IMPACTS OF CLIMATE SENSITIVE PLANNING STRATEGIES ON OUTDOOR ENVIRONMENT COMFORT IN COLD MONTHS OF TABRIZ

by

ZEINAB SAMI

(Under the Direction of John Crowley)

ABSTRACT

This thesis studies the effect of Sky View Factor (SVF) on thermal comfort sensation during cold months in Tabriz, Iran. In this direction, one historic district and one newly developed district in Tabriz are selected to analyze and compare the physical structure of built environment. AutoCAD and 3DMax modeling as well as site photos are used to analyze the physical structure of built environment. Thermal comfort is investigated in a target point from each area for five selected days of Tabriz's winter. To quantify the thermal comfort sensation, a thermal index namely Universal Thermal Climate Index (UTCI) is used. RayMan model is employed to calculate UTCI based on metrological and geographical input parameters such as air temperature, wind speed, urban topology, vegetation, height and shape of buildings and SVF. Comparison of UTCI values in two selected target points reveals that pedestrians in the historic district expose less thermal stress during winter in the day-time.

KEYWORDS: Sky view factor, Outdoor thermal comfort, Cold months, UTCI.

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DEDICATION

This thesis work is dedicated to my lovely parents, my sweet mom Tahereh and my supportive dad Ali for their love and their support in every step of my life. Also, I could not have done this thesis without my handsome husband, Amin, who has been there for me with his constant encouragement to make my dreams come true during the challenging graduate school life.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 BACKGROUND

Winters in cold regions have specific characteristics such as heavy snow fall, frