2017)[124] used microclimatic considerations as the standard of priorities for thermal sensitive Public Space Design(PSD).

Evaluation Methodology

In the discussion of the evaluation method of outdoor thermal comfort, Cheunge et al.(2017)[18] summarized the research on outdoor thermal comfort, established a conceptual framework of the human thermal environment. They recommended a package of analytical methods and explained how to determine the scope of the outdoor thermal benchmark as well. Thermal behavior and the comfort conditions were taken into consideration in the research of Ruiz et al.(2017)[125].

At present, the evaluation methods of outdoor thermal comfort can be divided into questionnaire evaluation, physiological parameter evaluation and model evaluation.

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123 Marianna Tsitoura, Marina Michailidou and Theocharis Tsoutsos, "A bioclimatic outdoor design tool in urban open space design." *Energy and Buildings*, 153, 2017, pp.368-381.

124 A. S. Nouri, J. P. Costa and A. Matzarakis, "Examining default urban-aspect-ratios and sky-view-factors to identify priorities for thermal-sensitive public space design in hot-summer Mediterranean climates: The Lisbon case." *Building and Environment*, 126, 2017, pp.442-456.

125 M Angélica Ruiz, M Belén Sosa, Erica N Correa, et al., "Design tool to improve daytime thermal comfort and nighttime cooling of urban canyons." *Landscape and Urban Planning*, 167, 2017, pp.249-256.

Research conducted by Huang et al.(2017)[126] compared three kinds of thermal comfort models and questionnaire survey results, characterized that elevated buildings have benefits on microclimate at pedestrian level but the models need to be refined. Because of the feature of subjective consciousness of thermal comfort, it is most direct and effective to make evaluation by scientific and reasonable questionnaire. However, this method only relies on responses, neglects all physical environment, and therefore is easily disturbed by the subjective cognition and psychological state of the respondents.

In order to reduce the influence of subjectivity, some studies used the physiological parameters based on body temperature balance and body physiological adjustment to evaluate thermal comfort. But the representativeness of physiological parameters for thermal comfort is lacking in textual research. Thus theoretical or empirical models were proposed. These models are used to simulate the thermal sensation of human body and establish an evaluation system which is not influenced by subjective factors. Such as Cold Sense Degree Hour(CSDH) and Hot Sense Degree Hour(HSDH) given by Kee(2015)[127] were verified in 6 cities of different climate zones.

According to the type of evaluation model, thermal comfort evaluation indexes

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126 Taiyang Huang, Jianong Li, Yongxin Xie, et al., "Simultaneous environmental parameter monitoring and human subject survey regarding outdoor thermal comfort and its modelling." *Building and Environment*, 125, 2017, pp.502-514.

127 Hyun Joo Kee, A Study on Evaluation Method of the Outdoor Thermal Comfort, Master's degree. (SungKyunKwan University, 2015), Pages.

can be divided into two categories. The early research results are mostly index based on the empirical model.

Among them, human thermal stress index Effective Temperature(ET) and Corrected Effective Temperature(CET) which are based on the main factors of air temperature, relative humidity and wind speed; The empirical formula of human heat dissipation rate based on wind speed and temperature called Wind Chill Index(WCI)[128]; Wet Bulb Globe Temperature(WBGT) which is one of the most widely used indicators of thermal safety at present; And the basic temperature index Discomfort Index(DI), which calculates the numbers of days of cooling degree; Evaluation index of Heat Stress Index(HSI) and Apparent Temperature(AT) with two meteorological elements of combination of temperature and relative humidity; are still widely used nowadays[17].

This kind of indexes is simple and easy to understand, but the factors to be considered are insufficient, especially the related factors of the human body mechanism. And there are also some shortcomings such as low accuracy and limitation in temporal and spatial.

With the development of Biometeorology and computer technology, the development of the thermal comfort model is based on the mechanism of human energy balance and heat exchange. And various factors such as environmental factors, metabolism of human body, respiration and heat dissipation, clothing heat

128 Sun Meishu and Li Shan, "Empirical Indices Evaluating Climate Comfortableness: Review and Prospect." *Tourism Tribune*, 30 (12), 2015, pp.19-34.

resistance, are taken into consideration in the simplified model of theoretical type.

[Table 1-2] Evaluation index of thermal environment

Type	Index	Range
Empirical type	Effective Temperature(ET)	24.28-28.59℃
	Wind Chill Index(WCI)	
	Wet Bulb Globe Temperature(WBGT)	<18℃
	Discomfort Index(DI)	18-21℃
	Heat Stress Index(HSI)	38.24-60.13
	Apparent Temperature(AT)	<27℃
Theoretical type	Predicted Mean Vote(PMV)	-0.5 - 0.5
	Perceived Temperature(PT)	0-20℃
	Outdoor Standard Effective Temperature(OUT_SET*)	23.8-28.5℃
	Physiologically Equivalent Temperature(PET)	18-23℃
	Universal Effective Temperature(UET)	
	Universal Thermal Climate Index(UTCI)	9-26℃

Common indicators for theoretical type include: The most representative index of indoor comfort, Predicted Mean Vote(PMV); Perceived Temperature(PT) based on the equivalent temperature of the complete thermal budget model of the human body; Outdoor Standard Effective Temperature(OUT_SET*) which combines air temperature, relative humidity, mean radiation temperature, wind speed, clothing thermal resistance and activity level; Physiologically Equivalent Temperature(PET) as an evaluation index of outdoor thermal comfort considering human physiological factors and meteorological elements[129]; Universal Effective Temperature(UET) that can indicate both universal and separate effects of environmental factors with consideration of solar radiation and heat conduction[130]; And a comprehensive evaluation index named Universal Thermal Climate Index(UTCI) that considering outdoor meteorological elements and physiological thermal parameters and so on[129].

So far, although PET and PMV have the largest number of applications, UTCI is becoming more and more popular for the evaluation of outdoor thermal comfort. Indicators and the corresponding thermal comfort range are shown in Table 1-2.

Beyond the topics above, due to the difference in perception of thermal environment among different populations, based on these physical environmental indicators, more and more research begin to study the relationship between human behavior and microclimate(Chokhachian et al., 2017; Chapman et al., 2017; Xue et al., 2017; Salata et al., 2017)[131, 132, 133, 134].

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129 Ricardo Forgiarini Rupp, Natalia Giraldo Vásquez and Roberto Lamberts, "A review of human thermal comfort in the built environment." *Energy and Buildings*, 105, 2015, pp.178-205.
130 K. Nagano and T. Horikoshi, "New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions." Ibid., 43 (7), 2011, pp.1694-1701.
131 A. Chokhachian, D. Santucci and T. Auer, "A Human-Centered Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces." *Buildings*, 7 (4), 2017, pp.23.
132 David Chapman, Kristina Nilsson, Agneta Larsson, et al., "Climatic barriers to soft-mobility in winter: Luleå, Sweden as case study." *Sustainable Cities and Society*, 35, 2017, pp.574-580.
133 Fei Xue, Zhonghua Gou and Stephen Siu Yu Lau, "Green open space in high-dense Asian cities: Site configurations, microclimates and users' perceptions." *Sustainable Cities and Society*, 34, 2017, pp.114-125.

Thermal Comfort of Pedestrians

Research on thermal comfort of the pedestrian is mostly carried out in urban canyon layer. The thermal comfort evaluation indicators summarized above are also used to evaluate the thermal comfort of pedestrians. What others that Nasrollahi et al.(2017)[135] evaluated the situation of thermal comfort, including performing field measurements in the intended historical sites, and determined the thermal comfort range of tourists through questionnaires.

In the thesis of Wang(2016)[136] on the thermal environment of commercial streets, the thermal comfort was analyzed using Rayman model based on the measured data, and an optimization proposal to increase the membrane structure and use the air curtain at the entrance of the shopping mall to enhance the local airflow was proposed as a research conclusion.

In the study of the influencing factors of thermal comfort of pedestrians, as concluded in the section1.2.2, canyon geometry is the most popular research. What's more, there are also many studies on the impact of greening and pavement materials. For example, the effects of street trees on the thermal comfort of

134 F. Salata, I. Golasi, R. Proietti, et al., "Implications of climate and outdoor thermal comfort on tourism: the case of Italy." *International Journal of Biometeorology*, 61 (12), 2017, pp.2229-2244.
135 N. Nasrollahi, Z. Hatami and M. Taleghani, "Development of outdoor thermal comfort model for tourists in urban historical areas; A case study in Isfahan." *Building and Environment*, 125, 2017, pp.356-372.
136 Wang Yaxin, Measurement and Evaluation of Thermal Environment in Outdoor Pedestrian Space of Commercial Complexdegree. (Guangxi University, 2016), Pages.

pedestrians were studied by Han et al.(2013)[137] and Jo et al.(2017)[120]. These studies generally believe that increasing street greening rate can reduce solar radiation and reduce heat island intensity.

In addition, many types of research focused on the improvement of thermal comfort have paid much attention to pavement material(Rosso et al., 2017; Rosso et al., 2018; Djekic et al., 2018)[138, 139, 140]. With respect to the effect of pavement material on the thermal comfort of pedestrians, the higher the reflectivity and permeability of the material, the stronger ability of the temperature and humidity interaction, which has a positive effect on the thermal comfort.

In other words, designers can improve the thermal comfort of pedestrians by choosing reasonable street landscape designs, such as greening configuration and pavement material.

1.2.4 Enlightenment and Outlook

To sum up, the elements of the microclimate include solar radiation,

137 Bong Ho Han, Jeong In Kwak, Tai Hwan Noh, et al., "A Study on Impact Analysis of Thermal Environmental Index per Rodeside Tree Type Using ENVI-met " *Journal of Korean Institute of Environmental ecology*, 2013 (2), 2013, pp.96-97.

138 F. Rosso, A. L. Pisello, V. L. Castaldo, et al., "On Innovative Cool-Colored Materials for Building Envelopes: Balancing the Architectural Appearance and the Thermal-Energy Performance in Historical Districts." *Sustainability*, 9 (12), 2017, pp.13.

139 F. Rosso, I. Golasi, V. L. Castaldo, et al., "On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons." *Renewable Energy*, 118, 2018, pp.825-839.

temperature, humidity, wind, precipitation, longwave radiation, heat reflection and sunshine. Among them, the influence of solar radiation, temperature, humidity and wind on outdoor thermal comfort is the most important. Factors that can influence microclimate contain spatial form elements, such as building density, floor area ratio, aspect ratio, building height, street orientation, space enclosure and architectural layout mode. And other factors, covering vegetation, water, surface material, color, building material, detail structure and so on(Table 1-3).

When considering outdoor thermal comfort, human factors certainly can never be ignored. But in this study, human activities and psychological aspects are not discussed.

The previous researches show that although the development of micro-scale measuring tools is progressing, the means of improving thermal comfort through improvement of microclimate elements are increasing. But so far, this cannot directly guide the process of outdoor microclimate optimization.

As the application of microclimate, although current researches involve different climatic zones and local microclimate, most of them are launched only in summer and daytime, and lack of continuous consideration of seasons and at night. That’s why a long and periodic study should be carried out in future research. Moreover, it is necessary to increase the study on the improvement of microclimate

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140 J. Djekic, A. Djukic, M. Vukmirovic, et al., "Thermal comfort of pedestrian spaces and the influence of pavement materials on warming up during summer." *Energy and Buildings*, 159, 2018, pp.474-485.

conditions in the built environment.

[Table 1-3] Relationship between factors affecting microclimate & meteorological elements

Factors		Temperature	Wind Speed	Radiation
Urban Form	Aspect ratio	■	■	■
	Street orientation	■	■	■
	Space enclosure	■	■	■
	Architectural layout	■	■	■
	Building density	■	■	■
	Floor area ratio	■	□	■
Building	Building height	■	■	■
	Building material	■	-	■
Landscape	Vegetation	■	■	■
	Water	■	-	■
	Surface material	■	-	■
	Color	■	-	■
	Design structure	-	-	■

(■ means significant relationship; □ means weak significant; - means not significant.)

On the aspect of outdoor thermal comfort, because the evaluation system covering all the factors of meteorological, geography, humanities, physiology and psychology, universality standard is not applicable. The evaluation of outdoor thermal environment should use indicators specially designed for outdoor space.

As a whole, there are many papers focusing on the design of walking space. Until recently, this field began to notice the microclimate of walking space. But most of these studies are based on the condition of microclimate or outdoor thermal comfort and the influence of urban form is mainly concerned. There are a few types of research on landscape design, and most of them only put forward qualitative improvement suggestions. However, there are issues on whether the design decision can improve the outdoor thermal comfort, how much can it improve, what kind of plan is the best choice……Only by answering this series of questions can designers really make scientific plans. This is also one of the fields for scientific research to explore.

1.3 Research Methodology

This study uses the visualization and quantization tools to show how the design choices affect the outdoor thermal comfort at the pedestrian level. And this can help architects and designers get a better understanding of the microclimate of outdoor space when working on an environmental-friendly and human-centered solution during renovation and regeneration processes.

1.3.1 Methods

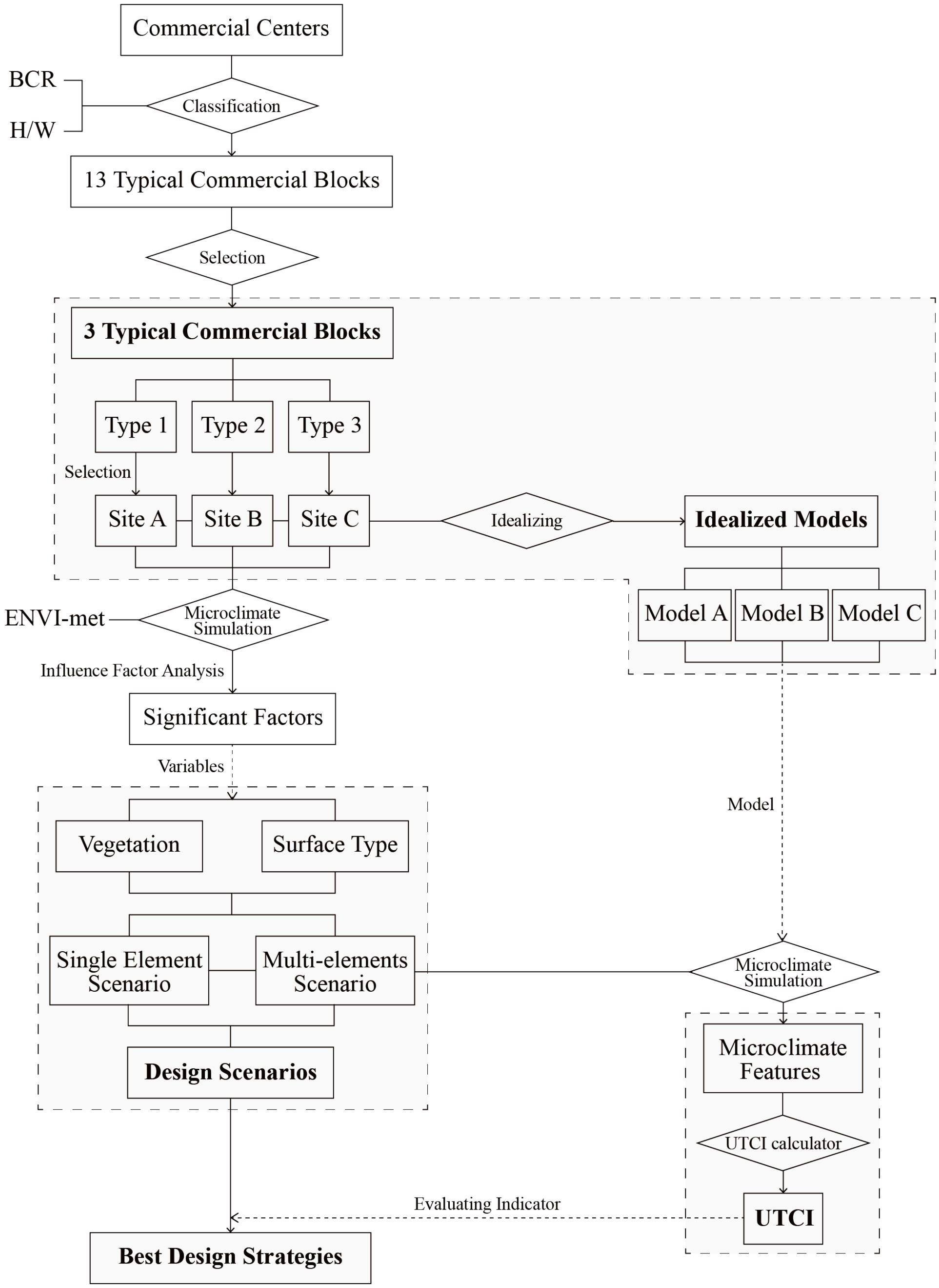
After classifying the commercial centers in Seoul metropolitan city according to urban form conditions, three typical blocks are selected as research areas. Then by idealizing the typical real sites, design scenarios about vegetation and surface type are set up to study the effects of different design strategies on alleviating the outdoor heat stress by using an outdoor thermal comfort indicator, in commercial streets based on idealized models.

The first tool used in this study is ENVI-met, which is used to simulate microclimate elements in this study. Compared with other tools, on the time scale, it can simulate every hour. On the spatial scale, many details for the street environment needed to be studied in this paper can be analyzed by this tool. On the other hand, in the aspect of pedestrian space design, it can establish vegetation models and provide simulating vegetation functions while many tools cannot. Besides, its operating system is simple and clear, and its application is very extensive.

Secondly, UTCI Calculator will be used to calculate UTCI to evaluate the outdoor thermal comfort of pedestrians. Compared with many other evaluation indexes based on indoor thermal comfort, UTCI considers the outdoor meteorological elements and the thermal adaptability of human body, which has been verified at a different scale and climate zones as well.

The research process of the whole study is shown in Figure 1-1.

1.3.2 Research Process



[Figure 1-1] Research Process

Chapter 2 Real Site and Idealized Model

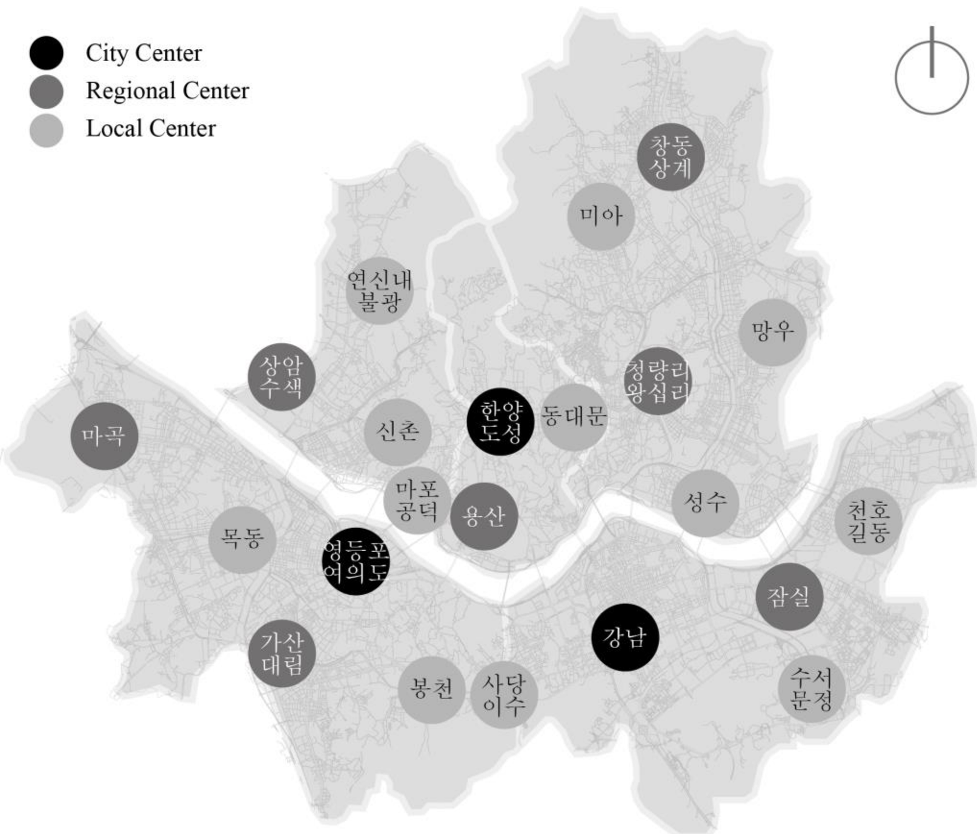
2.1 Archetypal Commercial Block

2.1.1 Real Commercial Block

The walking space discussed in this study is focused on the latter two of the three kinds of layer discussed in the field of urban microclimate, which are urban boundary layer, urban canopy layer and urban street canyon. From the architectural point of view, urban canopy layer corresponds to urban texture, which mainly includes road network and block structure. And urban street canyon corresponds to the urban street space. Previous research shows that the design of urban block and street space has a significant impact on the microclimate of the urban street canyon. This is also the scale for the selection criterion of typical areas in this chapter.

The archetypal forms of Seoul commercial block are enumerated and analyzed in this section to ascertain typical real forms. In the '2030 Seoul Plan', 3 city centers, 7 regional centers and 12 local centers were planned. The position of which is shown in Figure 2-1.

As the empirical basis for this categorization, urban forms of these 22 commercial areas are identified. Which are evenly distributed in the northeast, northwest, southeast, southwest and central areas of Seoul. Although local or microclimate condition of these areas differ significantly, they are all in the same climate zone of temperate monsoon climate, and located in the same city. The completion time and the development modes of these commercial areas are quite different, but whether they are generated by planning or not, they have undergone the same urban rapid change in recent decades. Precisely because of this heterogeneity, studying on improving the outdoor thermal comfort of pedestrians in different types of commercial block form, allows for a far-reaching meaning on the construction of 53 living zone centers planned in the '2030 Seoul Living Zone Plan'.



[Figure 2-1] 22 commercial centers planned in '2030 Seoul Plan'

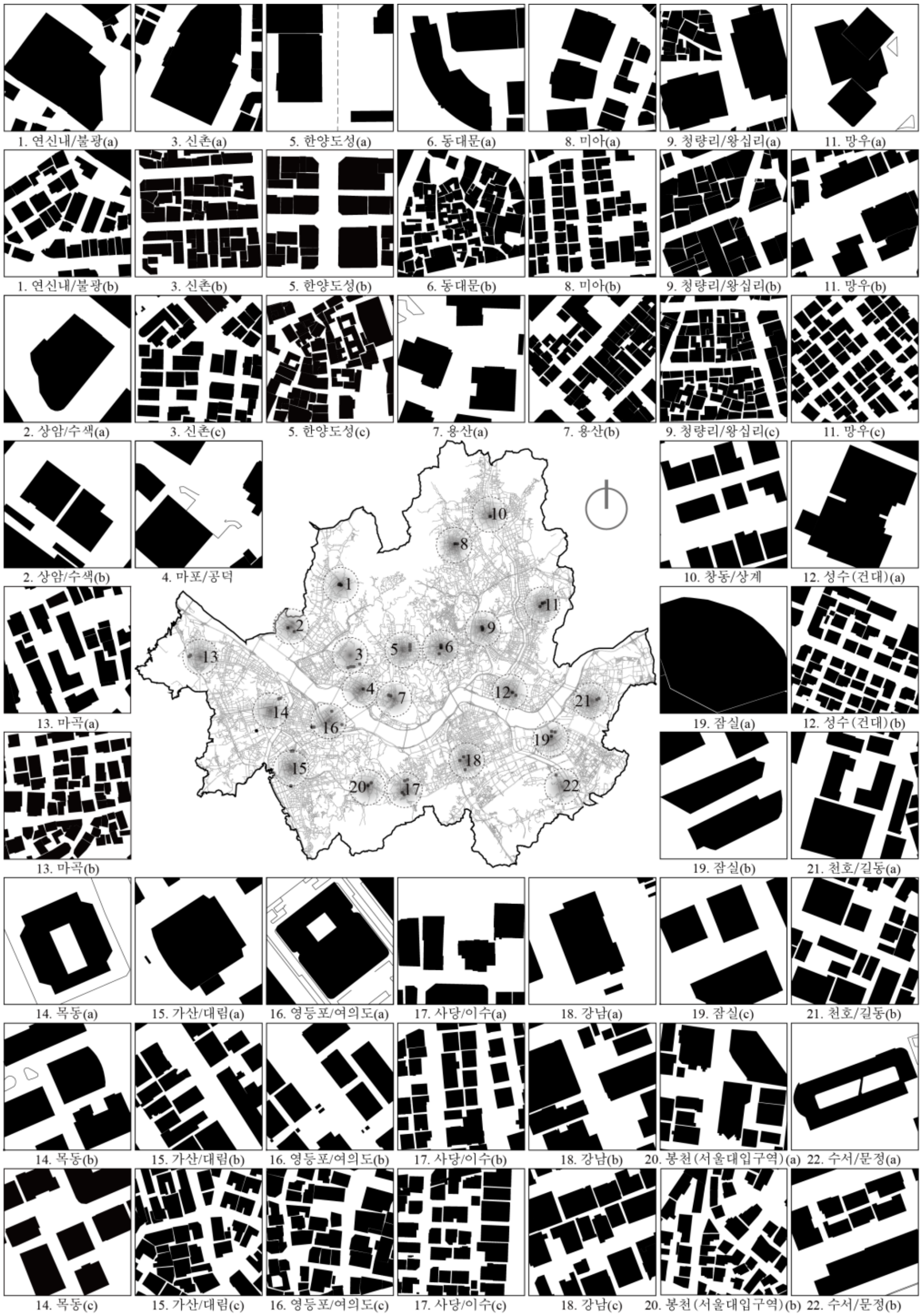
2.1.2 Categorization

The categorization of real commercial block types aims to create generic idealized models, which will be modeled for studying the effect of different landscape design strategies in Chapter 5.

Firstly, this study initial scanned the all 22 commercial blocks in the 2D map such as Daum Map. Then the urban form in those blocks is explored via visual maps such as 3D Seoul(3dgis.seoul.go.kr).

[Table 2-1] 52 blocks in 22 commercial centers in Seoul

	Name		Name		Name		Name
1	연신내/불광(a) 연신내/불광(b)	7	용산(a) 용산(b)	13	마곡(a) 마곡(b)	17	사당/이수(a) 사당/이수(b) 사당/이수(c)
2	상암/수색(a) 상암/수색(b)	8	미아(a) 미아(b)	14	목동(a) 목동(b) 목동(c)	18	강남(a) 강남(b) 강남(c)
3	신촌(a) 신촌(b)	9	청량리/왕십리(a) 청량리/왕십리(b) 청량리/왕십리(c)	15	가산/대림(a) 가산/대림(b) 가산/대림(c)	19	잠실(a) 잠실(b) 잠실(c)
4	마포/공덕	10	창동/상계	16	영등포/여의도(a) 영등포/여의도(b) 영등포/여의도(c)	21	천호/길동(a) 천호/길동(b)
5	한양도성(a) 한양도성(b) 한양도성(c)	11	망우(a) 망우(b) 망우(c)	20	봉천(a) 봉천(b)	22	수서/문정(a) 수서/문정(b)
6	동대문(a) 동대문(b)	12	성수(a) 성수(b)				



[Figure 2-2] Figure & grounds of archetypal blocks in 22 commercial centers

On the basis of the building density, building height, building size, street width and aspect ratio of the urban block, it is found that there are two or even three kinds of urban forms in each of them when looked into these 22 commercial centers. So an area of 100 × 100 m is tailoring to show the different urban forms discovered, a total of 52(Table 2-1 and Figure 2-2).

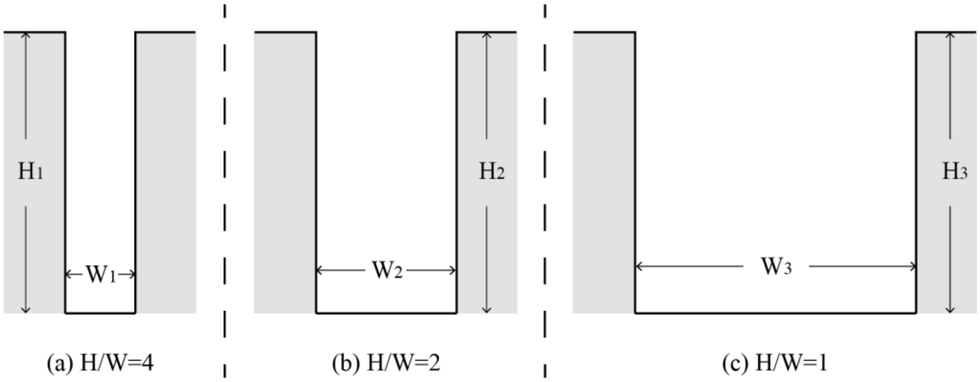
For convenience, 연신내/불광(a) in Table 2-1 is referred to as “1a” for short. The number "1" in "1a" represents the commercial center number 1(연신내/불광), and "a" means 연신내/불광(a). So as 14c means 목동(c), and 수서/문정(b) as 22b.

Additionally, according to the section 1.2.2, the spatial morphological factors such as the building density and the street aspect ratio are closely related to the microclimate condition. Hence the building coverage ratio(BCR, 건폐율) and aspect ratio(H/W) of the street are used to determine the typical blocks.

Fang(2014)[141] used the concept of the scope of vision combined with Gestalt theory to determine the relative scale of the streets. In the field of vision analysis, the street aspect ratio was divided into H/W≤0.75, H/W=1, H/W=2, H/W=4.

According to the aspect ratio distribution of the archetypal commercial areas shown in Figure 2-3, the aspect ratio of the archetypal commercial streets can be divided into shallow, deep, very deep, which correspond to 0<H/W≤2, 2<H/W≤4,

H/W>4 in this study.



[Figure 2-3] Regular types of the aspect ratio of commercial streets

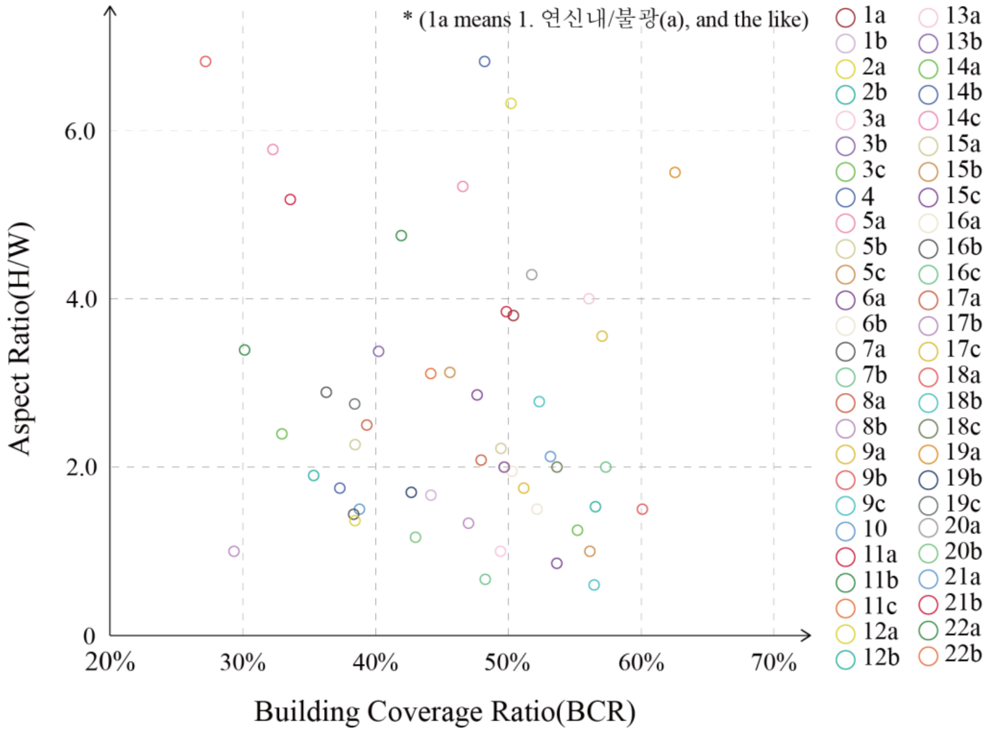
Meanwhile, based on the distribution of the building coverage ratio of the archetypal commercial areas shown in Figure 2-3, the BCR can be divided into low, medium and high levels, corresponding to 20%<BCR≤40%, 40%<BCR≤50%, 50%<BCR≤70%, correspondingly.

However, when calculating BCR, the area of a square of 100 × 100 m chosen by us is taken as the denominator. So before using BCR directly as an indicator, separating the types of only one or two buildings in the 100 m square is needed, with avoiding mixing the large volume buildings with the small ones in the classification. Base on the building size, which is used to calculate BCR, 1000 m^2 is used as a critical value in this study.

Using this benchmark, big building size is including 1a, 2a, 2b, 3a, 4, 5a, 6a,

141 Fang Zhiguo., Song Kun. and Ye Qing., "Reflection of Yoshinobu Ashihara's Research about the Proportion of Street Width to Building Height: A Study of Street Space Based on Human Scale." *New Architecture* (5), 2014.

7a, 9a, 11a, 12a, 14a, 15a, 16a, 18a, 19a, 19b, 19c, 21a, 22a. The others are classified into small building size group relatively.



[Figure 2-4] Distribution diagram of 52 areas based on BCR and aspect ratio

Then the average values of building coverage ratio and aspect ratio in 52 areas are separately counted and shown in Figure 2-4.

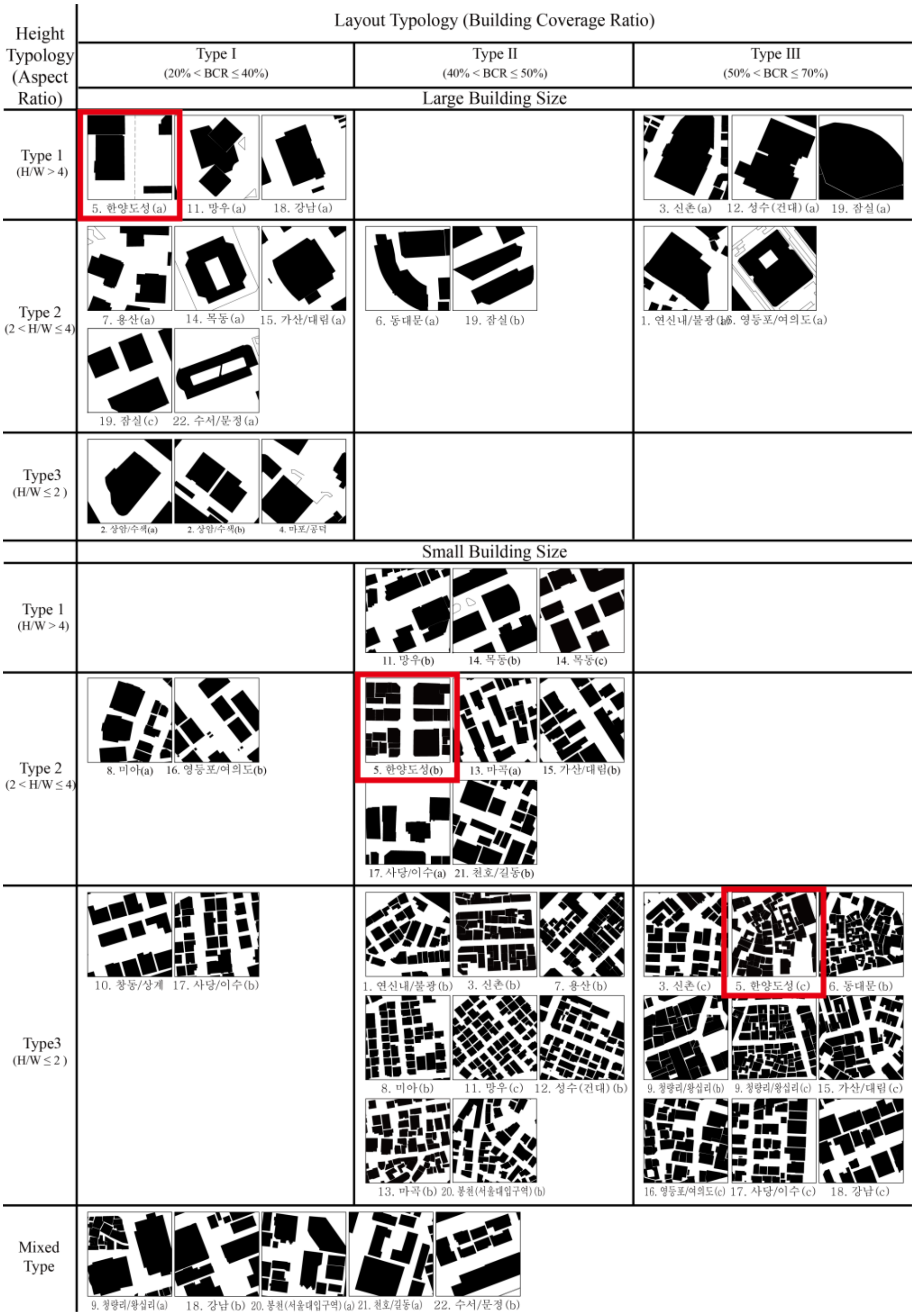
According to the classification criteria mentioned above, 52 areas in Figure 2-2 can be divided into 12 categories. However, considering the figure & ground, there are several of which the urban form has more than one type in such a small area of 100 × 100 m. These are classified as mixed type separately. Therefrom, the archetypal commercial blocks have these 13 categories.

[Table 2-2] Categories of archetypal commercial blocks based on layout and height typology

		Layout Typology(Building Coverage Ratio)		
		20%<BCR≤40%	**40%<BCR≤50%**	**50%<BCR≤70%**
		Large Building Size		
Height Typology (Aspect Ratio)	**H/W>4**	5a, 11a, 18a	-	3a, 12a, 19a
	2<H/W≤4	7a, 14a, 15a, 19c, 22a	6a, 19b	1a, 16a
	0<H/W≤2	2a, 2b, 4	-	-
		Small Building Size		
Height Typology (Aspect Ratio)	**H/W>4**	-	11b, 14b, 14c	-
	2<H/W≤4	8a, 16b	5b, 13a, 15b, 17a, 21b	-
	0<H/W≤2	10, 17b	1b, 3b, 7b, 8b, 11c, 12b, 13b, 20b	3c, 5c, 6b, 9b, 9c, 15c, 16c, 17c, 18c
Mixed type				
9a, 18b, 20a, 21a, 22b				

Due to the limitation of time, it is difficult to study all these 13 types. And urban microclimate located in the same commercial center is comparable. Because not more than three areas are selected in a same commercial center above, 3 representative types will be considered as three typical real sites in this study. In the 22 commercial centers, only in 한양도심(5a, 5b, 5c), three regions have different layout and height typology.

As other commercial block types in Seoul metropolitan city, further research is looking forward to being carried out in the future.



[Figure 2-5] Categories of archetypal commercial blocks based on layout and height typology

[Table 2-3] Parameters of typical commercial blocks as research objects

	Type	Building Coverage Ratio	Street Aspect Ratio
1	Compact Low-rise	50%<BCR≤70%	0<H/W≤2
2	Compact Mid-rise	40%<BCR≤50%	2<H/W≤4
3	Open High-rise	20%<BCR≤40%	H/W>4

Therefore, three areas as 한양도심(a), 한양도성(b), 한양도성(c) are selected as typical real sites in this study. In the light of the characteristics of their urban form, these three types are named as compact low-rise, compact mid-rise and open high-rise. The urban form parameters of which are shown in Table 2-3.

2.2 Typical Real Site

2.2.1 Spatial Scope

In order to study the outdoor thermal comfort of the commercial streets, combined with the above typical block types, three areas contiguous to each other are selected. The reason for selecting an adjacent site is to control climate variables and minimize the mesoscale and large-scale difference between types.

Three areas of 한양도심(5a), 한양도성(5b) and 한양도성(5c), also called as area A, B and C, have main streets named Jongno 11-gil(종로11길), Jongno 12-gil(종로12길) and Euljiro 7-gil(을지로7길) respectively, located in Seoul Jonggak(종각) financial circle. Which are defined as street A, B and C in the following study. The three roads are south-north direction, with the location of the same longitude, perpendicular to Euljiro(을지로), and across Cheonggyecheon(청계천) and Jongno(종로).

(1) Jongno 11-gil (2) Jongno 12-gil (3) Euljiro 7-gil

[Figure 2-6] Scene photos in the streets of three types(from Daum Map street view)

The average value of building coverage ratio and street aspect ratio of the blocks where three roads located are shown in Table 2-4. And street A, B, C correspond to type 1(Compact Low-rise), type 2(Compact Mid-rise), type 3(Open High-rise), respectively.

[Table 2-4] Typical blocks and corresponding study area

Type	Area	Average Building Coverage Ratio	Average Street Aspect Ratio
1	A	56.14%	1.0
2	B	49.44%	2.22
3	C	32.27%	5.77

[Figure 2-7] The location of three roads

2.2.2 Basic Condition

Transportation

Jongno 11-gil and Jongno 12-gil are located at Jongno-gu(종로구), on the north side of Cheonggyecheon and near Jonggak Station(종각역). Euljiro 7-gil is located in Jung-gu(중구), on the south side of Cheonggyecheon, near Eulji-ro Entrance Station(을지로입구역). Jongno 12-gil connects the No. 12 entry of Jonggak Station, while the Euljiro 7-gil in the south is about 200 meters away from the entry of No. 4 of Eulji-ro Entrance Station. And within the distance of 50 meters from these roads, there are 7 bus stops, and an entry for Cheonggyecheon, the No. 4 step entry. In short, from the view of the convenience of the traffic infrastructure, it can be said that these three roads have a good adaptability on walking.

Land Use

Besides, except the Cheonggyecheon Hanbit Square(청계천한빛광장), near the north end of Euljiro 7-gil with the land use of green space, the surrounding areas of these roads are all general commercial use. Jongno 11-gil, also named Pimatgol(피맛골), can be traced back to the Joseon Dynasty. It is a cultural sightseeing alley which also has many restaurants. Jongno 12-gil, also called The Streets of Youth(젊음의거리), is the center of a commercial circle of The Streets of Youth. This road is a pedestrianization, with buildings on both sides and the east-west alleys distributed with many shopping malls, trattorias and entertainment facilities. The Streets of Youth is also connected to the underground commercial street of Jonggak Station. For the more, Euljiro 7-gil in the south, which has another name as Eulji Hanbit Street(을지한빛거리), also linked with the Eulji-ro Entrance Station subterranean street.

Distinct from the features of The Streets of Youth, both sides of Eulji Hanbit Street are super high-rises of large companies such as banks and communications agencies. It can be conjectured that this region may have a large human flow from such kind of land use conditions.

Climate conditions

In the past 90 years, the overall average temperature of South Korea has risen 133%[142] of the world's level 0.75℃ during the past 100 years[143]. According to the statistical data of annual mean temperature in Comprehensive Climate Change Detection System(종합기후변화감시정보 시스템), in the past 40 years from 1975 to 2015, the average temperature rise of more than 1.0℃ in Seoul[144].

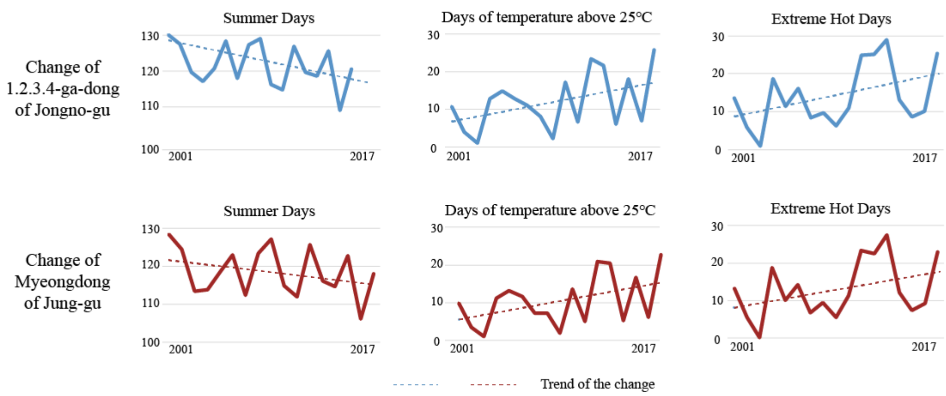
Figures showed below counted the number of days of summer, temperature

142 National Institute of Meteorological Research, "Understanding the climate change III." National Institute of Meteorological Research, 2009.

143 Korea Meteorological Administration, "How Should We Use Climate Change Information of Region: Suggestions for Adapting to Climate Change Policy." Korea Meteorological Administration, 2011.

144 Comprehensive Climate Change Detection System, 2018, from http://www.climate.go.kr/home/09_monitoring/index.php/main.

above 25℃ and extremely hot days in 1.2.3.4-ga-dong of Jongno-gu and Myeongdong(명동) of Jung-gu where three roads located during the year of 2001-2017. As the result, summer in this two regions have gradually shortened, and the number of days above 25 degrees centigrade and extremely hot days are increasing.



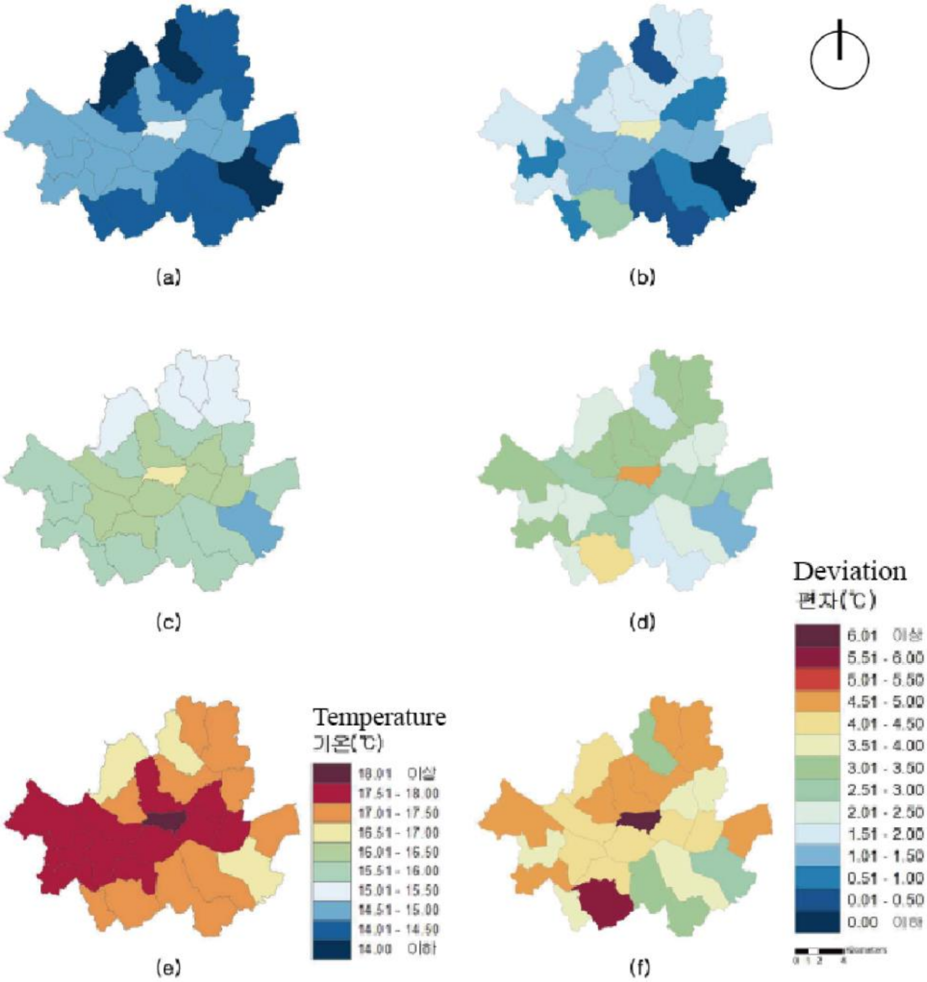
[Figure 2-8] The change of days of summer, temperature above 25℃ and extremely hot days during the year of 2001-2017 in 1.2.3.4-ga-dong and Myeongdong[145]

Additionally, the average annual temperature in Jung-gu, is lower than that of other areas in Seoul, and the precipitation is less than that in the other areas(Figure 2-9). However, according to the report, Jung-gu will be facing severe climate challenges in the future in Seoul[146]. In a word, the area where these three roads are located is facing severe climate challenge in the future, especially the thermal environment.

145 Climate Information Portal, 2018, from http://www.climate.go.kr/home.

146 Korea Meteorological Administration, "Climate Change Report of Seoul." Korea Meteorological Administration, 2011, pp.86-88.

These roads have different urban form, walking environment(not mentioned above though) which affects microclimate, and have many human flows but with a big challenge of climate. For this reason, they have been selected as the research area of this paper.



[Figure 2-9] Forecast of the future average temperature of administrative regions in Seoul (a)(b) 2011-2040, (c)(d) 2041-2070, (e)(f) 2071-2100[146]

Block From

Around Jongno 11-gil is full of ‘protosomatic’ houses built in the 1970s without planning. Roads are narrow and interlaced, land parcels are broken. Houses are distributed along the road without clear boundaries between houses and roads. Most buildings near the road are built in the 60s-70s of last century. And those far away from the main road are in the 1950s, many of which even could not be traced. These buildings are generally single or two-floor family house. Where still has many traditional Korean-style houses(한옥).

Buildings surrounding The Streets of Youth were built from the 60s to 90s of last century. These buildings are not only widely distributed in time, but also uneven in height. In addition to a few tall buildings, most are middle or low-rises. This area has been arranged by urban planning, roads crisscross, and small urban blocks appear. But the road red lines and the building red lines are very close, except street space, there has almost no other outdoor space.

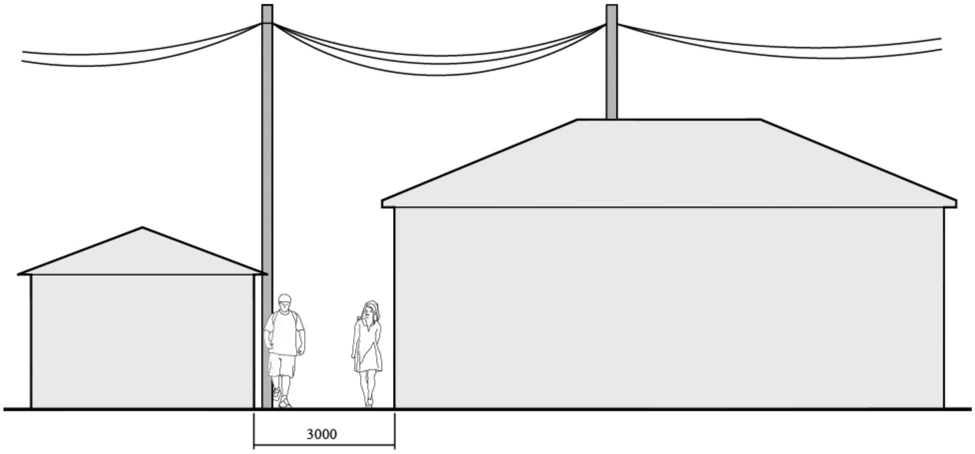
Both sides of Eulji Hanbit Street are super high buildings built after the 1980s. Compared with the first two regions, the built form is different. Instead, there is a high proportion of open space. In contrast to The Streets of Youth commercial circle, urban blocks here are larger and roads are wider.

Street Canyon

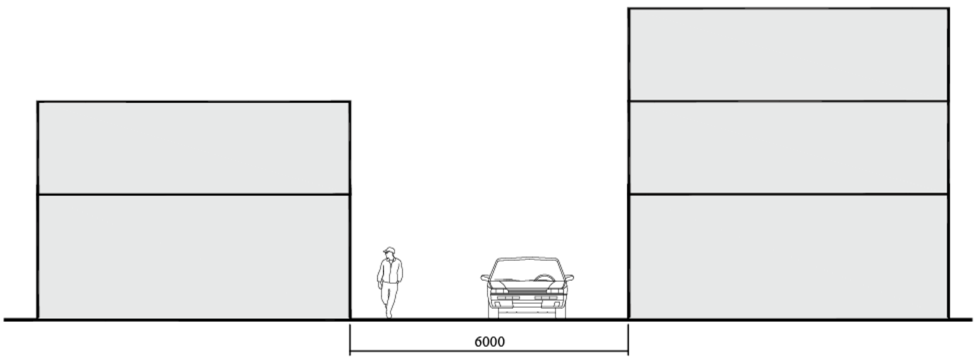
These three typical real streets in commercial areas respectively represent only pedestrian path where too narrow only allow for pedestrian or bicycle; Single lanes where pedestrians are mixed with vehicles; Double lanes with separation of pedestrians from vehicles. In Seoul, many single lanes which do not distinguish between left and right lanes, are opposing traffic, and the road red line is very close to the building red line where has no pedestrian space at all.

In this case, not only driving safety, but also walking safety is threatened. Although many single lanes use the means of the speed limit and one-way traffic to reduce the passage, the current situation for pedestrians is still a potential hazard. And many areas in Seoul still can be found as only-pedestrian-allow alleys. Even there is no potential threat to motor vehicles, it is a multiple zones of accidents such as crime, fire, and others. Howbeit no potential threat of vehicles, there had a frequent occurrence of crimes, fires and other incidents in the past.

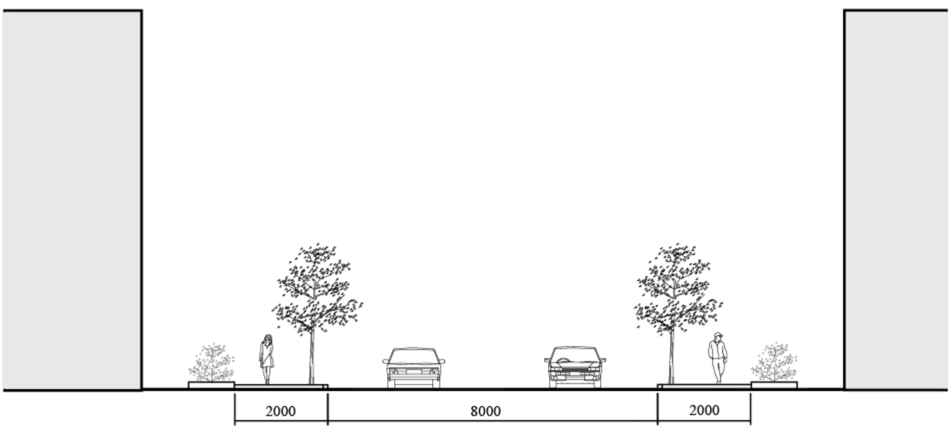
The three typical streets are north-south orientation and are connected with the streets in the east-west orientation. Both sides of the street A and B are shops, whose main structure is a brick structure or reinforced framing. Both sides of street A are mostly low-rise buildings, while street B is mid-rise buildings. And high-rise shops and office complex buildings in street C. Meanwhile, the facades on both sides of the street A and B are mainly composed of windows and billboards, while buildings in street C are mainly covered by high reflectivity materials.



(a) Only Pedestrian: Too narrow only allow for pedestrian



(b) Single Lanes: Pedestrians mixed with vehicles



(c) Double Lanes: Separation of pedestrians from vehicles

[Figure 2-10] Sections of roads and pedestrian path of three archetypal commercial streets

Landscape Elements

In addition to street trees and shrubs in street C, street A and B did not have street trees. It can be observed that the greening rate of the blocks is C>A>B from high to low respectively. There are also small patches with dense planting trees in three regions. The species of trees include conifers and deciduous trees.

The pavement of street A and surrounding alleys is granite or brick. And the area, where street B locates, is asphalt roads, except the pedestrianization of street B with granite pavement. Street C is separated from human and vehicle, so the sidewalk is granite pavement and the carriageway is asphalt road. The open space of the surface around buildings and parking lots in three areas are concrete pavement.

Because of the location of the research sites, there is a water body in the Cheonggyecheon river. But there is very few waterscapes on the streets actually.

2.3 Idealized Model

2.3.1 Archetypal Idealizing

As shown in Section 2 of this chapter, there are many complex variables in the physical condition of real sites. To study the impact of landscape design elements on outdoor thermal comfort, variables other than the landscape design elements should be controlled, including parameters of block form and climate condition. So even the simplification process inevitably leads to information inauthenticity, loss of real information especially detail, and decontextualizes from the surroundings. For isolating unwanted interference factors and individual effects, the research models need to be simplified based on real ones.

First of all, the size of each model is assumed to be the entire area of a square of 100m×100m. Which accords with the scale of the pedestrian street, and is consistent with the size of typical archetypal commercial areas in the previous section.

The process of idealizing in this study is referred to the process proposed by Alexander et al.(1977) in the book "A Pattern Language"[147]. This process mainly includes collecting important source patterns; adding relevant patterns recommended in the book; removing unnecessary patterns; and make a design

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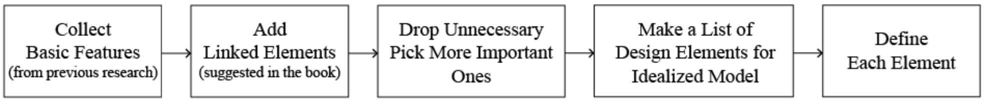
147 Christopher Alexander, Sara Ishikawa, Murray Silverstein, et al., *A pattern language*: Oxford University Press, New York, 1977), ibid.

list[148]. Based on this process, some adjustments are made to meet the needs of this research. The specific steps are shown in Figure 2-11.



[Figure 2-11] Idealizing process of a typical area

Creating the idealized models started by identifying the most basic features of commercial blocks in Seoul, three categorized types in this study. Referring to the previous research in Chapter 1, the following 13 factors of commercial block related can be got: Building density; Floor area ratio; Aspect ratio; Building height; Street orientation; Space enclosure; Architectural layout; Vegetation; Water; Surface material; Color; Building material; Landscape structure.

Moreover, block size, street network, building-related factor mentioned in other works are added as linked elements.

In the steps of “drop and pick”, elements defined as controlling variables of this study need to be determined. Landscape factors will be dropped because they are the dependent variables in this study. Meanwhile, because of the duplication of some of the urban form related factors, computable elements are selected. It includes building density, street aspect ratio, street orientation, building size and height. Other descriptors of block forms, for example, building orientation, sky

148 Ibid., Yunmi Park, "The network of patterns: creating a design guide using Christopher Alexander's pattern language." *Environment and Planning B: Planning and Design*, 42 (4), 2015, pp.593-614.

view factor(SVF), space enclosure and so on, are not included due to extreme diversification in this simplification process. While architectural layout will be simplified according to the original configuration of the three areas.

As a result, the basic features listed below are taken into consideration.

- Building shape and size
- Street pattern and orientation
- Building density
- Building height
- Street width

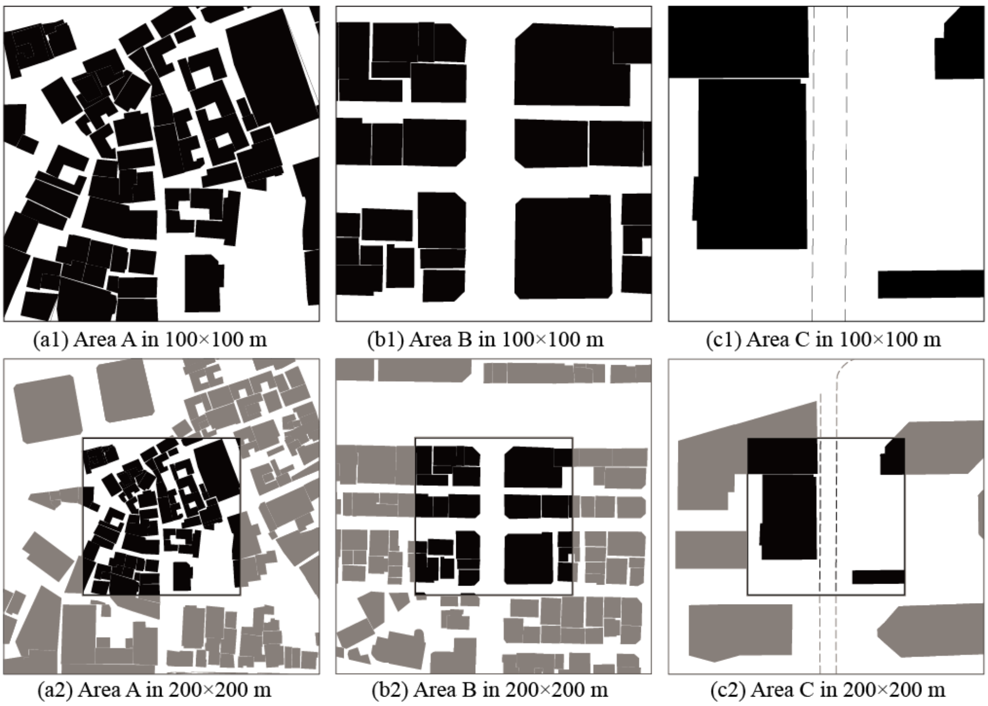
And the quantitative description of idealized forms of commercial blocks is composed of the above indicators. Some of these are defined as the averages of the key parameters selected from basic features above, will help to reproduce real sites in the simplest possible way:

- Building shape and size: The building units in three typical real areas are got rid of the bump and design, regarded as boxes. The size of the building units takes the average of the typical areas.
- Street pattern and direction: In order to constrain the influence of complex street network and orientation, the simplified models only set north-south and east-west oriented street canyons. As the north-south oriented streets provide more shadows than the east-west ones, they are considered as the main observation streets.
- Building density: Which represented by BCR in this study, is defined as the average value of the blocks in the typical area.
- Building height: The average height of the buildings in typical areas are used.
- Street width: The width of the streets is also taken from the average value of the typical areas.

From this, there is going to simplify the model in the light of the architectural layout of the real sites and the above values.

2.3.2 Idealized Model

In order to obtain the idealized model of three typical commercial streets, the architectural layout is the basis for idealizing work. According to the suggestion from Yoshie et al.(2007)[149], when applied to the target area, it is required that there are two or more rows of buildings around.



[Figure 2-12] Figure & grounds of typical commercial streets used for idealization

149 R Yoshie, A Mochida, Y Tominaga, et al., "Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan." *Journal of Wind Engineering and Industrial Aerodynamics*, 95 (9-11), 2007, pp.1551-1578.

The areas of 100 × 100 m previously prepared in section 2.1, have two or more rows of buildings, and centered on the commercial streets. Which is in conformity with the requirements of Yoshie et al.(2007)[149] suggested.

Base on the areas above, most of the architectural layout in area A and B are close to each other with very small spacing, while area C is relatively dispersed. The interval between buildings is different in the same area. But simplification will discard the heterogeneity of the building spacing. Except for pedestrian roads in area A, the layout of buildings is arranged in a tight mode according to the very narrow gap. Area B has a small number of alleys between buildings. Therefore, in the design of the simplified model B, the alleys will be put into the same position with the same width. The architectural pattern and spacing in area C will also be reflected in the simplified model C as much as possible.

In the aspect of building orientation, area B and C are both north-south directions, while the buildings in area A have various changes. In order to remove the interference of building orientation, buildings in three models are simplified to the right north-south direction.

When determining building shape, area A and B have many irregular shapes includes square and rectangle. Relatively square is more universal. The buildings in the compact high-rise area are almost rectangular, so the architectural shape of model C is defined as a rectangle.

In this study, the average value of all buildings in the area of 100 × 100 m is calculated as the building area of the idealized model. However, due to the building size of area C, the complete building cannot be shown in the area of 100 × 100 m. Only area C takes the average building size in the area of 200 × 200 m.

Since the building form of model C is rectangular, whose length of a side cannot be simply calculated by the radical sign. The average length and width ratio of buildings in area C is used.

About the property of the street, the direction of the main street located in the center of area A, B and C are all north-south orientation. And branches that connect with the main street are east-west orientation. And the main street widths are 4m, 16m, 12m (walking area of two sides is 2m, and the distance between buildings is 22m). 2m of alley in area B and respectively 3m, 6m of branches in both the area A and B.

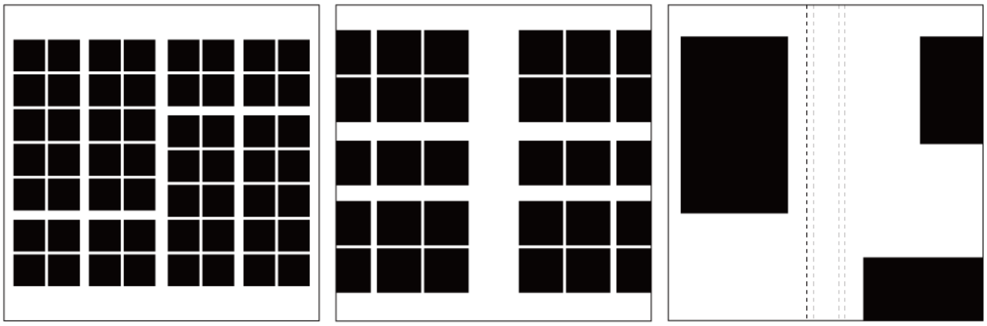
The average building coverage ratio of area A, B and C in Table 2-4 are used as building density for three idealized models.

[Table 2-5] Parameters of idealized models

Model	Type	Building Size	BCR	Building Height	Street Width
A	Compact Low-rise	10m × 10m	0.56	4m	4m
B	Compact Mid-rise	14m × 14m	0.49	20m	16m
C	Open High-rise	56m × 34m	0.32	130m	12m(2+8+2m)

To get the average value of building size and building height in three typical real streets, the size and height of each building in each area are calculated, and the parameters of the three idealized models output through the above process are shown in Table 2-5.

Using these parameters, three models of compact low-rise, compact mid-rise and open high-rise are drawn in blocks of 100m × 100m as the Figure 2-13.



(1) Model A (2) Model B (3) Model C

[Figure 2-13] Figure & grounds of the idealized models

These three idealized commercial block form models, which have eliminated uncontrollable factors, will be used as the block form of the basic scenario in later chapters to explore the different design strategies.

Chapter 3　Outdoor Thermal Comfort

3.1 ENVI-met

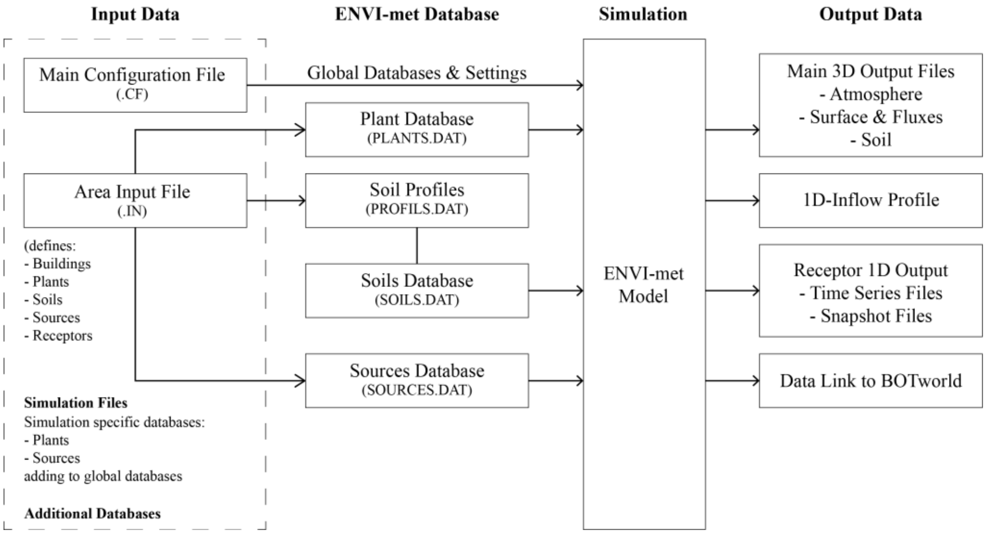
The microclimate simulation tool used in this study is called ENVI-met, a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions not only limited to, but very often used to simulate urban environments. It is designed with a spatial resolution of 0.5-5 meters, a temporal frame of 24-48 hours with a time step of 1-5 seconds[150]. On account of this resolution, the micro-scale interactions between buildings, surfaces and plants can be simulated. This tool is developed by Michael Bruse, et al.[151], which is widely applied in the fields of urban design, building energy conservation, landscape architecture.

Structure and Sub-model

The basic layout of ENVI-met is made up of main 3D model, 1D model, soil model and nesting area. The main 3D model is designed with 2 horizontal dimensions(x, y) and one vertical dimension(z). In this model, the typical elements such as buildings, vegetation, soil and surfaces which represent the area are placed.

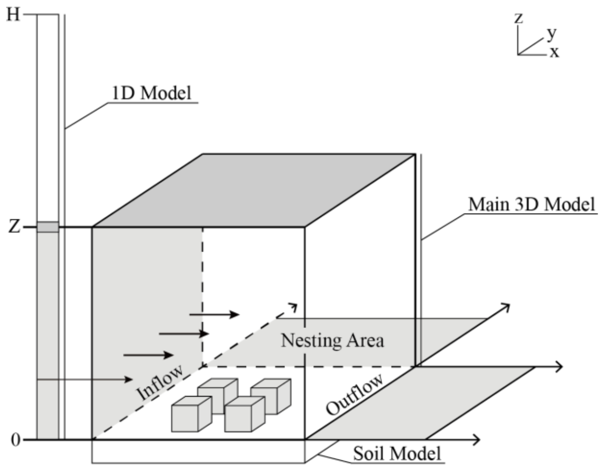
150 ENVI-met, 2018, from http://www.envi-met.com/.

151 Michael Bruse and Heribert Fleer, "Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model." *Environmental modelling & software,* 13 (3-4), 1998, pp.373-384.



[Figure 3-1] The operation process of ENVI-met

To use a numerical model, the study area must be transformed into grids. The smaller the single grid is, the finer the resolution of the simulation is. In order to get an accurate simulation of the boundary layer, the model needs to be extended to the minimum height of 2500 meters. But it is not possible or necessary to extend the main 3D model up to this height. 1D model, which can help to limit the memory storage, help to calculate from the top the main 3D model and the total model top at the height of 2500m. The soil model is used to calculate the heat transfer between surface and ground. It can also provide the information about soil moisture content which is closely related to the evapotranspiration of vegetation. The nesting area is made of buffer grids that surrounding the main 3D model. Its function is to keep the core of the model away from the boundary and avoid the interference generated by the boundary effect, so as to improve the accuracy of the result.



[Figure 3-2] The schematic of ENVI-met[152]

Input, output parameters

In addition to the establishment of a numerical model, ENVI-met needs to input some parameters, including meteorology, surface, vegetation parameters and simulation control parameters when simulating. Among that, this tool simplifies the vegetation into one dimension, and gives the parameters such as the normalized Leaf Area Index(LAD) and the Root Area Index(RAD). So not only vegetation models can be selected, also vegetation can be autonomously defined according to the local conditions.

The input and output parameters of the simulation project are as follows.

[Table 3-1] Input parameters in simulation project of ENVI-met

<table>
<tr><th>Inputs</th><th colspan="2">Type</th><th>Parameter</th></tr>
<tr><td>Area</td><td colspan="2">Area file</td><td>INX file built in ENVI-met SPACES</td></tr>
<tr><td>Time</td><td colspan="3">Start date and time</td></tr>
<tr><td rowspan="7">Meteorology parameters</td><td colspan="2" rowspan="2">Wind</td><td>Wind speed in 10m height</td></tr>
<tr><td>Wind direction</td></tr>
<tr><td colspan="2">Temperature</td><td>Initial temperature of atmosphere</td></tr>
<tr><td colspan="2" rowspan="2">Humidity</td><td>Specific humidity at model top(2500m)</td></tr>
<tr><td>Relative humidity in 2m</td></tr>
<tr><td colspan="3">Solar radiation</td></tr>
<tr><td colspan="2">Clouds</td><td>Cover of low, medium, high clouds</td></tr>
<tr><td rowspan="4">Surface parameters</td><td rowspan="3">Soil</td><td rowspan="3">Wetness & Initial temperature</td><td>Upper layer(0-20cm)</td></tr>
<tr><td>Middle layer(20-50cm)</td></tr>
<tr><td>Deep layer(50-200cm)</td></tr>
<tr><td colspan="3">Roughness length at the measurement site</td></tr>
<tr><td>Vegetation parameters</td><td colspan="2">Plant model</td><td>The normalized Leaf Area Index
The Root Area Index et al.</td></tr>
<tr><td>Simulation control parameters</td><td colspan="3">Start date, Start time, Total simulation time
Turbulence Model
Lateral boundary conditions(LBC)
Time step in different solar angle condition
Update timing
Nesting cells</td></tr>
</table>

152 "Basic Layout of ENVI-met." from https://zh.scribd.com/document/364821906/envi-met.

[Table 3-2] Output parameters of ENVI-met

Outputs	**Parameter**
Microclimate parameters	Wind speed, Wind direction, Air temperature, Spec. humidity, Relative humidity, Turbulence, Direct, Diffuse, Reflected sw radiation, Leaf temperature, et al.
Structure parameters	Vegetation LAD, Building number
Biological meteorology parameters	Mean radiant temperature, et al.
Pollutant parameters	CO_2, et al.

Retrieved 03/16, 2018.

3.2 Microclimate Simulation of Real Site

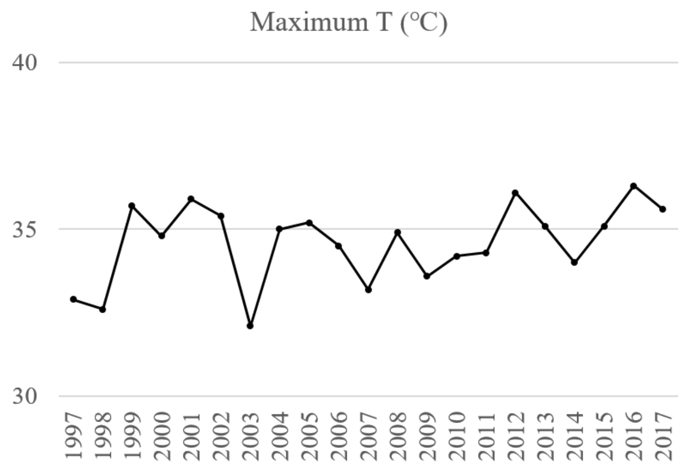
3.2.1 Simulation Process

ENVI-met(science) V4.3.1 Winter1718 (64bit) was used in this study, which was downloaded from http://www.envi-met.com/.

Before the simulation of microclimate, the SPACE tool was used for spatial modeling. First of all, geographic properties of the study area that have to be input including the name of the location, the latitude and longitude. At the same time, wall and roof material and soil profiles for nesting grids can be defined here.

In terms of setting grid parameters, the number of grids in the basic version of ENVI-met is up to 100 × 100 × 45 grids, but no limits in this science version. Both the grid number of the main model area need to be set, the size of the gird cell in the meter of x, y, z-axis should be modified as well. The height grid(z-axis) used in this study is an isometric grid, that is, there is no expansion factor in every grid at a vertical height.

After that a background bitmap which with full ground information such as building location, vegetation location, ground paving, compass, scale need to be imported. Then get information about building and pavement materials, vegetation types and so on using site investigation results and visual maps(such as VWORD and DAUM map). DEM, single wall and other three-dimensional data can be input as well of course. Using this information, a three-dimensional model of the research area can be built. And after save it as INX file, it is ready for setting parameters before simulation.



[Figure 3-3] Changes in the maximum diurnal temperature of Jongno(No.419) during 1997-2017

In the setting of meteorological parameters, the data of the meteorological observation station of Jongno(No.419)(종로) near the study area. When some of the meteorological data are insufficient, the diurnal data of Seoul station(No.108) was used. The statistics of the maximum diurnal temperature of Jongno(No.419) during the years of 1997-2017 shows that the highest temperature appears at 33.6℃ on August 11, 2016. The hourly temperature and humidity of that day are shown in Table 3-3. These data are downloaded from the national climate data center and the data open portal of the Meteorological Administration(기상청)[153, 154].

153 National Climate Data Center of the Meteorological Administration, 2018, from http://sts.kma.go.kr/jsp/home/contents/main/main.do.

154 Meteorological Data Open Portal, 2018, from https://data.kma.go.kr/cmmn/main.do.

[Table 3-3] Hourly air temperature and relative humidity of Jongno on August 11, 2016

Time	Air Temperature(℃)	Relative Humidity(%)
0:00	26.1	75
1:00	26.8	74
2:00	26.4	75
3:00	26.2	78
4:00	26	80
5:00	26.1	81
6:00	25.7	82
7:00	26.9	77
8:00	27.7	71
9:00	29.3	65
10:00	28.9	60
11:00	29.5	60
12:00	31.3	52
13:00	34.6	44
14:00	33.9	45
15:00	33.9	43
16:00	35.3	37
17:00	34.4	43
18:00	32.9	50
19:00	30.8	59
20:00	29.4	60
21:00	28.2	65
22:00	27.3	72
23:00	26.9	74

And the specific humidity at the model top(2500m, g/kg) came from the Upper Air Data Map from the University of Wyoming[155]. Because there is no data of the Seoul station, Osan(오산) station which is near Seoul metropolitan city was selected(Station No.47122, Latitude 37.10, Longitude 127.03, Elevation 52.0). The MIXR value at 2536m on August 11, 2016, was 8.04 g/kg.

Due to the fact that the settings of the wind cannot input the change per hour, diurnal data is needed. Although diurnal data of wind speed can be found, the wind direction is not. So the wind direction data used in the simulation is the average of hourly wind direction on August 11, 2016. Different layers of the cloud amount and soil temperature of this area on August 11, 2016, obtained from the Seoul station(No.108). On the choice of the index of roughness length at the measurement site, 0.001 indicates very smooth roughness area with fewer buildings such as a plan or water; 0.01 refers to the intermediate degree, mostly selected for the regular urban area; And 0.1 applies to the roughest area, maybe downtown area with a lot of high-rises. In this study, area A and B correspond to 0.01 and C is 0.1.

Other parameters use the default settings. See details in the following table.

The intense heat watch temperature(33℃)[156] is used as the critical temperature for determining the simulation time. According to this, 1 pm to 5 pm was the hottest time of the hottest day in the past 20 years. Since the two first hours

155 Upperair Air Data, 2018, from http://weather.uwyo.edu/upperair/sounding.html.
156 ""Boiling in the heat wave?" It may be a reality." from http://web.kma.go.kr/notify/focus/list.jsp?bid=focus&mode=view&num=950. Retrieved 04/0, 2018.

can be unreliable during the process, the simulation time starts from 11 am to 5 pm.

[Table 3-4] Diurnal parameter settings

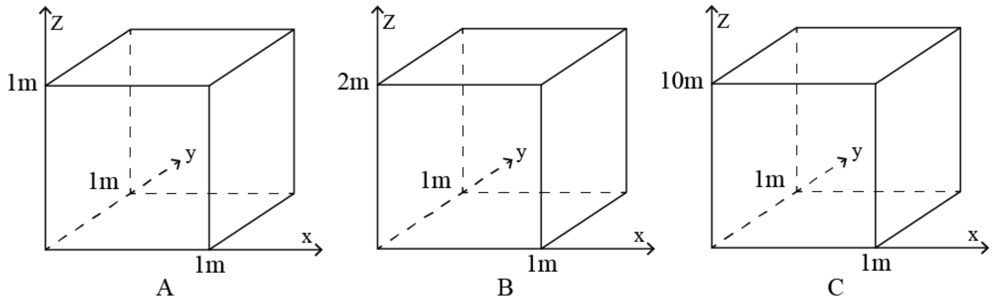
Type		**Parameter**
Area	INX file built in ENVI-met SPACES	INX file for area A, B, C
Time	From August 11, 2016 11:00(7hours)	
Wind	Wind speed measured in 10m height	1.4 m/s
	Wind direction	276.6 deg
Temperature		As shown in Table 3-3
Humidity	Relative humidity in 2m	As shown in Table 3-3
	Specific humidity at model top(2500m)	8.04 g/kg
Clouds	Cover of low clouds	0.3 octas
	Cover of medium clouds	0.3 octas
	Cover of high clouds	0.0 octas
Soil	Upper layer(0-20cm)	Wetness 50 %, 304.05 K
	Middle layer(20-50cm)	Wetness 60 %, 301.15 K
	Deep layer(50-200cm)	Wetness 60 %, 297.35 K
Roughness length at the measurement site		0.01 in area A, B; 0.1 in C
Other control parameters include plant		(Default)

After importing INX file and setting up the input parameters mentioned above, simulation running can be started.

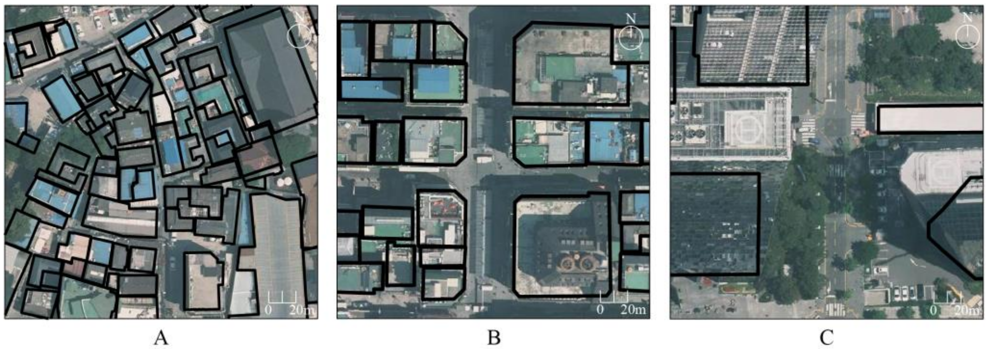
3.2.2 Simulation Setting

Considering both the accuracy of the model and the size of the grid, the simulation area is set to a 100m ×100m square centered on the walking space were chosen. Because the pedestrian level is focused in this study, the accuracy of 1m is more appropriate. So the dx and dy of 2D grids are set to 1m, but dz is different according to the height of the highest building in area A, B and C. As the highest building in area A, B and C is 20m, 38m, 148m high.

Following the rule of the total height of the grids should be twice the height of the highest building, the main model area of three areas are 100 × 100 × 40, 100 × 100 × 40, 100 × 100 × 40 respectively. The size of the unit grid in all three areas on the x and y-axes is 1m × 1m, but on the vertical z-axis, are 1m, 2m and 10m respectively. And the number of nesting grid is set to 5 in all three areas.



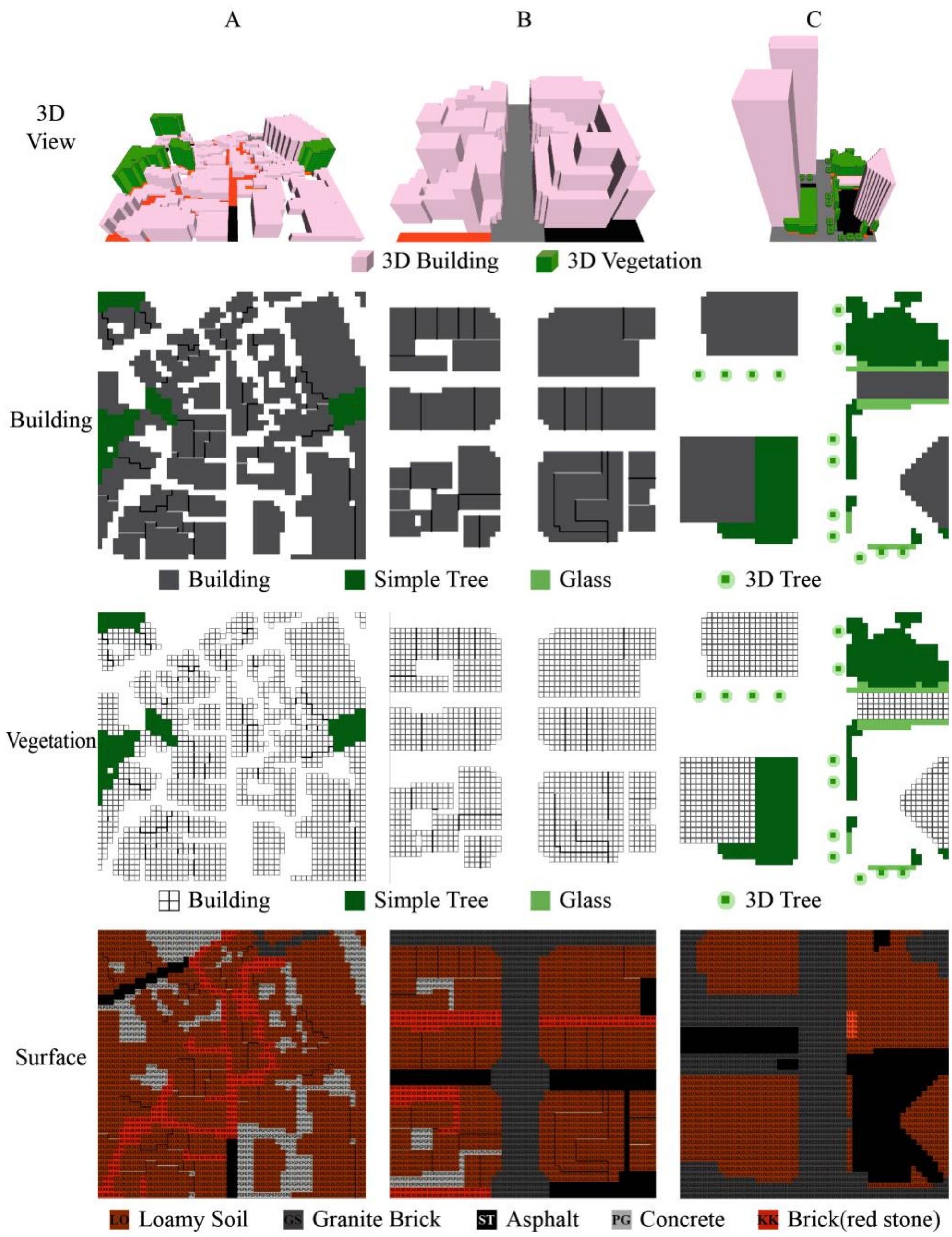
[Figure 3-4] The size of every grid of area A, B and C



[Figure 3-5] Remote sensing images of street A, B and C

The size of the unit grid in the three areas and the modeling plan are shown in

Figure 3-4 and Figure 3-5.



[Figure 3-6] Modeling of vegetation and surface of area A, B, C and 3D views

The main vegetation of these three areas are conifers such as Abies Alba and Pine, deciduous trees including Ginkgo, Platanus Acerifolia and Koelreuteria paniculata. The distribution of vegetation is mostly equidistant single planting street trees and mixed planting in a small patch. Except for water in Cheonggyecheon and loamy soil, the species of the surface are:

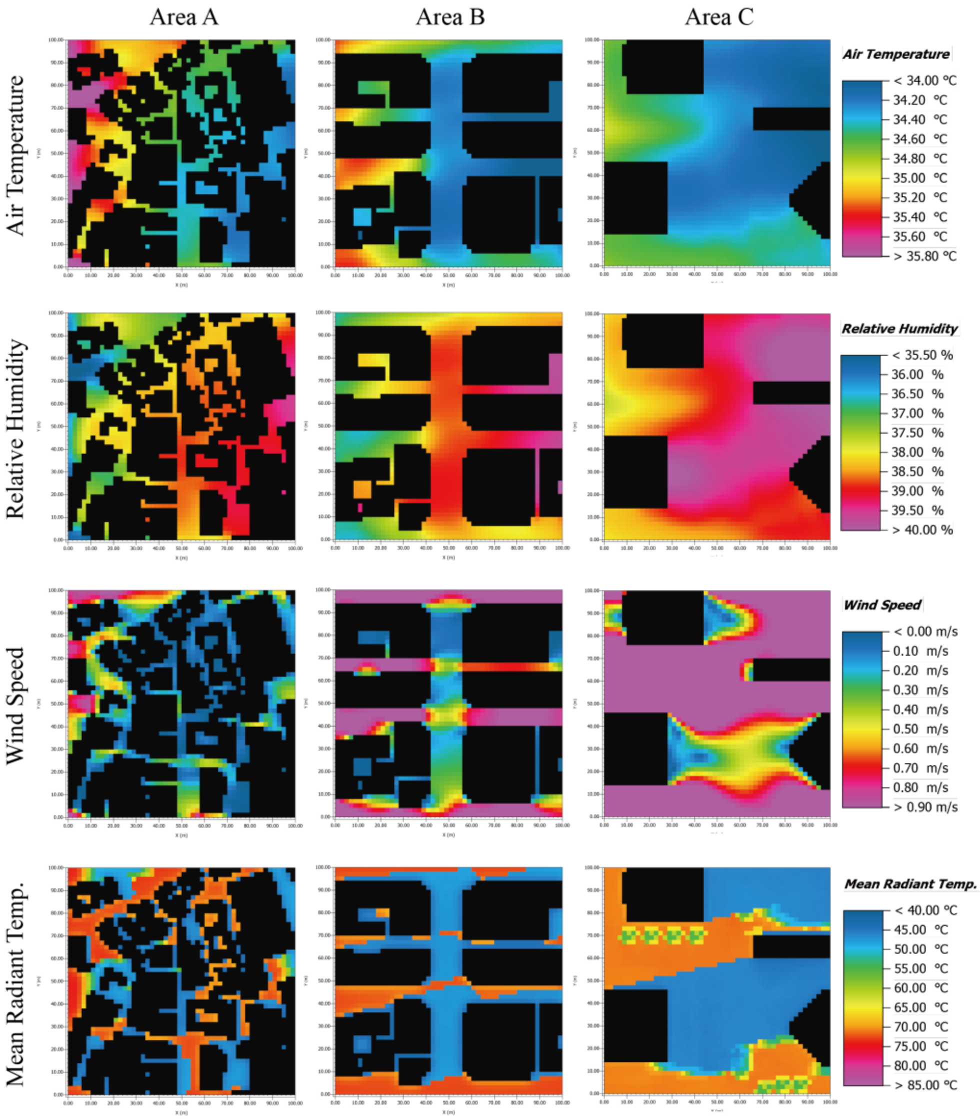
Pavements in area A are including asphalt roads, granite pavement(single stone) and brick road(yellow stones) in walking spaces, concrete pavement light in parking lots or other open spaces, and a little bit brick road(red stones) and terre battue(smashed brick) which means red clay brick. The area B is mainly paved with asphalt roads and granite pavement(single stone). Types of the surface in area C are asphalt roads, granite pavement(single stone), concrete pavement dark around buildings, and very little red clay brick and sandy soil as well.

The vegetation and surface setting and 3D building model of three areas are shown in Figure 3-6.

3.2.3 Microclimate Simulation Results

In this study, LEONARDO 4.3.0 of ENVI-met is used to analyze the results of microclimate simulation. Air temperature, relative humidity, wind speed and mean radiant temperature are read. Which is also the four inputs for computing UTCI. Meanwhile, because the thermal experience of pedestrians is studied as the main goal, data on the 1.5m height which can represent pedestrians' level is analyzed.

As a whole, the average air temperature value of three areas from high to low was A>B>C, and both the relative humidity and wind speed were A<B<C. This result has obviously closely related to urban form.



[Figure 3-7] The spatial variation of air temperature, relative humidity, wind speed and mean radiant temperature in three areas at 4 pm, August 11, 2016(the highest temperature time of the hottest day in recent 20 years) (The north direction is the same as the world map)

According to the spatial variation of microclimate factors in Figure 3-7, it can be seen that the air temperature of the main streets in area A, B and C was 34-35℃. In the main streets of area A and B, the air temperature was higher on the entrance of both sides of the north and south, while in area C, it was higher in the south entrance. However, the main streets of area B and C were basically covered with the relatively low temperature of the regions. The area temperature near high-density green space in area C was lower. So compared with traditional low-rise-high-density development, the open type of urban form has lower air temperature.

The relative humidity of the main streets in area A, B and C were quite different. The spatial distribution of relative humidity in the main street in area A was relatively low on both sides of north and south. The relative humidity of the main street in area B was about 39℃, with the south part slightly higher than the north. It was obviously higher than that of the other two areas that the relative humidity of the main street of area C was. It was mostly in the 39-40℃ interval, and where near green space had higher humidity. The distribution of relative humidity is similar to that of air temperature, but the value was opposite.

The difference in wind speed between the three areas was significant. On August 11, 2016, area A was basically breezeless, and the wind speed at the south entrance of the main street was relatively bigger. In the main street of area B, the wind speed at the south entrance was larger than that on the north. Apart from the relatively high wind speed at the intersection, the wind speed in other parts of area

B was also small. In addition to the side of buildings, the wind speed in most regions in area C was much larger.

The spatial variation of the mean radiant temperature was very distinct. Which in most regions of the main streets in area A and B were low. However, some parts of the main street in area C had a higher value. Although the minimum value of area C was the highest in three areas(area B was the lowest), the maximum value was lower than the other two areas.

The above results are the spatial distribution of microclimate simulation at 4 pm on August 11, 2016. It can be found that in the hottest time of the hottest day in the past 20 years, the microclimate condition of area C was better than those of the other two areas. The results of different microclimate factors are various with each other. This may be the consequence of the combination by many factors including climatic conditions, urban form, landscape design and so on.

Additionally, single or multiple microclimate elements cannot represent the outdoor thermal comfort of pedestrians. Therefore, this study uses the indicators which can express the actual outdoor thermal comfort of human body as an evaluation index of landscape design strategies.

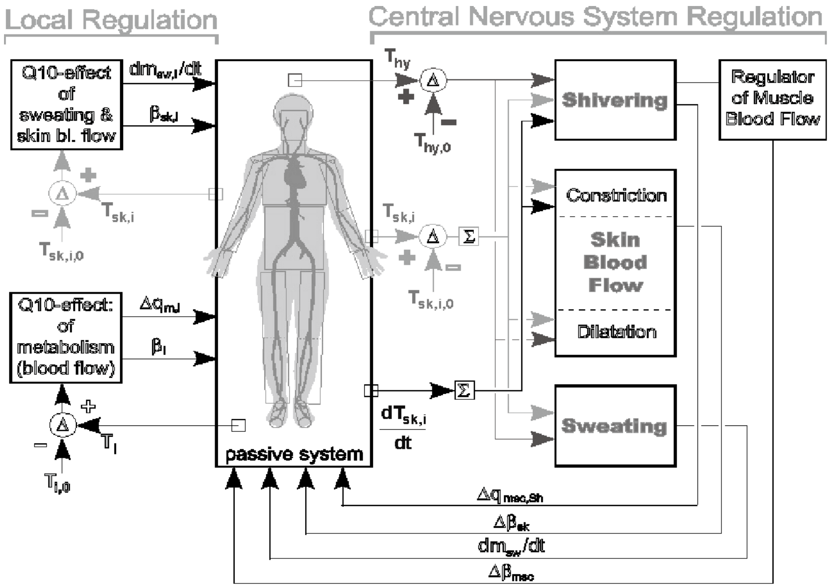
3.3 Outdoor Thermal Comfort Evaluation Index

Since this study focuses on the pedestrian level of outdoor thermal comfort, both the traditional evaluation index based on indoor conditions or the common theoretical indexes which are not fully considered for human biometeorology, cannot meet the needs of this study. Universal Thermal Climate Index(UTCI), which based on multi-node Fiala model and garment model takes both the influence of outdoor meteorological factors and the physiological thermal parameters into account. Thus UTCI can describe the whole body heat balance system and effectively reflect the human subjective thermos-physiological response[17]. This index is not restricted by climatic conditions, seasons or scales. And it can do a good job of expressing the actual thermal comfort of human body through verification.

As a theoretical indicator, UTCI was developed by International Society of Biometeorology(ISB)[17]. It can be directly applied in the related fields of human biological meteorology, and can reflect the role of different forms of heat exchange on human physiological state. It has few applications in Korea, mostly contrastive studies of different index. But the results of research by Yoon et al.(2014)[157], Ryu et

157 Young Han Yoon, Seung Hwan Park, Won Tae Kim, et al., "Analyses on Comparison of UTCI, PMV, WBGT between Playground and Green Space in School." *Korean Journal of Environment and Ecology*, 28 (1), 2014, pp.80-89.

al.(2015)[117] and Kwon(2017)[158], have shown that UTCI has a good application prospect in South Korea.



[Figure 3-8] Schematic of UTCI Model[159]

[Table 3-5] Input parameters used for UTCI calculation

Parameters	Unit	Source
Air temperature	Ta(℃)	From simulation result
ΔTmrt = Tmrt - Ta	Kelvin	Calculate from simulation result
Water vapor pressure or Relative humidity	hPa or %	From meteorological station data or From simulation result
Wind speed in 10m	m/s	From simulation result

158 Ki Uk Kwon, Evaluation of the Thermal Environmental Condition for Green Building through Empirical Analysis on Environmental Performance, Doctor's degree. (Konkuk University(Chungju Campus), 2017), Pages.

159 "UTCI homepage." from http://www.utci.org/. Retrieved 5/4, 2018.

The UTCI Calculator provided by UTCI homepage can be used to calculate UTCI. The parameters that need to be input include the air temperature, ΔTmrt, water vapor pressure or relative humidity and wind speed in 10m(Table 3-5)[160]. when the submit button is pressed, the value will be automatically calculated.

Tmrt in the table represents mean radiant temperature. And air temperature, Tmrt, relative humidity, wind speed in 10m can all be obtained from the simulation results of ENVI-met. While the hourly value of water vapor pressure is based on the observed meteorological data from Seoul station(No.108).

[Table 3-6] UTCI stress category

Stress Category	**UTCI Range(℃)**
Extreme heat stress	> 46
Very strong heat stress	38 ~ 46
Strong heat stress	33 ~ 38
Slight heat stress	26 ~ 33
No thermal stress	9 ~ 26
Slight cold stress	9 ~ 0
Moderate cold stress	0 ~ -13
Strong cold stress	-13 ~ -27
Very strong cold stress	-27 ~ -40
Extreme cold stress	≤ -40

The existing research has divided the value of UTCI into 10 grades as the criteria for evaluating the intensity of cold and hot.

160 "UTCI Calculator." from http://www.utci.org/utcineu/utcineu.php. Retrieved 5/4, 2018.

The higher the UTCI value, the worse the outdoor thermal comfort is, as shown in the table above. Usually, between 9-26℃, there is no thermal pressure; while 26-33℃ is slight heat stress; 33-38℃ is classified as strong heat stress; more than 38℃ is very strong heat stress; even more than 46℃ is extreme heat stress.

As mentioned above, UTCI is not restricted by climatic conditions, seasons or urban scale. So this classification is also suitable for summer climate in Seoul metropolitan city.

Chapter 4 Landscape Design Strategy

4.1 Landscape Factors

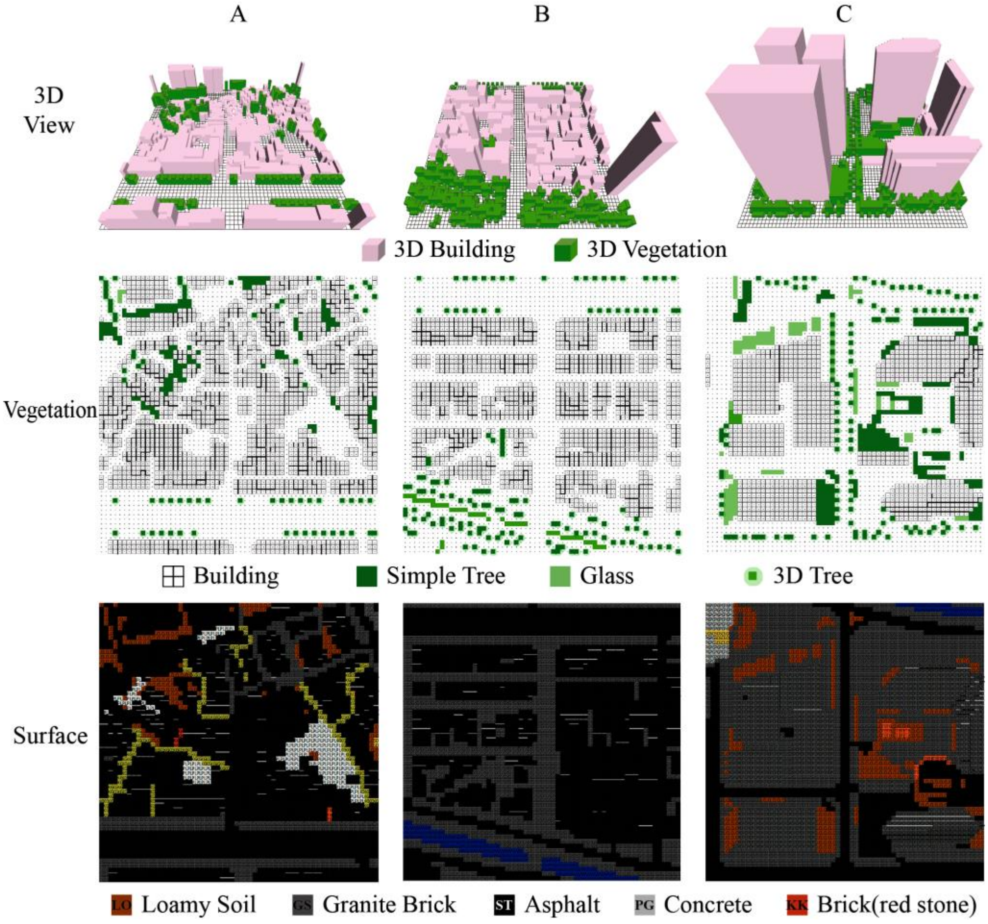
The design strategy involved in this paper is that can be achieved through landscape design. In previous research, many scholars have studied issues related to urban form, microclimate, outdoor thermal comfort, vegetation and so on. But most conclusions about provide a correct way to build new ones. Which is not the same as the point of view of this study. When issues on a topic are found, researchers should try best to improve the status instead of waiting for updates. And that's the original intention of this study. The meaning of which is not to negate those research, but try to make better suggestions.

The cheapest and quickest way to improve the outdoor thermal comfort of commercial streets is landscape design. The improvement plan of the outdoor thermal comfort of commercial street is explored by different design strategies.

4.1.1 Correlation Analysis

Before strategy designing, it is necessary to find out how many landscape elements appear in three typical commercial streets, and which of them has a significant impact on the microclimate.

Referring to the previous research, the influence of air temperature, relative humidity, wind speed and solar radiation on outdoor thermal comfort is the most important. So these four are regarded as dependent variables in this part. While these factors have mean, maximum and minimum values, they are subdivided as dependent variables.



[Figure 4-1] Simulation model for correlation analysis

For the sake of detecting the impact of landscape elements on microclimate as more as possible, this part selected a scope of 240 × 240 m with the commercial street in the center including the water area of Cheonggyecheon. And 24 hours of the hottest day in 2017, July 25th is simulated. The simulation model is shown in

Figure 4-1.

In this scope, it is found that three quantifiable elements as vegetation, surface type and water, specifically green coverage, surface type(pavement), distance to water and vegetation in the gird or not. Taking these as independent variables, correlation analysis is used to find significant landscape elements for the outdoor thermal comfort of these three streets.

As an ANOVA analysis process, correlation analysis can be used to describe the statistical relationship between two predictive variables and continuous response variables. This study explores the relationship between different landscape elements and microclimate factors based on SPSS 25.0.

4.1.2 Significance Analysis

In the correlation analysis, correlation and significance are two inspection index of whether independent and dependent variables have any correlation with each other. Because the minimum value of radiation in 24 hours is 0, only the value of mean and maximum of radiation are select as the dependent variable.

The correlation of landscape elements and microclimate factors can be found in Table 4-1. If the number in the table higher than 0 is a positive correlation, and lower than 0 is negative correlation contrarily. The numerical value indicates the intensity of the correlation. As the absolute value closer to 1, the correlation between the factors is stronger. And the “ * ”symbol behind the number means significance. “ ** ” represents it is significant at the 0.01 level; “ * ” indicates that it is significant at 0.1 level; while no “ * ” is not significant.

[Table 4-1] Correlation analysis results

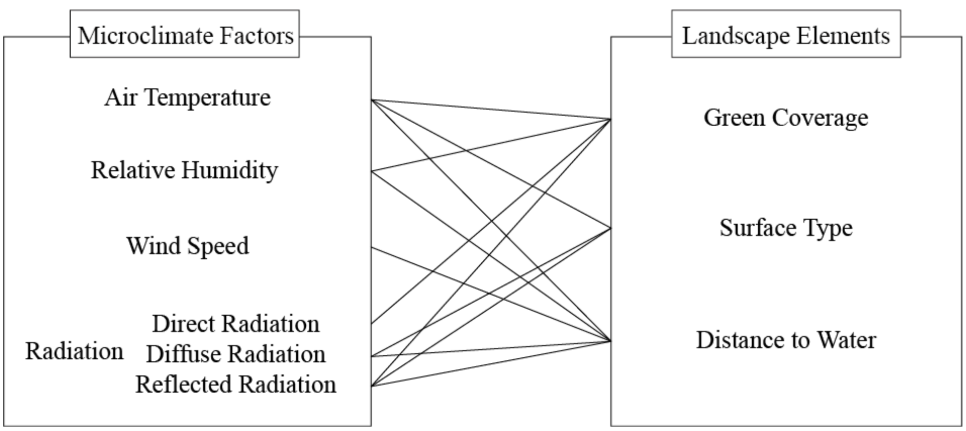
Microclimate Factors		Green Coverage	Surface Type	Distance to Water	Vegetation in Grid
Air temperature	Tmean	**0.899****	**0.454****	**0.894****	0.001
	Tmax	**0.693****	0.317**	**0.808****	0.01
	Tmin	**0.56****	0.219**	**0.668****	0.028*
Relative humidity	Hmean	**0.705****	0.29**	**0.768****	0.048**
	Hmax	**0.639****	0.299**	**0.772****	0.029*
	Hmin	**0.519****	0.204**	**0.673****	0.001
Wind speed	Vmean	0.224**	0.131**	**0.635****	0.017
	Vmax	0.269**	0.127**	**0.598****	0.032*
	Vmin	0.201**	0.128**	**0.644****	0.01
Radiation	Direct Rmean	0.364**	0.005	0.372**	0.17**
	Direct Rmax	**0.594****	0.025*	0.247	0.275**
	Diffuse Rmean	**0.535****	0.078**	**0.576****	0.086**
	Diffuse Rmax	**0.535****	0.078**	**0.576****	0.086**
	Reflected Rmean	**0.61****	0.312**	**0.599****	0.074**
	Reflected Rmax	**0.752****	**0.403****	**0.69****	0.076**

From the results in Table 4-1, it can be found that all correlations are positive. The relationship between green coverage and all the microclimate factors listed have passed the significance test at the 0.01 level. Meanwhile, it is highly correlated with the mean and maximum value of air temperature, relative humidity and reflected radiation.

Surface type and microclimate factors except direct radiation have passed 0.01 significance tests as well. But except air temperature and reflected radiation, the correlation intensity with others is very low.

The landscape elements of distance to water and the microclimate factors except for the maximum value of direct radiation have passed the significance test at the 0.01 level. It is especially strongly related to air temperature, relative humidity, wind speed and reflected radiation.

As for the element of vegetation in the grid, although passed the significance test at the 0.01 level with mean relative humidity, direct radiation, diffuse radiation and reflected, its correlation with microclimate factors is very weak. This indicates that the influence of vegetation on microclimate is not independent or in a small scope.



[Figure 4-2] Significant landscape elements and microclimate factors affected

The data above are consistent with the principle of interaction between landscape elements and microclimate factors.

4.1.3 Factors for Design Scenario

On the basis of the results above, which can be sum up are that the landscape elements with a significant impact on the microclimate in these three typical commercial streets, and the microclimate factors that are affected by the elements.

Previous studies have mentioned that green coverage can mitigate thermal environment, and GLM analysis also shows that it has a significant correlation with many microclimatic factors. This corresponds to that vegetation can provide shade and absorb heat and long-wave radiation which can reduce air temperature and radiation; can affect both relative humidity and air temperature through transpiration; and its canopy can reduce wind speed and introduce airflow to the pedestrian height(the GLM analysis result is not significant though). However, in fact, many commercial streets in Seoul as street A and B are not covered with vegetation. So the value of green coverage used above is the total greening coverage in the scope of 240 × 240 m of area A, B, C. In view of the limitations of actual conditions, it is difficult to increase the green coverage rate of commercial streets, especially in areas such as type A and B. Therefore, microclimate can be improved by increasing the green coverage of the surrounding area of the commercial street. The green coverage in this study is set as a value of a scope of 120 × 120 m(distributed around an area of 100 × 100 m).

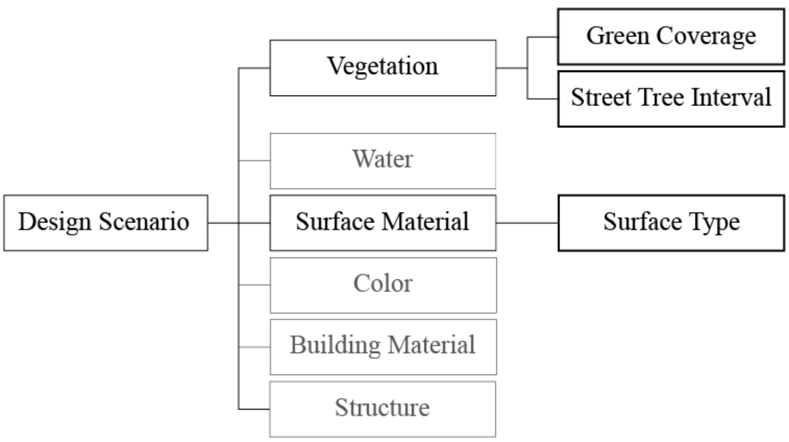
According to previous research, the main factors affecting the temperature of the microclimate are solar radiation and surface type. The heat exchange between surface and air is the direct cause of the change of micro-scale air temperature. Besides the meteorological factors such as transpiration, wind and air temperature, relative humidity is also affected by surface's water storage capacity and other factors(although the result in the GLM analysis is not significant). The temperature and relative humidity of the surfaces of commercial streets are different because of their different heat capacity, perviousness and reflection ability. Which means different pavement have different effects on the outdoor thermal environment of pedestrians.

Based on the GLM analysis, distance to water is strongly related to four microclimate factors. However, the installation of waterscape facilities needs a certain space, and the construction and maintenance of which cost a lot. Although water plays a significant impact on microclimate, its comfort effect, aesthetic should be weighed with practical needs, cost and budget when the application. For the vast majority of commercial streets, water has no universality for landscape design, especially in northern cities with scattered commercial centers, shortage of land resources, high density and four distinct seasons. Stated thus, in the later design strategy section, the landscape element of water is not considered.

As mentioned, it is more difficult to increase vegetation in the commercial streets. But street tree which is commonly used in the street design is important to landscape elements in streets, especially for the pedestrian. The regulating effects on the microclimate of the street tree can affect the outdoor thermal comfort of pedestrians.

Many research studied on the street tree through observation or simulation, especially the effect of the crown size and species of street tree on the microclimate. While a small number of works have focused on the layout and orientation of street tree. Actually, the arrangement of street trees is influenced by the aspect ratio, street orientation and features about buildings. Therefrom, this chapter will take one species of street tree as an example to study the best interval in different kinds of typical commercial streets.

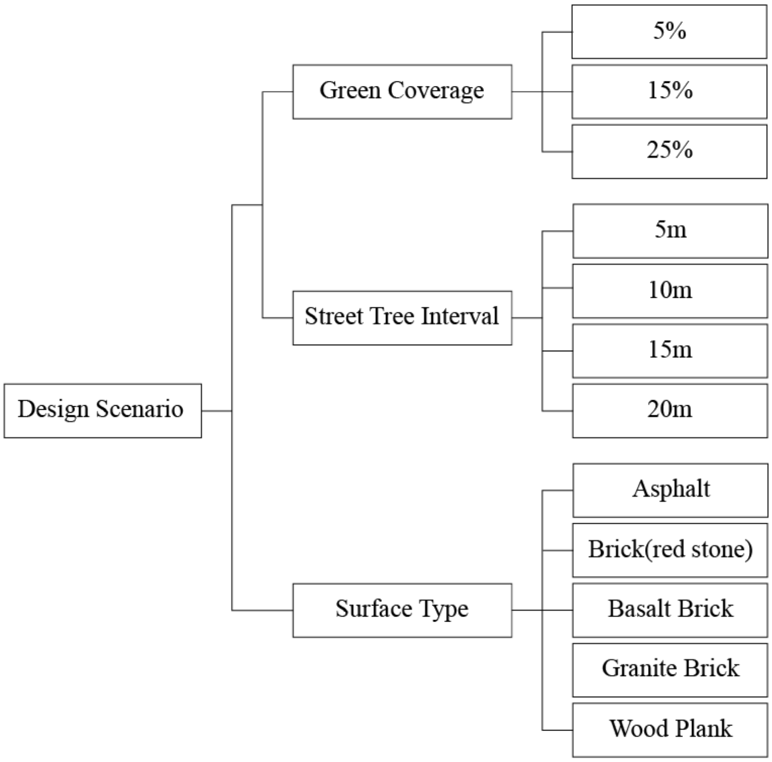
In summary, although there are many ways to use landscape design improving outdoor thermal environment according to the previous research, this study will only set up landscape design scenarios based on three kinds of landscape design elements as green coverage, road tree interval, and surface type.



[Figure 4-3] Matrix of landscape design elements and three elements selected

4.2 Design Scenario

Firstly, each scenario shown below only varies by one parameter, and then their comprehensive effects will be tested.



[Figure 4-4] Matrix of landscape design scenarios in this study

In terms of scenario simulation, August 11, 2016, the hottest day in recent 20 years is simulated based on three idealized models.

As a certain percentage of vegetation around the idealized area is required in the green coverage scenario, the scenario model should be expanded from the scope of 100 × 100 m. The main model area of three areas of 120 × 120 × 10, 120 × 120 × 40 and 120 × 120 × 40 with 5 nesting grids are used in this chapter. The size of the unit grid in all three areas on the x and y-axes is 1m × 1m, but on the vertical z-axis, are 1m, 1m and 8m respectively.

In order to study the outdoor thermal comfort of pedestrians, the data of air temperature, Tmrt, the relative humidity in 1.5m are used for simulation by ENVI-met to calculate the outdoor thermal comfort evaluation index UTCI. And the data on wind speed in 10m is needed as well. However, because of the difference of vertical grids in the models, wind speed in 10m of model A and B are replaced by 8.5m and 10.5m respectively; And in model C, 1.5m data is replaced by data in 0.8m, wind speed in 10m is replaced by the value of 12m.

4.2.1 Vegetation

Green Coverage

There has been a lot of research revealed that tree is more effective in improving outdoor pedestrian comfort than grass, because tree provides more shade and effectively reduce the radiation temperature[161, 162].

Studies have also pointed out that increasing the coverage rate of 10% of large

161 Cynthia Skelhorn, Sarah Lindley and Geoff Levermore, "The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK." *Landscape and Urban Planning*, 121, 2014, pp.129-140.
162 Hyunjung Lee, Helmut Mayer and Liang Chen, "Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany." *Landscape and Urban Planning*, 148, 2016, pp.37-50.

trees can reduce the average radiation temperature of 1k(Kelvin temperature)[163]. Forasmuch as the least value of green coverage in three typical areas is 5%(Figure 4-3), the scenario of green coverage is set to start at 5%, increasing by 10%. And it is not common for the rate of green coverage exceeds 30%. Therefore, three scenarios of green coverage are set at 5%, 15%, 25%, respectively.

In the context of green coverage, trees are often clustered in the real sites. Simple plants are also set as patches in the setting of the model. In order to avoid the disturbance of vegetation distribution to microclimate, vegetation patches are distributed evenly around. Moreover, for minimizing the impact of overcrowding on ventilation, it is also important to make gaps when setting up trees.

As the effect of the larger tree is the better. And there is no need to consider the species and crown size of the trees around in an ideal simulation here. So when constructing models in ENVI-met, vegetation selection is trees with 20m dense, distinct crown layer of simple plants.

[Table 4-2] Design scenario of green coverage in idealized model A, B, C

Model	**Design Scenarios of Different Green Coverage**		
A	5%	15%	25%
B	5%	15%	25%
C	5%	15%	25%

163 Wiebke Klemm, Bert G Heusinkveld, Sanda Lenzholzer, et al., "Street greenery and its physical and psychological impact on thermal comfort." *Landscape and Urban Planning*, 138, 2015, pp.87-98.

Street Tree Interval

In the study of street tree, many kinds of literature focus on the influence of different tree species on the canyon thermal environment. But this research will focus on the study of the interval of the street trees.

Referring to the "Ordinance for Building and Managing Street Trees in Seoul Metropolitan City(서울특별시 가로수 조성 및 관리 조례)" which starting from the year of 2015, the planting interval of trees is 6-8 m, but can be adjusted according to tree species, crown width and growth speed. In this study, through field investigation of three typical commercial streets, four kinds of the spacing of street trees includes 5m, 10m, 15m and 20m can be found. Thus, in this scenario, four types of the spacing of street trees will be set up in three idealized model to study the optimal street tree interval of different typical commercial streets.

Avoiding the effect of species of street trees on the results, one species need to be selected. The five main street trees in South Korea are ginkgo biloba, platanus acerifolia, populus tomentiglandulosa, populus and salix babylonica[164]. Except for ginkgo biloba, other street trees are gradually decreasing due to diseases and another disadvantage. But the primordial vegetation database of ENVI-met does not contain ginkgo biloba which is the highest utilization street tree, populus tomentiglandulosa, populus and salix babylonic. Although users are allowed to

164 "Street Tree of South Korea." from https://terms.naver.com/entry.nhn?docId=1190053&cid=40942&categoryId=31876. Retrieved 5/4, 2018.

build their own vegetation database, data such as CO2 fixation type, leaf type, albedo, plant height, root zone depth, leaf area(LAD) profile, root area(RAD) profile and season profile are needed, some of which can be acquired by measurement. Because measurement is time-consuming and laborious, and this study focuses on the influence of street tree interval rather than species. Therefore, populus alba, which is often used in the commercial area, is chosen as the representative of street trees for simulation.

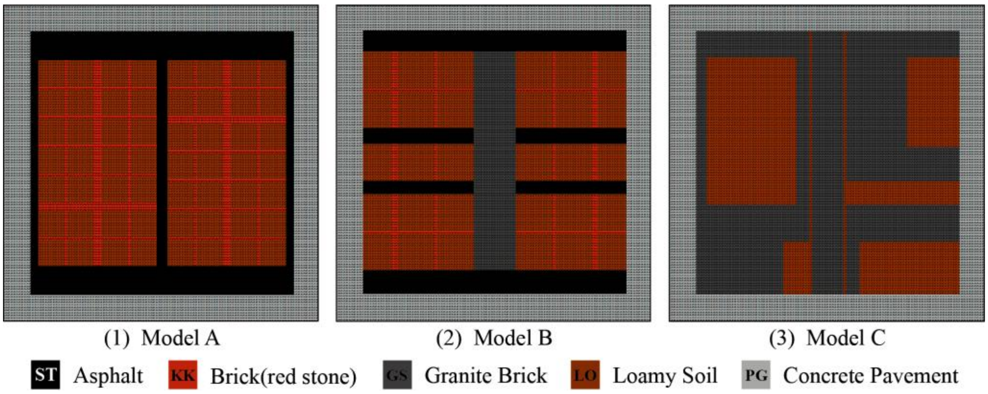
Except for model B, model A and C have a certain degree of greening. Type A represented by model A often has trees in gaps between buildings or in courtyards. As an open high-rise type, model C is often afforested in the middle of buildings or between buildings and roads.

On the basis of typical area C, vegetation configuration in model C can be simplified into a strip green space with east-west oriented between high-rise buildings, and a green patch beside the road. The size and shape of the greening are based on the actual area. And trees with 20m dense, distinct crown layer of simple plants is used. Meanwhile, the type of open high-rise mostly has isolated green belts between roads and buildings. So the grass with 50cm aver, dense of simple plants are set up along the road in this scenario in model C.

It is noteworthy that, although in the simulation of vegetation scenarios, three idealized models are used as the basis, which only fixed with urban form information, to explore which are the most suitable green coverage and street tree interval for each model. But surface type, which belongs to those three types, should also be embedded into the model. Only in this way the green coverage or the street tree interval is the real single variable. That may make the models of different scenarios correspond to the actual situation as much as possible.

[Figure 4-5] Design scenario of street tree interval of 5m, 10m, 15m, 20m in three models

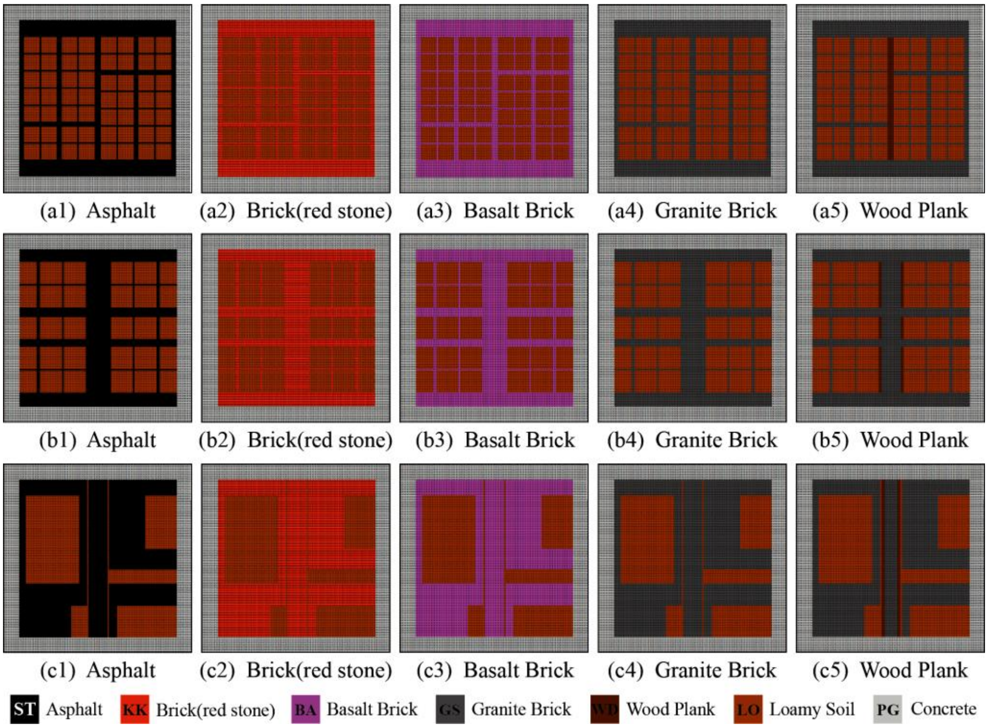
According to the archetypal situation of three typical commercial blocks as compact low-rise, compact mid-rise and open high-rise, surface type of the main streets in model A is asphalt, and granite brick in model B and C. All branches and alleys in model A are brick(red stone) roads. While branches are covered with asphalt and alleys with brick(red stone) in model B. model C is fully covered with granite brick pavement. Besides, the surface type of the building area is set to loamy soil, and space outside 100 × 100 m block is set as concrete pavement that will not be involved in the surface type scenario.



[Figure 4-6] Surface type settings for design scenarios of green coverage and street tree interval

4.2.2 Surface Type

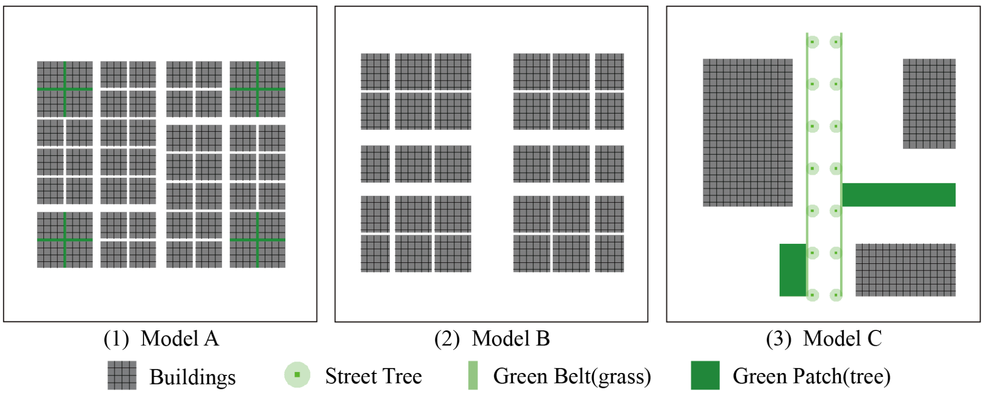
Asphalt and concrete have high radiation and poor perviousness. And the main surface type of commercial streets in Seoul are the cheapest brick(red stone), regular material granite brick in pedestrianization, and asphalt in pedestrian and vehicle mixed streets. But the main type of commercial streets in Seoul is the cheapest brick(red stone), which is a common granite brick in pedestrianization. What's more, basalt brick and wood plank are also familiar pavements in landscape design.



[Figure 4-7] Design scenario of five surface types in idealized model A, B, C

Based on the contents above, the surface type in three types is respectively set up to five pavements as asphalt, brick(red stone), basalt brick, granite brick and wood plank for scenarios. Among them, because roads in those areas still need to run vehicles, all pavements cannot set to be the wood plank. In fact, the wood plank is often used only in pedestrianization area. Consulting this, wood plank pavement with the width of 2m on both sides of the main streets in set in three types respectively, with granite brick paving on remaining areas. From this, the influence of wood plank pavement through the comparison of granite brick scenario and wood plank scenario can be understood. Additionally, the surface type of the building area is also set to loamy soil, and the space outside 100 × 100 m block as concrete pavement.

Similar with vegetation scenarios, the current status of the vegetation in three types is also embedded in the scenario models, for studying the effect of pavement on the outdoor thermal comfort of three types of commercial streets on the basis of the current situation. Vegetation setting for design scenarios of the surface type of three models is shown in Figure 4-8.

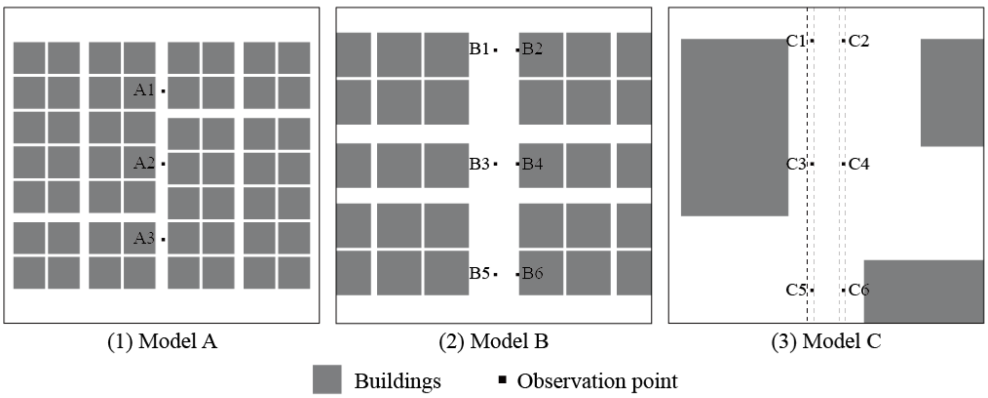


[Figure 4-8] Vegetation settings for design scenarios of surface type

4.3 Comparison and Combination

4.3.1 Comparison of Strategies

For comparing the outdoor thermal comfort of different scenarios, several observation points are set in 3 idealized models respectively. They are mainly distributed in the north, middle and south of the main street. The main street in model B is pedestrianization, so two groups of observation points are set up in the north, middle and south. One group is in the center of the street, and the other is on the side. While the chief walking area in model C is the sidewalk on both sides of the main street. The observation points are set on both sidewalks in the north, middle and south. The specific location of the observation points is as shown in the following figure.



[Figure 4-9] Observation points in model A, B and C

Green Coverage

In the green coverage scenario, the value of UTCI of three observation points

A1, A2 and A3, are the same as each other, except that in the 4 pm of the 15% green coverage scenario of A2(Table 4-3). Although these three points cannot characterize all the thermal comfort conditions in the main street in model A, for the convenience of analysis, the mean value of UTCI of those three observation points is taken.

[Table 4-3] UTCI of the observation points in three models under 3 scenarios of green coverage

Observation Points	Green Coverage	13:00	14:00	15:00	16:00	17:00
A1	5%	32.3	32.5	32.7	33.3	33.2
	15%	32.3	32.4	32.7	33.1	33.1
	25%	32.2	32.4	32.6	33.2	33.1
A2	5%	32.3	32.5	32.7	33.3	33.2
	15%	32.3	32.4	32.7	<u>33.3</u>	33.1
	25%	32.2	32.4	32.6	33.2	33.1
A3	5%	32.3	32.5	32.7	33.3	33.2
	15%	32.3	32.4	32.7	33.1	33.1
	25%	32.2	32.4	32.6	33.2	33.1

(Unit: ℃)

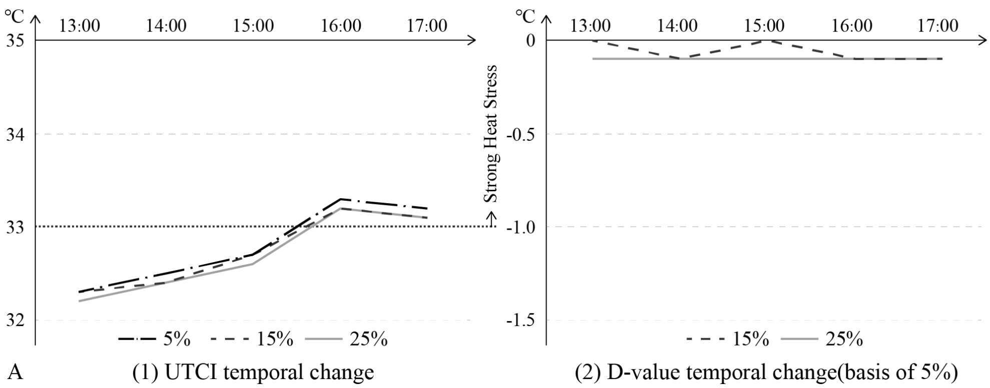
After calculation, it can be found that the UTCIs of model A under three scenarios of 5%, 15%, 25% green coverage, have identical temporal variation. From 1 pm to 4 pm, UTCIs of model A under all three green coverage scenarios increase as time goes on; After reaching the highest values, all of them decreased slightly. That means the worst thermal comfort of the pedestrian is at 4 pm on August 11, 2016. This is similar to the changes in the air temperature. Meanwhile, referring to the UTCI stress category in Table 3-6, 1 pm to 3 pm is slight heat stress, but 6pm-5pm is strong heat stress.

In order to compare the outdoor thermal comfort of model A in the 5%, 15%, 25% green coverage scenarios more clearly, this study subtracts the 5% scenario from the 15% and the 25% scenario respectively to get UTCI D-value of the 15% and 25% scenarios(as Table 4-4), to get the effect of increasing or reducing on outdoor thermal comfort in model A by green coverage.

[Table 4-4] Computing method of D-value of UTCI of 15%, 25% scenario on the basis of 5%

D-value of UTCI	Formula
15% scenario	(UTCI of 15% scenario) - (UTCI of 5% scenario)
25% scenario	(UTCI of 25% scenario) - (UTCI of 5% scenario)

As shown in Figure 4-10(2), most of D-value of UTCI in the 15% and 25% green coverage scenarios are lower than zero, which indicates that increasing green coverage does make the outdoor thermal environment better in model A.



[Figure 4-10] UTCI temporal variations of 3 scenarios in model A

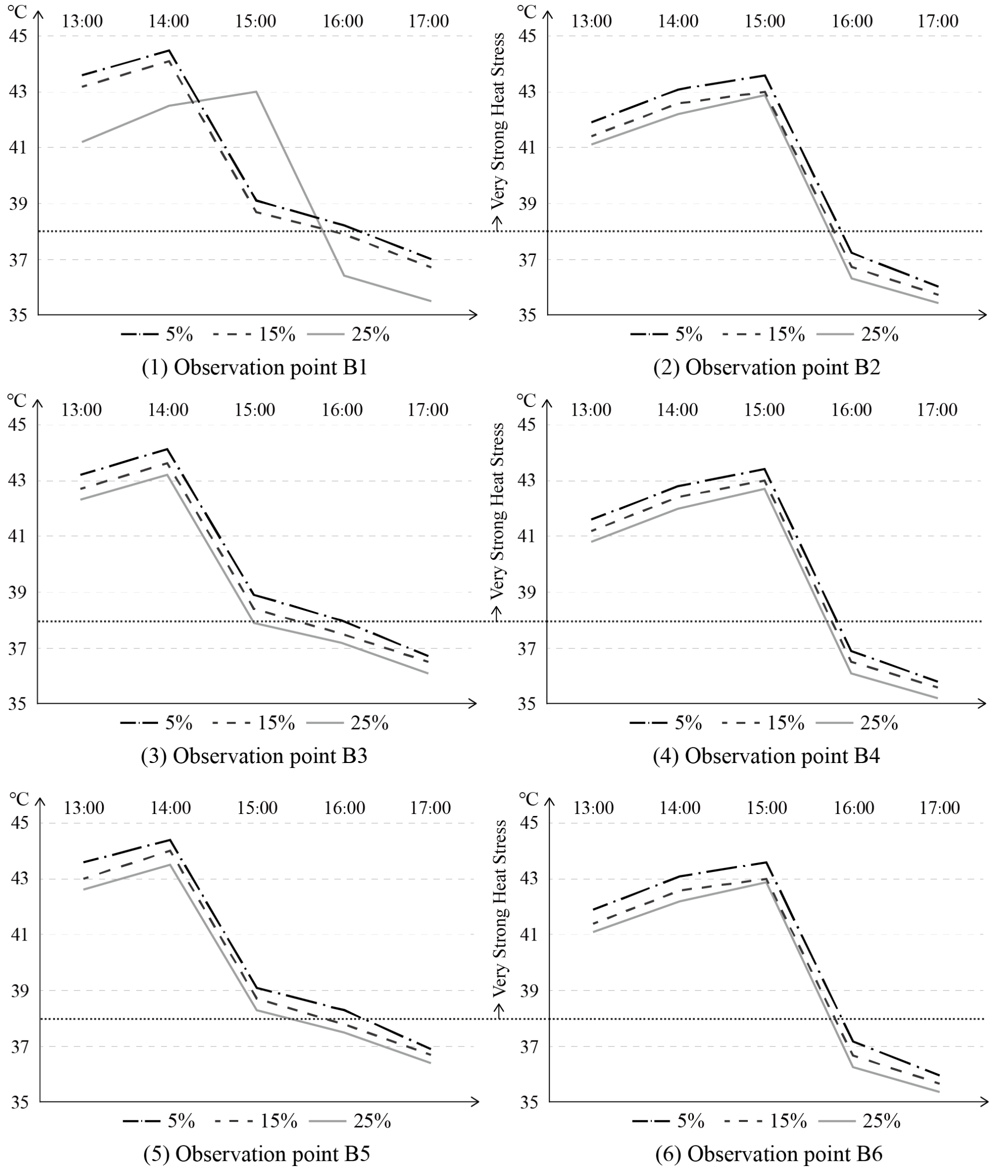
[Table 4-5] D-value of UTCI temporal variations of 15%, 25% scenario on the basis of 5%

Model	Green Coverage	13:00	14:00	15:00	16:00	17:00
A	5%	0	0	0	0	0
	15%	0	-0.1	0	-0.1	-0.1
	25%	-0.1	-0.1	-0.1	-0.1	-0.1

(Unit: ℃)

The temporal variations of UTCI of 6 observation points in model B under three scenarios are listed in Figure 4-13. It can be found that the UTCI value of model B is between 35-45 ℃, which is different from that of model A at 32-34 ℃. Correspondingly, the heat stress category is also different, as the heat stress level of model B is much higher. In addition, there are differences in the trend of UTCI temporal variations. Although the value of UTCI model A and B firstly increased and then decreased. Overall, different from the rising trend of model A, model B shows a downward trend.

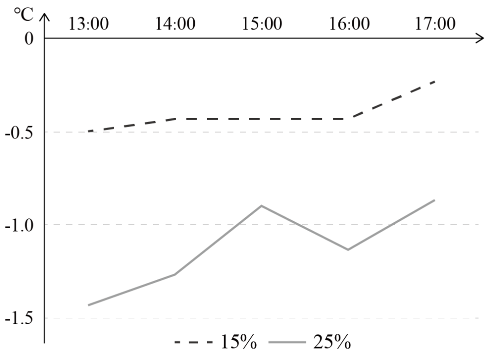
The observation points in Figure 4-11(1), (3), (5) are located in the center of the main street in model B(referred to as group mid-B for short). While observation points in (2), (4) and (6) are on the side of the road(group side-B for short). It can be seen from the graph that there has a difference in the UTCI temporal variations of the two groups. When group mid-B reaches a peak value at 2 pm, UTCI decreases with time; while the peak value of group side-B is 3 pm. The pelter time of UTCI of two groups is 2-3 pm and 3-4 pm, respectively. This result is not the same as the temporal variation of air temperature. It indicates that the outdoor thermal comfort of the main street in model B is more dominated by other microclimate factors.



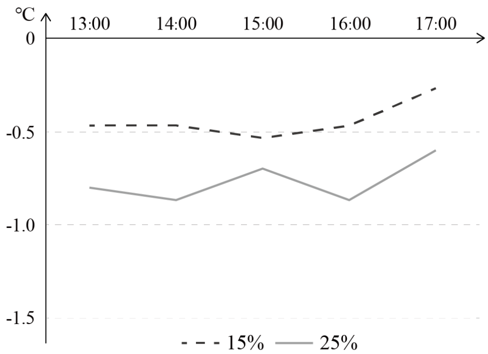
[Figure 4-11] UTCI temporal variations of three scenarios of observation points in model B

Before 4 pm, both groups show very strong heat stress, then reduced to strong heat stress. Meanwhile, the average value of UTCI of group side-B is lower than that of group mid-B, which tells that the outdoor thermal comfort on the side of the street is better.

Following the above classification, the D-value of UTCI of group mid-B under three scenarios is shown in Figure 4-12(1), and group side-B in (2). It can be found that the effect of 25% green coverage on group mid-B alleviating the outdoor thermal environment is the largest. And the 15% green coverage has a similar function of increasing the thermal comfort on both groups, but the impact of 25% green coverage on group mid-B is significantly larger than group side-B.



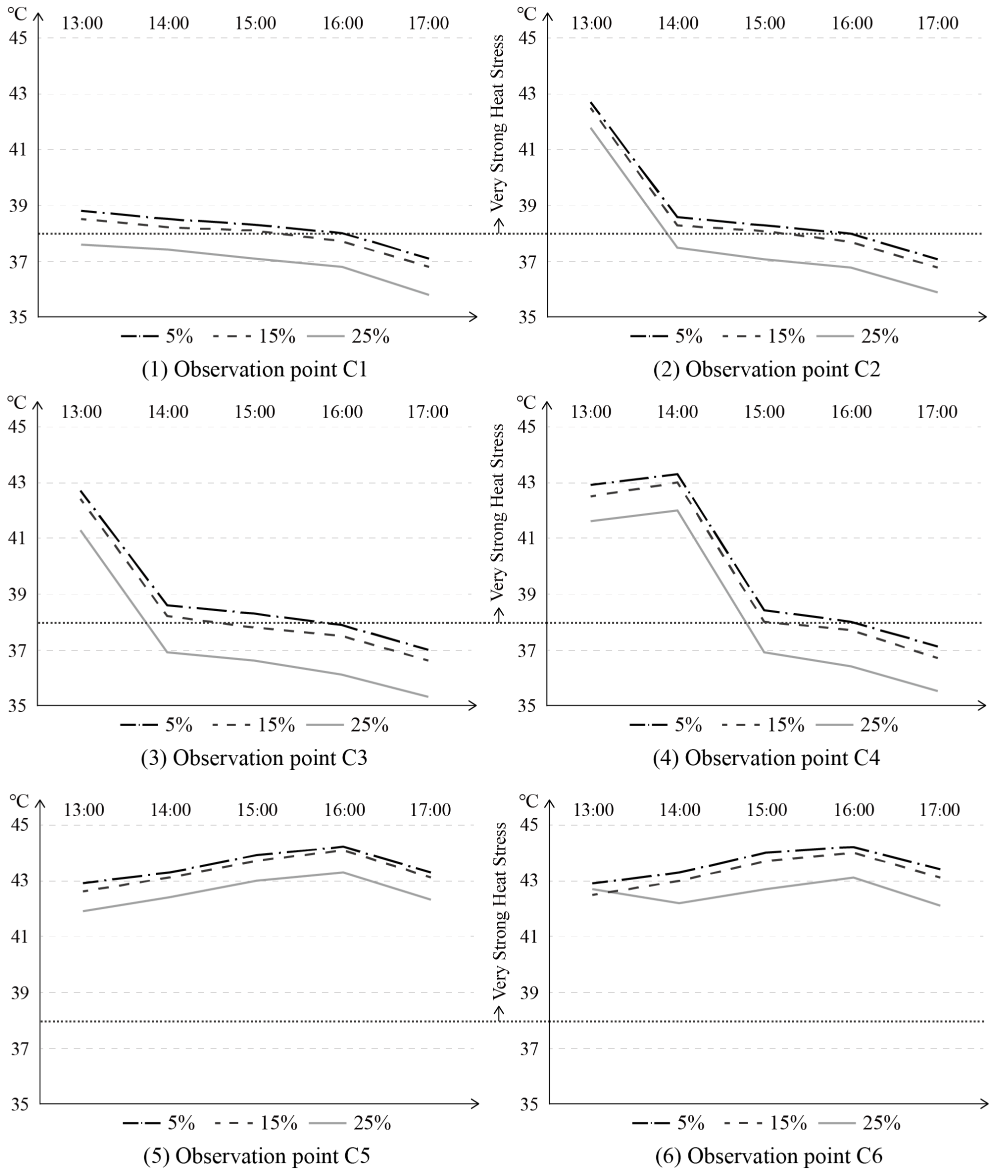
B(1) Average of 3 points in the middle of main street



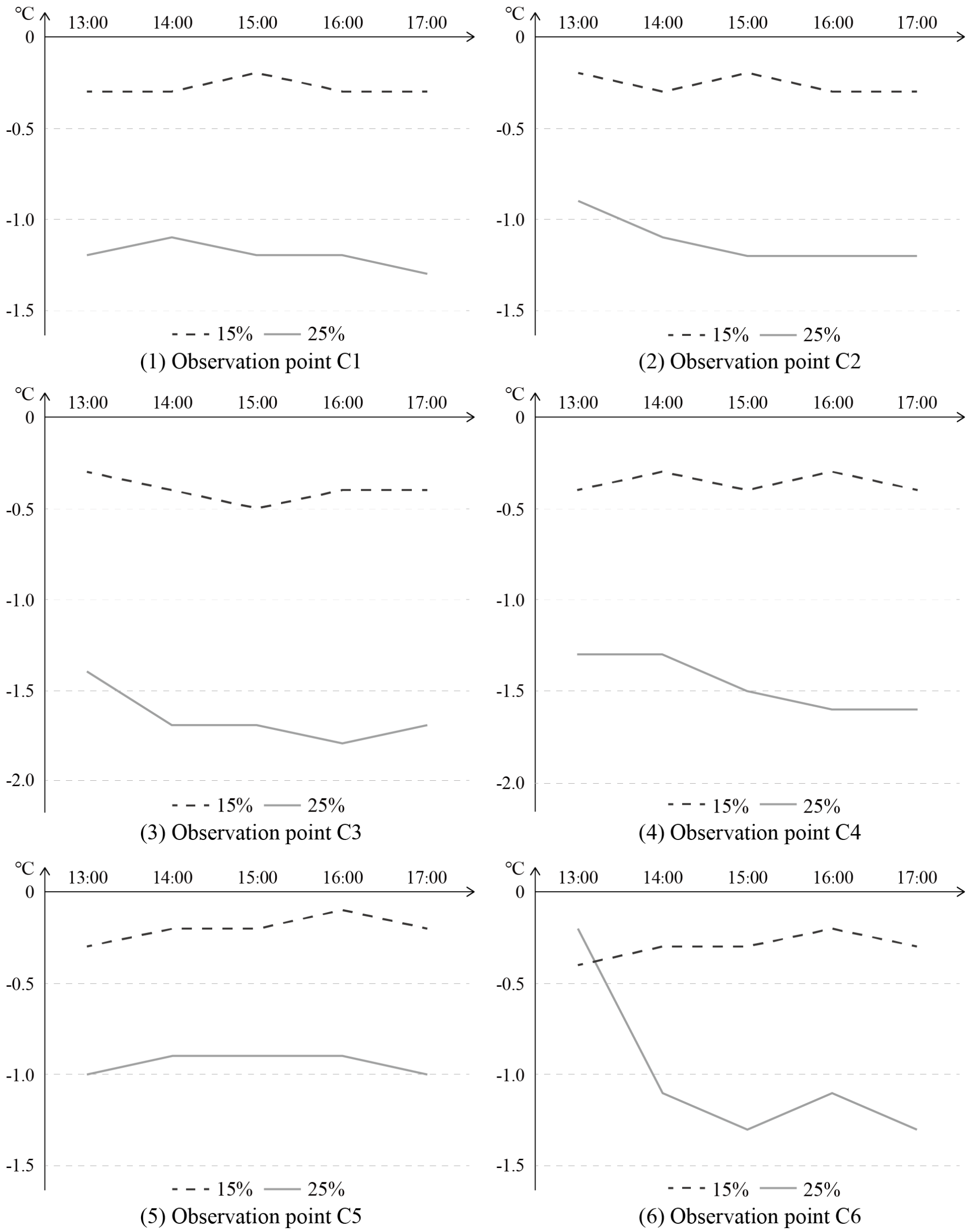
(2) Average of 3 points on the side of main street

[Figure 4-12] Temporal variations of D-value of 3 scenarios in model B(basis of 5% scenario)

Because of the asymmetry of the model C, the observation points are set up on both sidewalks. UTCI simulation results in different scenarios are shown in Figure 4-13. (1), (3) and (5) of Figure 4-13 are on the west of the main street, with (2), (4) and (6) on the east. Unlike model B, the simulation results of observation points in model C are different, which cannot be distinguished between the east and west groups.



[Figure 4-13] UTCI temporal variations of three scenarios of observation points in model C



[Figure 4-14] Temporal variations of D-value of 3 scenarios in model C(basis of 5% scenario)

Observation points C1, C2, C3 and C4 have very strong heat stress before 3 pm. The trend in these four observation points is similar to the results in model B.

However, the peak value of C1, C2, C3 is at 1 pm, while C4 at 2 pm. C2 and C3 have a sudden decline after 1 pm, while 2 pm of C4. On the contrary, the temporal variation of C5 and C6 increased first, then decreased after reaching the peak value at 4 pm. The overall trend of which is similar to that of model A. Also the UTCI value continued to be higher in C5 and C6, as well as the severity of heat stress.

The D-value of UTCI of six observation points is calculated respectively in Figure 4-14. According to this, six observation points can be divided into three types as C1 and C2 in the north, C3 and C4 in the middle, and a group on the south(C5 and C6).

Compared with model A and B, the effect of 25% green coverage on improving outdoor thermal comfort is most obvious in model C. Although the influence of 15% green coverage on model C is much similar to that of model B. What's more, the role of 25% green coverage is more prominent in the central observation points in model C.

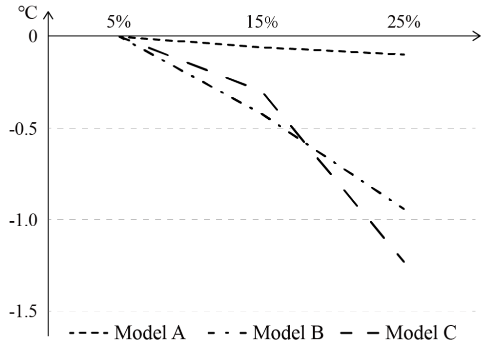
[Table 4-6] D-value of UTCI of three scenarios in model A, B, C(basis of 5% scenario)

Green Coverage	**5%**	**15%**	**25%**
Model A	0	-0.06	-0.1
Model B	0	-0.42	-0.94
Model C	0	-0.3	-1.23

(Unit: ℃)

The mean value of UTCI D-value at a different time of the observation points of three idealized models can be used to figure out the difference between the effects of increasing green coverage on the outdoor thermal comfort in three main streets.

In the first place, speaking about the outdoor thermal environment of three idealized model under the green coverage scenario, pedestrians' thermal comfort in model A is obviously better than other models.



[Figure 4-15] D-value of three scenarios in model A, B, C(basis of 5% scenario)

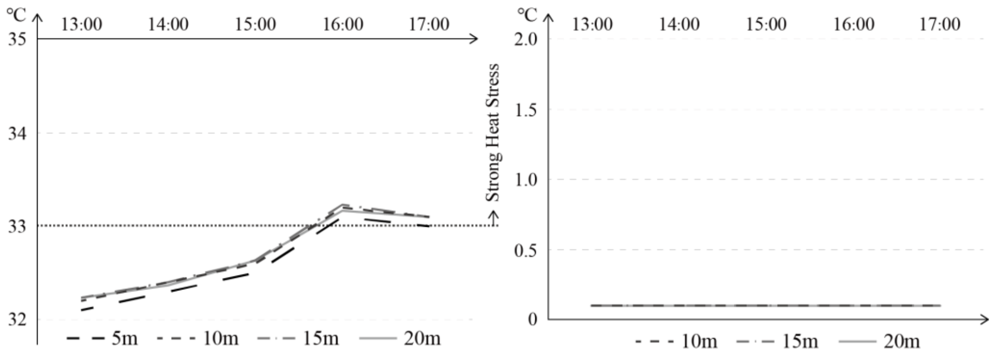
From the average level, the rise of green coverage has little effect on the outdoor thermal comfort in model A. In model B and C, increasing green coverage has a significant influence on reducing the heat stress in the commercial streets. Furthermore, raising green coverage by about 20% in model A and B can make a double effect of that of 10% on the outdoor thermal comfort. While green coverage increased by 20% in model C, the outdoor heat pressure significantly exceeded that of 10%. Additionally, it is said that an increase of 10% of green coverage can reduce the average radiation by 1k in the previous research. Although this study is unable to verify that point of view, the process of raising the green coverage in model B and C from 15% to 25%, do help reduce UTCI by about 1℃.

The above process of scenario simulation shows that the design of increasing green coverage has a significant impact on the outdoor thermal comfort of the main street in model B and C. Under a feasible premise, a rise of 25% green coverage is the best choice.

Street Tree Interval

[Table 4-7] Computing method of D-value of UTCI of 10m, 15m, 25m scenario on the basis of 5m scenario

D-value of UTCI	Formula
10m scenario	(UTCI of 10m scenario) - (UTCI of 5m scenario)
15m scenario	(UTCI of 15m scenario) - (UTCI of 5m scenario)
20m scenario	(UTCI of 20m scenario) - (UTCI of 5m scenario)



(1) UTCI temporal change (2) D-value temporal change(basis of 5m)

[Figure 4-16] UTCI temporal variations of 4 scenarios in model A

The scenarios of street tree interval include intervals of 5m, 10m, 15m, 20m. The same as the green coverage scenario, in order to compare the outdoor thermal comfort under these four scenarios, the interpolation of the other three scenarios on the basis of the 5m scenario is calculated. The result of this process is named

D-value of UTCI, and the operation process is shown in the table.

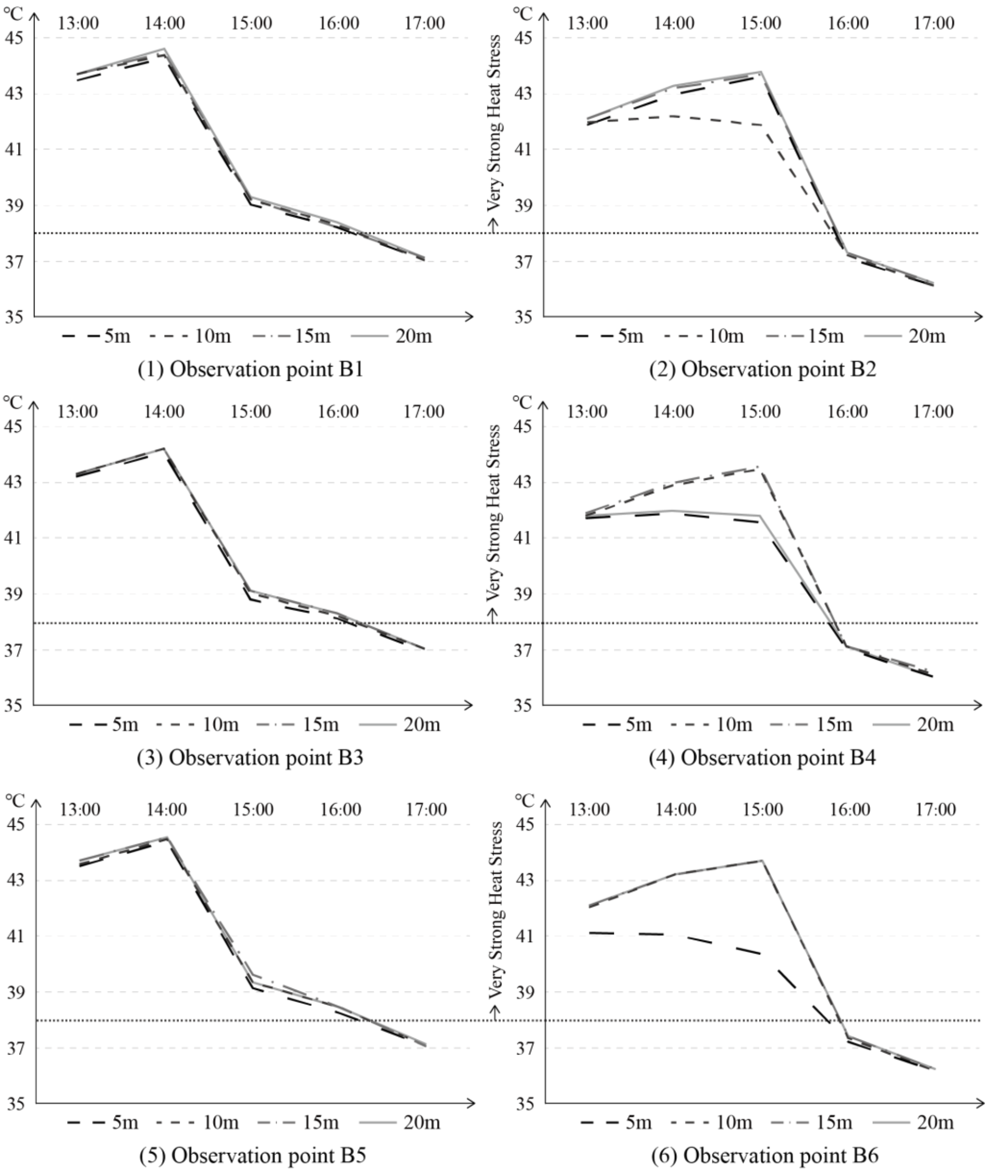
[Table 4-8] D-value of UTCI temporal variations of 10m, 15m, 25m scenario on the basis of 5m scenario

Model	Street Tree Interval	13:00	14:00	15:00	16:00	17:00
A	5m	0	0	0	0	0
	10m	0.1	0.1	0.1	0.1	0.1
	15m	0.1	0.1	0.1	0.1	0.1
	20m	0.1	0.1	0.1	0.1	0.1

(Unit: ℃)

Similar to the green coverage scenario, the UTCI value of observation points A1, A2, A3 in model A are almost the same. So as shown in Figure 4-16(1), the averaged UTCI results are taken to study the temporal variation.

The UTCI temporal variation of street tree interval scenarios in model A is similar to the scenarios of green coverage. The changes in the four scenarios have uniformity. From 1 pm to 4 pm, the UTCI of model A increased over time in all scenarios; after reached the highest value at 4 pm, it decreased slightly; and the outdoor thermal comfort of 4 pm was the worst. From 1 pm to 3 pm, it is slight heat stress, but strong heat stress from 6 pm to 5 pm.



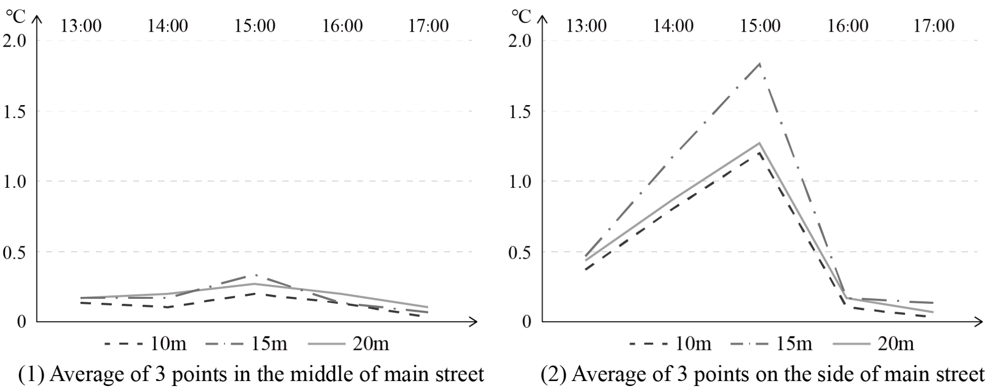
[Figure 4-17] UTCI temporal variations of 4 scenarios of observation points in model B

Comparing the differences between scenarios, it can be found that the outdoor thermal comfort in model A under the scenarios of street trees at 10m, 15m and 20m interval is basically the same, but worse than that of 5m. However, the gap is very small(only 1℃).

The simulation results of four scenarios in model B are analyzed. Besides the result of that the overall UTCI value of model B is obviously higher than that of model A, the observation points in model B can still be divided into group mid-B and group side-B according to their temporal trend, and the differences of four scenarios in these two groups can be found.

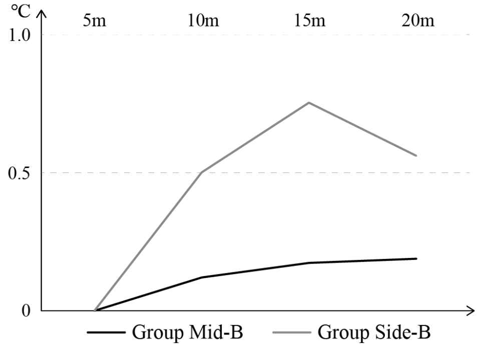
As in Figure 4-17, the temporal variation of UTCI simulation results of the two groups of observation points is similar to that of green coverage scenarios.

When group mid-B reach the peak value at 2 pm, UTCI decreased with time; the drop time was 2-3 pm; very strong heat stress appears before 4 pm in group mid-B. Group side-B also increased slowly and then plummeted. However, the peak values of different scenarios are disaccord with 2 pm or 3 pm; the pelter time is during 3-4 pm; and strong heat stress appears after 4 pm.



[Figure 4-18] Temporal variations of D-value of 4 scenarios in model B(basis of 5m scenario)

On the whole, the outdoor thermal comfort of pedestrians on the roadside is better.

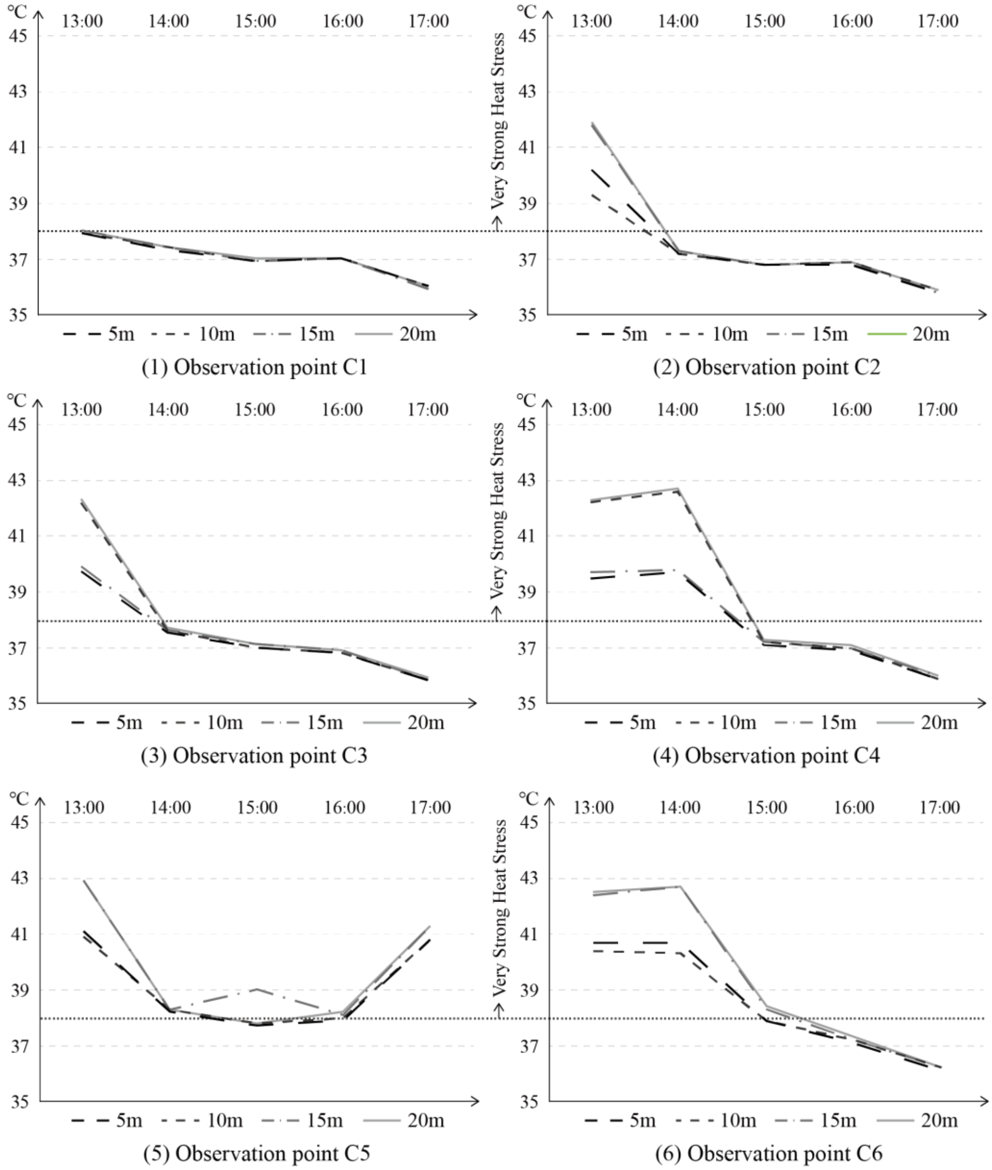


[Figure 4-19] D-value of 4 scenarios of 2 groups in model B(basis of 5m scenario)

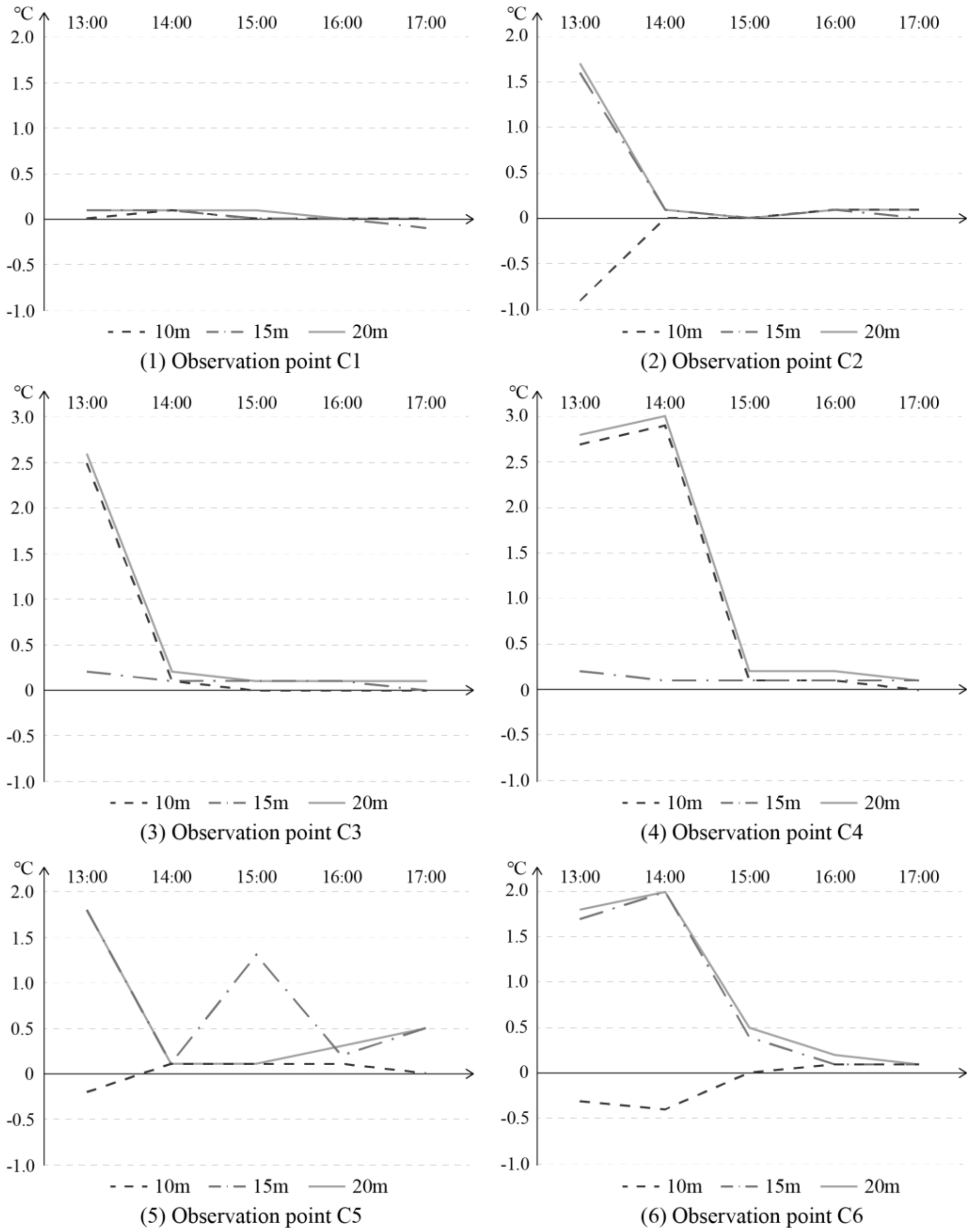
Through Figure 4-18 and Figure 4-19, the effect of different street tree spacing on alleviating outdoor thermal stress can be compared. Obviously, the 5m spacing has the best outdoor thermal comfort in four scenarios. Moreover, when compared to other time, the improvement of 5m scenario is the best at 3 pm.

Additionally, the difference between 4 types of street tree interval in group side-B is more significant. In group mid-B, the outdoor thermal comfort decreases in turn as 10m, 15m, 20m. But there is little difference between these three spacing. In group side-B, the UTCI simulation results of these three scenarios and 5m scenario have a gap of about 0.5℃. While the spacing of street trees to be 15m, the thermal comfort of pedestrians in model B is the worst.

The difference of the thermal comfort between the center and the edge of the road in this scenario is probably because the street trees are placed on the side of the road. In reality, street trees are often planted on both sides of the streets. In this case, pedestrians can enjoy the role of the road tree alleviating the thermal pressure on the sidewalks, but in the pedestrianization, the planting position of street trees need further consideration.



[Figure 4-20] UTCI temporal variations of 4 scenarios of observation points in model C



[Figure 4-21] Temporal variations of D-value of 4 scenarios in model C(basis of 5m scenario)

The UTCI temporal variations of six observation points in model C are shown in the figure. The variation trend of UTCI of the four observation points in the north and middle is similar to that in the green coverage scenario.

The value of UTCI starts declined in C1 from 1 pm. The whole research period of C1 is under strong heat stress. C2 and C3 have a peak value at 1 pm, with different UTCI values of 4 scenarios; then the UTCI value decreases gradually; 1-2 pm is a sag interval, and then both of these two places are strong heat stress degree after 1 pm. When C4 and C6 reach the highest value at 2 pm, UTCI dropped suddenly within one hour; but four scenarios appear differently during the 1-2 pm.

It is very unique that the UTCI simulation value of four types of street tree interval scenarios in the observation point of C5. Where UTCI decreases during 1-2 pm, and then increase again at 4-5 pm.

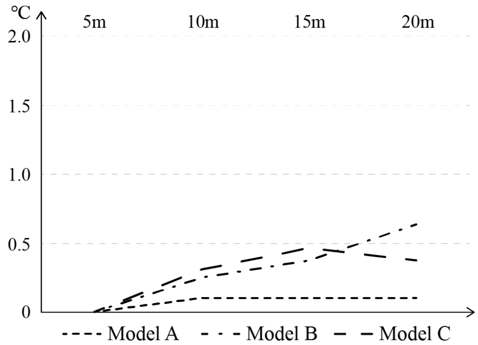
In Figure 4-21, the difference in street tree interval at different observation points can be clearly observed. the difference between the four kinds of the interval is very small at C1. At C2, the distance of 10m is better than 5m. Observation points in the middle of the main street in model C as C3 and C4, has a better effect of 5m and 15m intervals decreasing outdoor heat stress than the other two scenarios. At the observation point of C5, the 5m spacing is the best choice, while 10m is also not bad. And in C6, the outdoor thermal comfort in the scenario of 10m is better than that in the 5m scenario.

Resulted from the above analysis, in compact high-rise regions with irregular urban form as model C, a various distance of street trees has different effects on the outdoor thermal comfort of pedestrians at different locations.

[Table 4-9] D-value of UTCI of 4 scenarios in model A, B, C(basis of 5m scenario)

Street Tree Interval	5m	10m	15m	20m
Model A	0	0.1	0.1	0.1
Model B	0	0.31	0.46	0.37
Model C	0	0.25	0.37	0.64

(Unit: ℃)



[Figure 4-22] D-value of 4 scenarios in model A, B, C(basis of 5m scenario)

Looking through all four types of street tree interval scenarios, the 5m interval is the best choice when designing street trees in three typical idealized models. Besides the 5m scenario, the effect of the other three scenarios are similar in model A. In the case of model B, 15m spacing should not be selected for planting street trees. And although 20m is the worst choice in model C area, different location needs decision depending on circumstances.

Surface Type

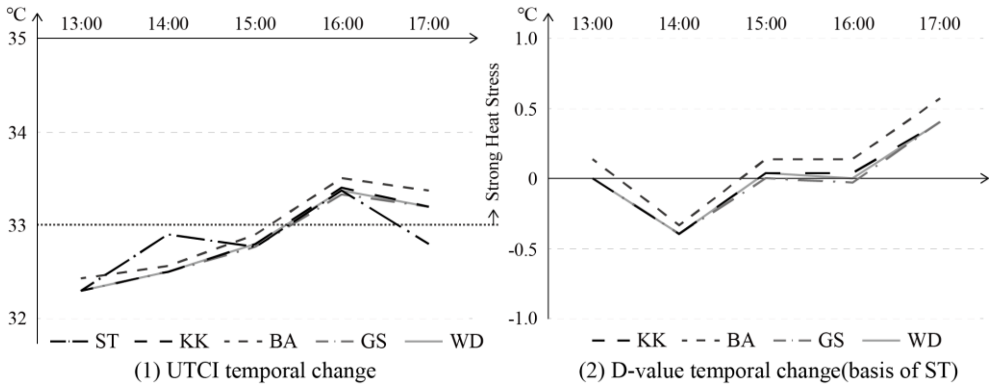
This section will explore different pavement scenarios, including asphalt, brick(red stone), basalt brick, granite brick and wood plank. They correspond to the surface materials in ENVI-met, which are referred to as ST, KK, BA, GS and WD. For convenience, these abbreviations are used in the following paper.

This part also calculates the D-value of UTCI of other four scenarios on the basis of the result of the most common pavement asphalt(ST) scenario. Which is used to compare the differences between the five scenarios(Table 4-10).

[Table 4-10] Computing method of D-value of UTCI of KK, BA, GS, WD scenario on the basis of ST scenario

D-value of UTCI	Formula
Brick(red stone)(KK) scenario	(UTCI of KK scenario) - (UTCI of ST scenario)
Basalt brick(BA) scenario	(UTCI of BA scenario) - (UTCI of ST scenario)
Granite brick(GS) scenario	(UTCI of GS scenario) - (UTCI of ST scenario)
Wood plank(WD) scenario	(UTCI of WD scenario) - (UTCI of ST scenario)

Except the ST scenario, the UTCI temporal variation of other surface type scenarios is similar to the vegetation scenarios(both green coverage scenario and street tree interval scenario) in model A. The ascending interval of UTCI is also during 1-4 pm; the highest value of UTCI is at 4 pm, which means the outdoor thermal comfort at 4 pm is the worst; and after that time, it gradually drops. As the results of vegetation scenarios, the change of UTCI in this scenario shows that 1-3 pm is the degree of slight heat stress, and 4-5 pm has strong heat stress. Unlike that, the ST scenario shows a temporal change of undulating, which only has strong heat stress at 4 pm with other time lower than 33℃.

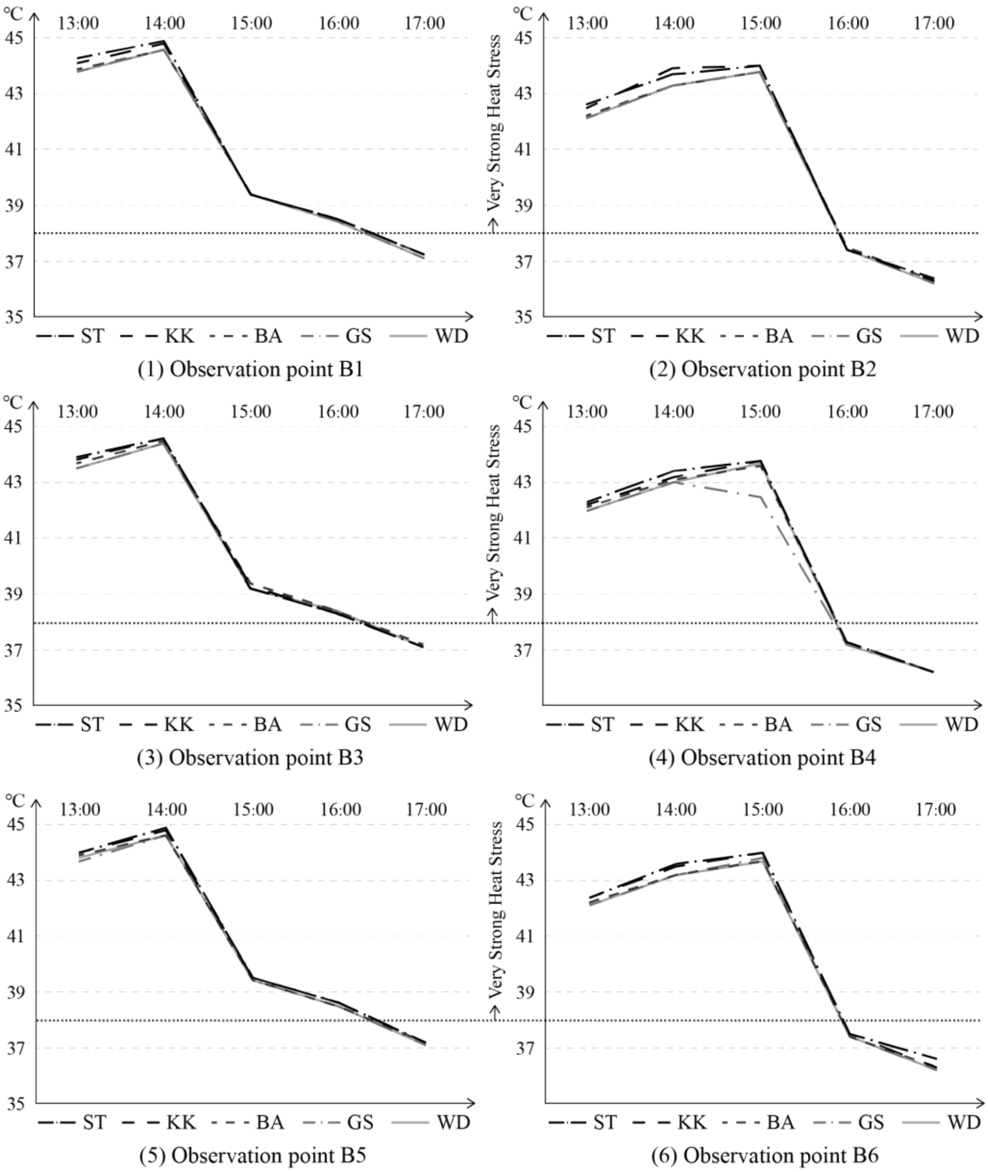


[Figure 4-23] UTCI temporal variations of 5 scenarios in model A

The D-value analysis in Figure 4-23(2) reveals that surface types perform differently in different time periods, which has a watershed at 3 pm. And at 2 pm, other pavements have less thermal stress than asphalt, while it is opposite at 5 pm.

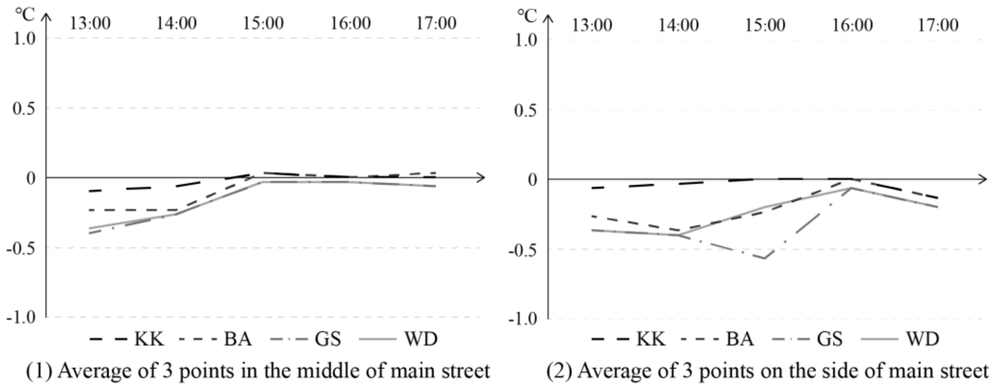
It can be found that except 5 pm, the UTCI of GS scenario is always lower than that of ST scenario, which is saying GS is more friendly to the outdoor thermal environment than ST. Compared with surface types such as KK, GS and WD, the outdoor thermal comfort of BA scenario in model B is the worst. So in the compact mid-rise areas as model B, basalt brick is one of the pavements need to be avoided.

The UTCI temporal variations of the six observation points in model B are similar to the results of vegetation scenarios as well. Also, the characteristics of group mid-B and group side-B are almost the same as in vegetation scenarios respectively. Thus this study will not give unnecessary details here about the temporal changes of observation points in model B.



[Figure 4-24] UTCI temporal variations in 5 scenarios of observation points in model B

With Figure 4-25, different pavement performance in different periods of the hottest time of the hottest day in the last 20 years can be analyzed.

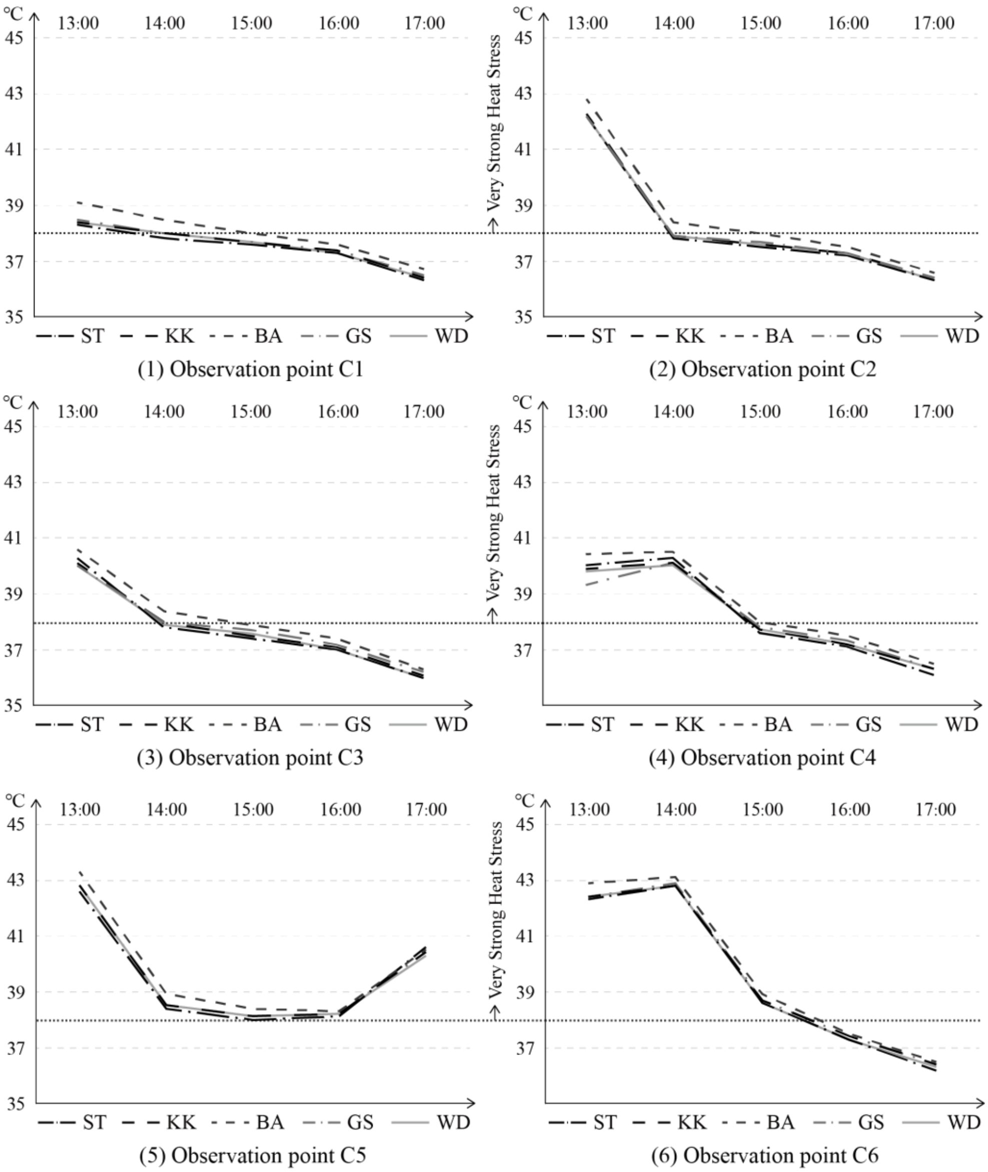


[Figure 4-25] Temporal variations of D-value of 5 scenarios of model B(basis of ST scenario)

Taking UTCI of the asphalt scenario as the benchmark, the D-value of UTCI of other surface type scenarios is basically less than 0. Which is to say, other four scenarios including KK, BA, GS and WD have better outdoor thermal comfort compared with ST scenario. In particular, the heat stress in the GS and WD scenario is the least, followed by BA. The commonly used pavement KK has a poor effect on reducing outdoor heat stress, which is rarely different with asphalt.

The UTCI temporal variations of six observation points in model C are shown in Figure 4-28. The variation trend of UTCI in surface type scenarios are very similar to vegetation scenarios, especially the street tree interval scenarios.

If it can be saying that there are similar UTCI changes in the six observation points in model C under the previous vegetation scenarios, the situation here in this scenario is totally different.



[Figure 4-26] UTCI temporal variations in 5 scenarios of observation points in model C

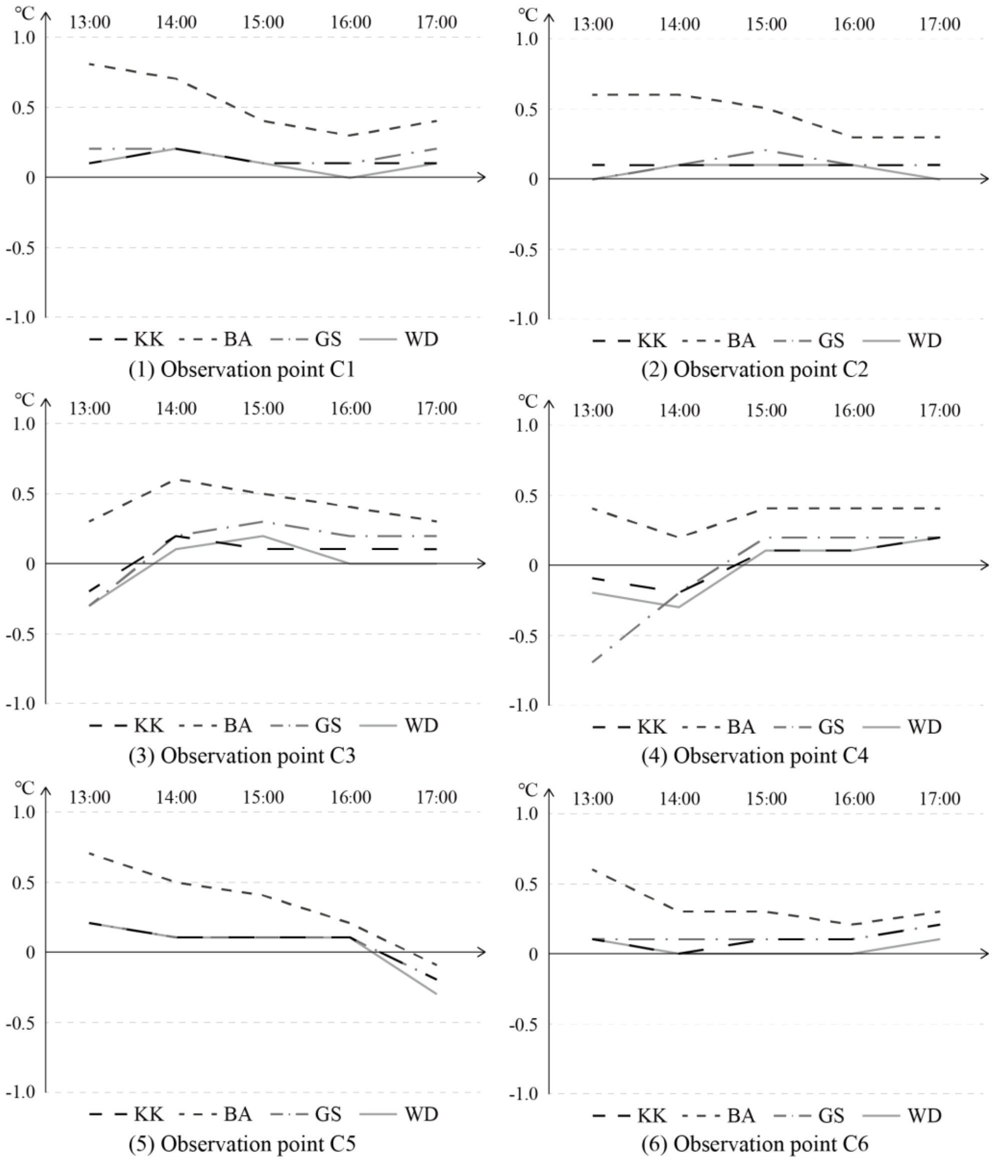
The UTCI of different surface type scenarios in the observation points C1 and C3 begin to decline slowly from 1 pm. But there is less temperature shift in C1. Both C2 and C5 have a sudden drop of UTCI during the period of 1-2 pm and then decreased slowly. But what's different is that the heat stress in C5 increases after 3 pm. The points of C4 and C6 are the type of increasing first then dropping. Although both of them reach the UTCI peak value at 2 pm in all surface type scenarios, their amplitude varies greatly.

Comparing the thermal comfort of different surface types in model C, it can be found that, although the performance of each surface material in different regions is various, the worst outdoor thermal comfort of all six observation points is in GS scenario. Moreover, in addition to the 1 pm of C3, 1-2 pm of C4, 5 pm of C5, most of the scenarios of KK, BA, GS and WD are superior to the ST scenario, the outdoor thermal comfort of the ST scenario is the highest in the other periods and observation points in model C. It indicates that all surface types in C models are better paved with asphalt than other pavements, followed by wood plank(WD).

This is a little unexpected. In fact, only a width of 4 m of wood plank pavement is set up in the WD scenario, the rest of which is granite bricks. But except ST scenario, WD and GS are the best and worst cases.

From the difference between the scenario of WD and GS, it can be concluded that designing a certain proportion of wooden pavement in walking space can effectively increase the outdoor thermal comfort of pedestrians.

This simulation result reveals the application effect of wooden pavement in optimizing outdoor walking thermal comfort, even with a small amount. Although the actual implementation and usage ratio or other issues of which needs more discussion, it provides some inspiration for the future design of outdoor pedestrian streets.



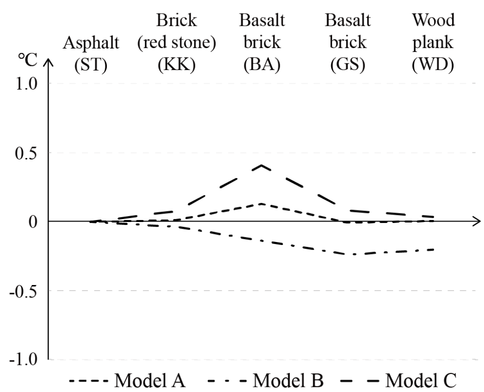
[Figure 4-27] Temporal variations of D-value of 5 scenarios of model C(basis of ST scenario)

In comparison, the performance of brick(red stone) in three models is almost the same as that of asphalt. Basalt brick’s ability to improve outdoor thermal comfort in model A and C is worse than that of asphalt. Especially in model C, the thermal pressure of basalt brick is maximum. In model B, the other three kinds of pavements are better than the commonly used pavement asphalt and brick(red stone), especially granite brick. But the ability of granite brick to mitigate the thermal environment is only mediocre in the other two models. The effect of the wood plank is only higher than asphalt in model B.

[Table 4-11] D-value of UTCI of 5 scenarios of model A, B, C(basis of ST scenario)

Surface Type	ST	KK	BA	GS	WD
Model A	0	0.01	0.13	-0.01	0.01
Model B	0	-0.04	-0.14	-0.24	-0.2
Model C	0	0.08	0.41	0.08	0.04

(Unit: ℃)



[Figure 4-28] D-value of 5 scenarios of model A, B, C(basis of ST scenario)

To sum up, although the UTCI simulation results of all five surface types scenarios are similar with each other, granite brick is a better choice for pavement in compact low-rise blocks as model A. And also granite brick for compact mid-rise areas as model B without doubt, while asphalt in open high-rise region presented by model C.

[Table 4-12] The UTCI mean of three models in three types of scenarios

	Scenario	A	B	C
Green Coverage	5%	32.8	40.4	40.5
	15%	32.7	40.0	40.2
	25%	32.7	39.6	39.3
Street Tree Interval	5m	32.6	40.0	38.5
	10m	32.7	40.3	38.2
	15m	32.7	40.5	38.1
	20m	32.7	40.4	37.9
Surface Type	Asphalt	32.8	40.8	38.4
	Brick(red stone)	32.8	40.7	38.5
	Basalt Brick	33.0	40.6	38.8
	Granite Brick	32.8	40.5	38.5
	Wood Plank	32.8	40.6	38.5

(Unit: ℃)

Through the simulation of the single scenario above, it can be found that:

Firstly, no matter how much different scenarios affect the simulation results, in view of the outdoor thermal comfort, model A is obviously better than that of the other models, with model C in the second place. And model B has the greatest heat stress. This shows that the urban form of compact low-rise, compact mid-rise and open high-rise have a great impact on the thermal environment of commercial streets.

[Table 4-13] The most effective landscape design elements in three models

Model	Best Elements	Remark
A	Street tree interval	Surface type is the worst
B	Green coverage	Surface type is the best for roadsides
C	Street tree interval	Obvious result of green coverage change

Although different scenarios have little effect on the UTCI simulation results of model A, the scenario of street tree interval is more effective in improving the outdoor thermal environment, while surface type is the smallest. For model B, the role of green coverage is greater, but the scenario of surface type performs better in the observation points of group side-B which located on the roadside. While the best design element for model C is obviously the street tree interval; however, the increase of green coverage can greatly reduce the heat pressure of pedestrians.

Additionally, the best simulation results of outdoor thermal comfort in these three single scenarios are 25% green coverage, 5m street tree interval, along with the surface type of granite brick in model A and B, asphalt in model C, relatively.

4.3.2 Combination of Strategies

In the simulation results of three kinds of scenarios above, 25% green coverage has an overwhelming superiority; 5m interval of street trees is relatively better; and the results of single factor analysis of surface type differ in three models. The single element scenario simulation results of the three models are shown in Table 4-14.

[Table 4-14] The best scenarios for three kinds of design elements in three models

Model	Landscape Element Scenarios		
	Green Coverage	Street Tree Interval	Surface Type
A	25%	5m	Granite brick(GS)
B	25%	5m	Granite brick(GS)
C	25%	5m	Asphalt(ST)

As landscape design is often the integration of multiple elements, in addition to considering the effect of single elements, the migmatization of multiple elements cannot be ignored at all. Therefore, in the three model of compact low-rise, compact mid-rise, open high-rise, the combination of two outstanding scenarios above and three combinations are simulated respectively.

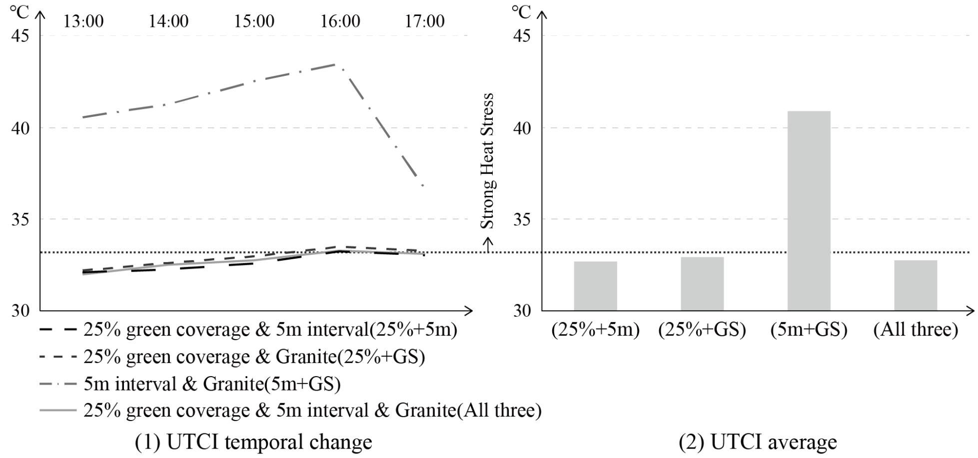
[Table 4-15] The combination of scenarios

Model	Combinations			
A	25% + 5m	5m + GS	25% + GS	25% + 5m + GS
B	25% + 5m	5m + GS	25% + GS	25% + 5m + GS
C	25% + 5m	5m + ST	25% + ST	25% + 5m + ST

(25% = 25% green coverage; 5m = 5m street tree interval; GS = Granite brick; ST = Asphalt)

For the convenience of explanation, the scenarios of 25% green coverage, 5m street tree interval, granite brick, asphalt are referred to '25%', '5m', 'GS', 'ST' respectively.

So how these elements working together in three models is going to be checked through the simulation of multi-elements scenarios composed of best scenarios of three landscape elements.

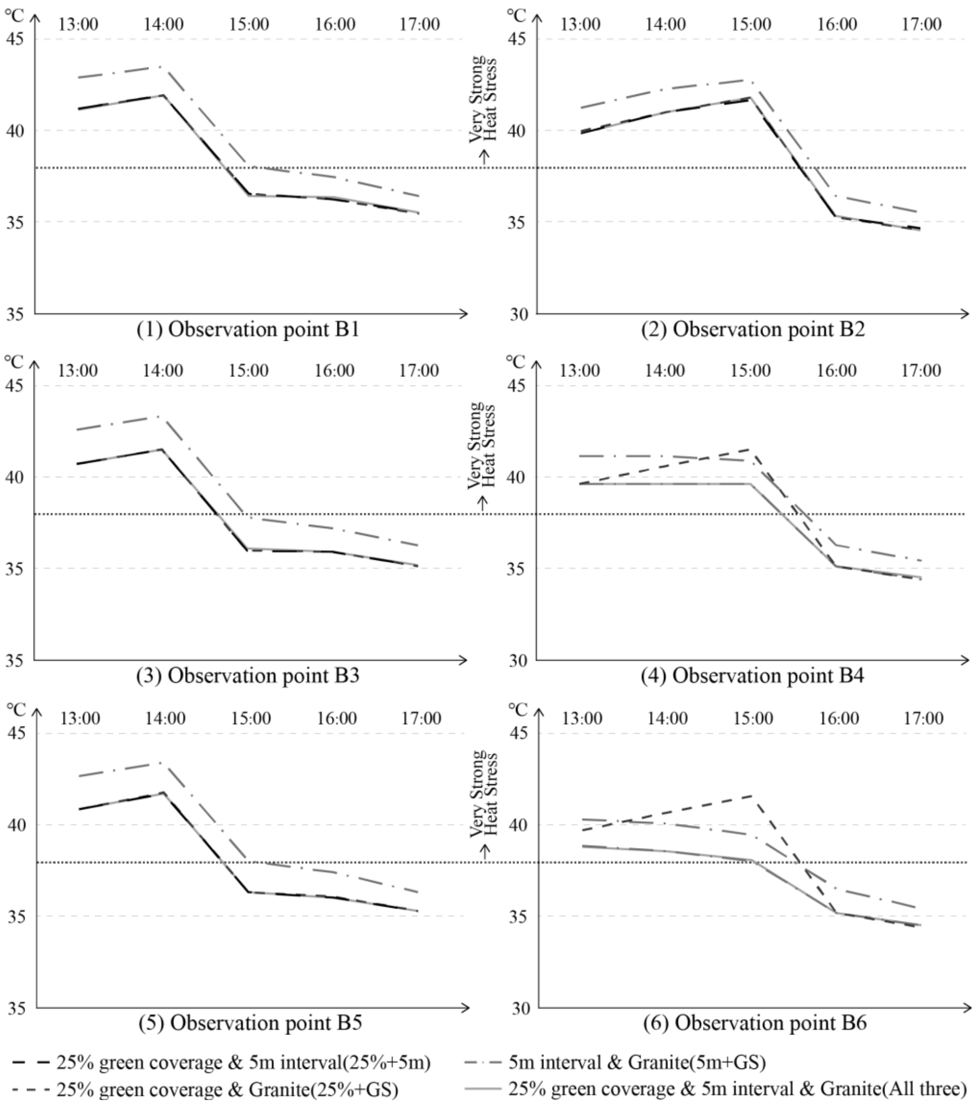


[Figure 4-29] Temporal changes&differences of UTCI in 4 multi-elements scenarios in model A

For model A, the temporal variations of the four multi-elements scenarios gradually increased before 4 pm and decreased after 4 pm when has the peak value. The scenario consisting of 5m interval and granite pavement has more significant temporal change than that of other multi-elements scenarios. Meanwhile, this scenario has the worst outdoor thermal comfort in all four multi-elements scenarios. According to the UTCI average value, it has very strong heat stress, while the other three are slight heat stress.

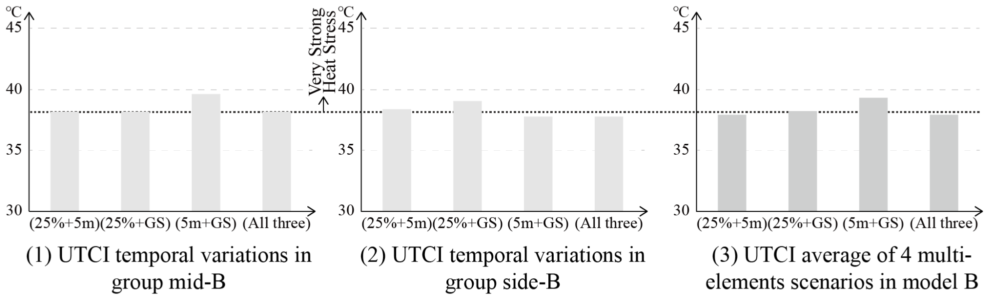
The UTCI temporal variations of four multi-elements scenarios in model B is similar to that of single element scenarios. The changes of outdoor thermal comfort time also can be divided into group mid-B composed of observation point B1, B3, B5 and group side-B composed of B2, B4, B6, based on the characteristics of temporal change.

The observation points of group mid-B reached their maximum value at 2 pm and dropped from very strong heat stress to strong heat stress at 2-3 pm, then slowly declined. Which is different is that the peak values of UTCI of group side-B are 3 pm or 1 pm in some multi-elements scenarios. The sudden drop interval is during 3-4 pm. And the very strong heat stress period is before 3 pm.



[Figure 4-30] UTCI temporal variations of 4 multi-elements scenarios in model B

Figure 4-31 compares the average of the outdoor thermal comfort of four multi-elements scenarios of observation points group mid-B, side-B and model B.

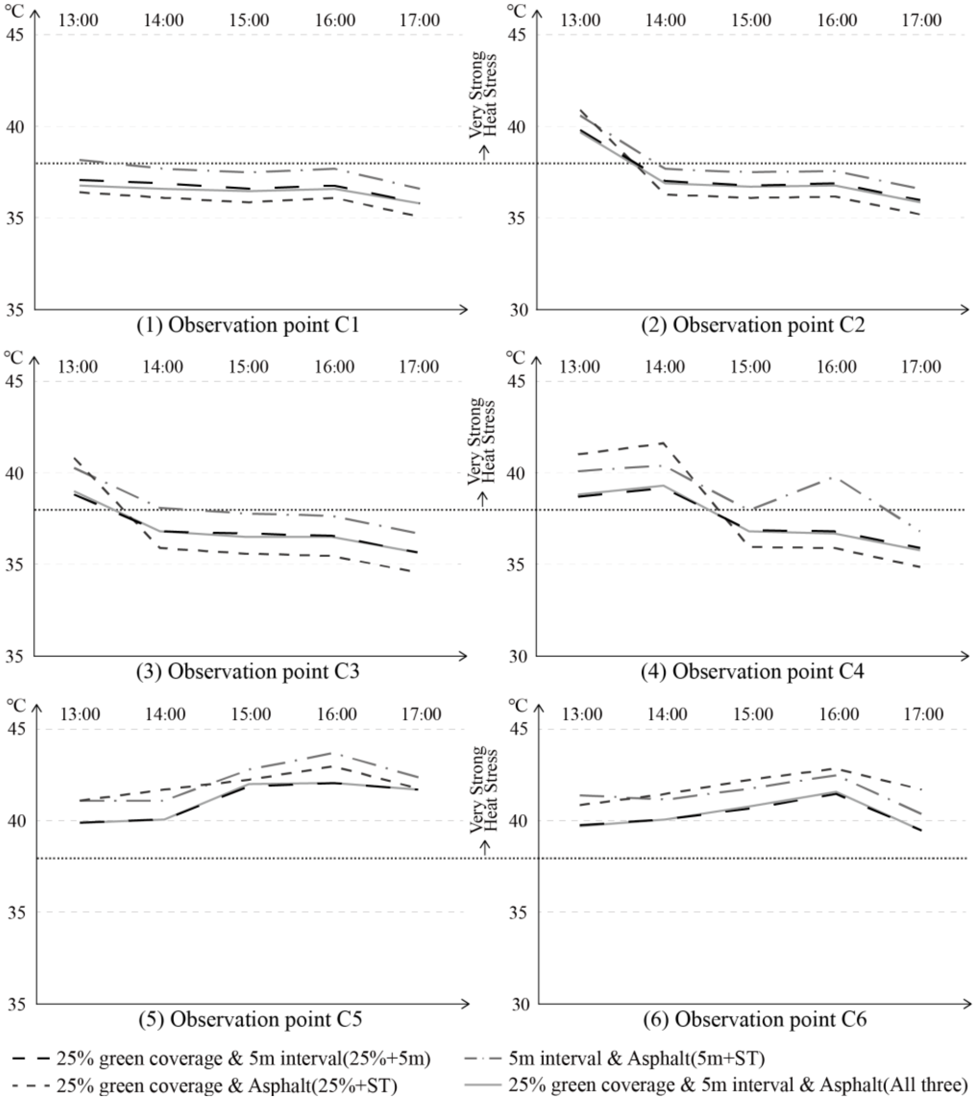


(25%+5m):25% green coverage & 5m interval
(25%+GS):25% green coverage & Granite
(5m+GS):5m interval & Granite
(All three):25% green coverage & 5m interval & Granite

[Figure 4-31] UTCI value of 4 multi-elements scenarios in model B

It can be found that as the group mid-B, the outdoor thermal comfort of 5m interval and granite pavement is the worst, and the other three are similar. Group side-B has the worst UTCI value in the scenario of 25% green coverage and granite pavement. The outdoor thermal environment of 5m interval and granite pavement, or the scenario with all 3 elements are the best. On the whole(Figure 4-31(3)), the scenario of 25% green coverage and 5m interval and the scenario with 3 elements have better outdoor thermal comfort. The use of 5m interval and granite pavement at the same time should be avoided.

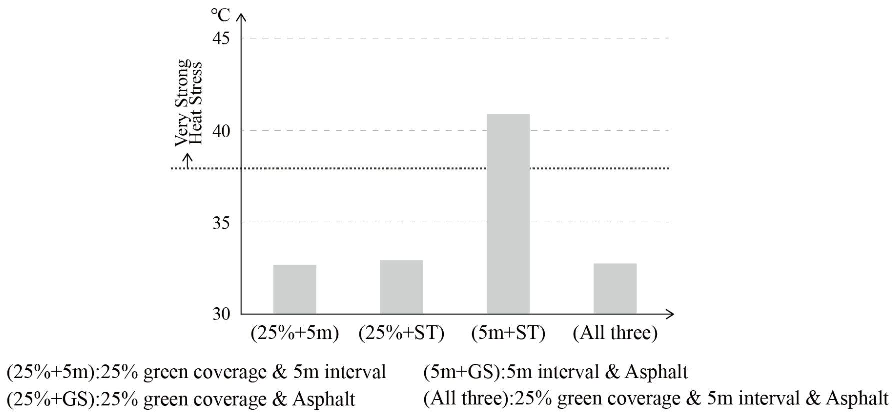
The four multi-elements scenarios are similar to the single element scenarios in model C. Four scenarios in the observation point C1 vary little with time, and almost all of them have strong heat stress. The outdoor thermal comfort of C2 and C3, which are gradually reduced after 1 pm after UTCI value rises during 1-2 pm. Then it drops to strong heat stress after 2 pm with a stable interval at 2-4 pm, and then a slight decline. At the observation point C4, four multi-elements scenarios vary with time. Points of C5 and C6 have very strong heat stress, and the peak value of which is at 4 pm.



[Figure 4-32] UTCI temporal variations of 4 multi-elements scenarios in model C

It can be found that the outdoor thermal comfort values of the scenario of 25%

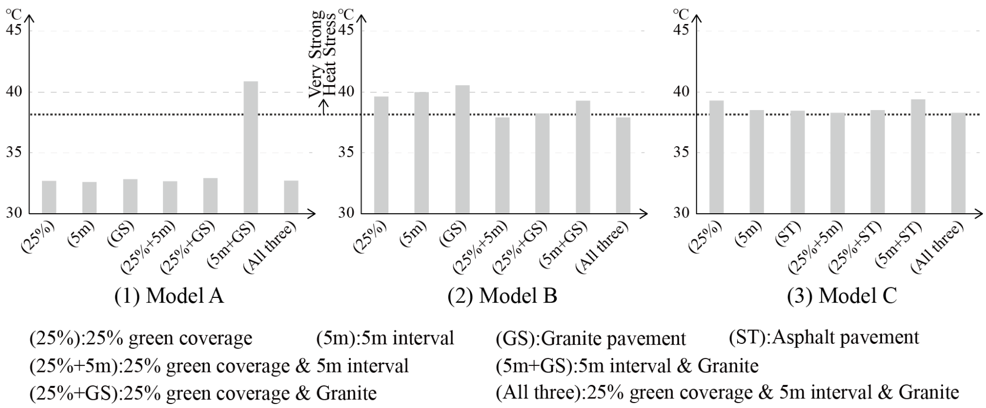
green coverage and 5m interval and the scenario with 3 elements are almost the same. And the outdoor thermal comfort of the southern of the model C is better than other regions, relatively. The scenario of 25% green coverage and asphalt has less thermal pressure than other observation points.



[Figure 4-33] UTCI average of 4 multi-elements scenarios in model C

On the whole, the scenario of 5m interval and asphalt pavement is the worst in model C; the other three are similar to each other. The scenario of 25% green coverage and 5m interval and the scenario with all 3 elements have the least thermal pressure.

According to the simulation results of multi-elements scenarios, the scenario of 5m street tree interval and the change of surface type is the worst among the three models, and the scenario of 25% green coverage and 5m interval, and the scenario with all 3 elements are the best. It shows that to improve the outdoor thermal comfort of pedestrians in the main street of the typical commercial areas, the increase of vegetation coverage and the setting of smaller street tree spacing have a good effect; while the efficiency of reducing the interval of street tree and changing the pavement at the same time is not good as expected.



[Figure 4-34] Comparison of landscape design scenarios in model A, B, C

In addition to the worst scenario of 5m interval and granite pavement, the outdoor thermal comfort of other scenarios in model A is better than the other two models. Most scenarios have little difference in model A. Comparatively speaking, the outdoor thermal comfort of 5m interval scenario is the best; but the multi-elements scenario of 5m interval and granite brick should be avoided when making a street landscape design plan.

In model B, the performance of multi-elements scenarios is better than single element scenarios. The scenario of 25% green coverage and 5m interval, or the scenario includes all three elements are the best. The thermal pressure level in these two is strong heat stress, while very strong heat stress level in other scenarios. The outdoor thermal comfort of the scenario of granite pavement is the worst. Therefore, based on the current situation of model B, the design of replacing pavement is not worth.

Under different scenarios, the outdoor thermal environment of pedestrians in model C is very strong heat stress. The difference between the UTCI value of different scenarios is not large. It is the same as model B that the scenario of 25% green coverage and 5m interval, and scenario includes all three elements have the least thermal stress. But single element scenario such as the surface type of asphalt also has better outdoor thermal comfort.

The above conclusion shows that the improvement of pedestrian space in the main streets of typical commercial areas is not more the design elements, the better. Designers should find out the best but economically viable solutions based on the status quo and different urban form.

Chapter 5　Conclusion

5.1 Conclusion

In this thesis, three typical commercial streets in Seoul metropolitan city are selected as the research objects. Through the design scenario simulation, the improvement effects of vegetation(green coverage and street tree interval) and surface type respectively on the outdoor thermal comfort of pedestrians in the three models are studied.

The main results are:

First of all, the commercial center of Seoul metropolitan city can be divided into nine categories according to the characteristics of urban form. Among them, the most common ones are compact low-rise, compact mid-rise, open high-rise. The compact low-rise type has little feedback on different landscape design, but its own urban form makes it have better outdoor thermal comfort. On the contrary, the heat stress of compact mid-rise is the largest.

In an aspect of alleviating the commercial street thermal environment by landscape design:

The increase of green coverage has a positive effect on improving outdoor thermal comfort, which is the same as other research results. In this paper, the effect of 25% green coverage is the best, especially in open high-rise type.

The 5m spacing of street trees is better than other intervals in the compact low-rise and compact mid-rise model. Compact mid-rise type is not suitable for planting street trees with 15m spacing. In areas with more complex of urban form, the planting of street trees should be non-fixed spacing.

As regarding the choice of pavement, compact low-rise and open high-rise types should avoid using basalt brick as far as possible. But the use of granite brick is recommended in compact mid-rise. Meanwhile, the ornament of wooden pavement is also one of the design considerations in the walking area.

On the streets with different urban forms, the landscape design options for improving thermal comfort may also be different:

Most of the scenarios show little difference in the outdoor thermal comfort of the compact low-rise area such as model A. Relatively, the outdoor thermal environment of the 5m interval scenario is the best. But the combination of the two elements of 5m interval and surface type of granite brick should be avoided in the landscape design of the streets;

In compact mid-rise areas such as model B, the analysis results of multi-elements scenarios are better than single ones. 25% green coverage and 5m interval scenario, or scenario includes all three landscape design elements are the best. But the scenario only designed with granite pavement relatively has poor outdoor thermal comfort;

In open high-rise areas such as model C, although the scenario includes all three elements is the best. But single ones such as asphalt pavement also have less thermal stress.

The conclusions above show that the two kinds of landscape design elements of vegetation and surface type have different effects on the outdoor thermal comfort of walking space with different urban form characteristics. Therefore, the landscape reform of the pedestrian space needs to be based on different local forms.

The sustainable development of cities and the improvement of citizens' physical and mental health need not only implement the concept of ‘walkable city’, but also entail the ‘smart design’. Through the exploration in this study, ENVI-met is an effective design tool for smart design.

5.2 Highlights and Prospects

This thesis systematically analyses how the landscape design can improve the microclimate in the urban canyon of three typical commercial blocks in Seoul metropolitan city by heating and cooling. The influence of which is also considered. Such kind of consideration of outdoor thermal comfort is not only a lack in the design of walking space but also in the field of thermal comfort in the canyon.

This study confirms many previous studies on the cooling effect of vegetation, but found that this cooling effect varies in different urban forms. Unlike some studies on the effects of surface materials on microclimate, it is found that different pavements perform differently in different urban forms. Therefore, the difference in the effect of vegetation, pavement and other landscape design elements on the improvement of microclimate in different urban forms can be one of the future research directions.

Meanwhile, according to the classification of the typical commercial blocks in Seoul, other typical types of urban forms will be the part of future work.

There are also some limitations to this paper.

Firstly, there is a certain sense of subjectivity in the idealization of the actual site and the setting of the landscape design scenarios, which is mainly based on the designer's thinking. In terms of scenario setting, this study focuses on improving the status quo, so the selection of landscape design plan is the simplest and most common. Therefore, the results of this paper need to be verified by field measurements, and it is the largest limitation of this research.

In addition, the default vegetation database is used in the simulation, which is not based on the real site trees; and this study only carries out a few hours of simulation in one day, which may produce data noise. What’s more, as landscape design is a science that pays attention to the temporal variation, research on seasons, difference of day and night, may be one of the concerns in the future.

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초 록

무질서한 확장으로 인한 도시 문제에 대응하여 보행 도시의 개발 개념이 점차 도시 계획과 개발의 트렌드가 되어 가고 있다. 불행하게도, 고밀도 개발 모드는 도시의 열 환경에 문제를 야기했다. 서울시는 보행 환경을 개선하기 위해 많은 노력을 기울였지만 보행 공간의 질은 여전히 개선의 여지가 있다.

보행 공간의 계획과 디자인은 인간 척도에 맞추는 것이 중요하다. 따라서 도시의 미기후와 같은 작은 요소가 보행자의 열 쾌적성을 평가하는 데 더 적합하다. 실외 온열 조건의 개선은 지구 온난화와 삶의 질 향상 및 도시의 지속 가능한 발전과 밀접한 관련이 있다.

본 연구의 목적은 전형적인 상업 가로의 실외 열 쾌적성을 개선할 수 있는 식물, 포장 등을 이용한 설계 전략을 탐구하는 것이다.

서울시 상업 중심지를 도시 형태에 따라 분류한 후, 밀집형 저층과 밀집형 중층 및 개방형 고층 으로 전형적인 세 블록을 대상지로 선택한다. 그리고 나서 대상지를 이상화함으로써 다양한 설계 전략이 상업가로의 실외 열 스트레스를 완화하는 데 미치는 영향을 연구하기 위해 식물과 포장에 관한 설계 시나리오가 설정된다.

본 연구의 주요 결과는 다음과 같다.

첫째, 본 연구에서 선정한 다양한 도시 형태 특징을 가지고 있는 세

가지 유형의 상업 블록 중에 밀집형 저층 유형은 다양한 경관 디자인에 대한 피드백이 거의 없다. 하지만 이의 도시 형태 자체가 더 나은 실외 열 쾌적성을 제공한다. 밀집형 중층 유형의 열 스트레스가 가장 크다.

둘째, 조경 요소에 대해서는 녹지율의 증가가 실외 열 쾌적성 개선에 긍정적인 영향을 미치고 있는데 이는 다른 연구 결과와 같다. 녹지율 25%와 가로수 간격 5m 및 화강암 벽돌 포장이 밀집형 저층 및 밀집형 중층 유형의 보행 공간 열 쾌적성을 완화시키는 효과가 가장 좋다. 개방형 고층 유형의 도로에서는 아스팔트가 좋은 포장이다.

마지막으로, 다양한 도시 형태가 있는 거리에서 열 쾌적성을 개선하기 위해서는 도시 형태의 특성에 따라 적용하는 조경 디자인이 다를 수 있다. 모델 A와 같이 밀집형 저층 유형에서 5m의 가로 수 간격을 선택할 수 있다; 모델 B와 같은 밀집형 중층 구역에서는 녹지율과 가로수 간격 및 포장 이 세 가지 조경 요소를 모두 변경하거나 식물만 변경하는 것도 열 쾌적성이 개선된다; 모델 C와 같은 개방형 고층 영역에서는 세 가지 조경 요소를 활용하거나 포장 만 변경할 수도 있다.

따라서 보행자 공간의 조성은 지역의 도시 행태에 기반으로 이루어져야 한다.

핵심어: 열쾌적성; 조경; 보행자; 상업가로; ENVI-met; UTCI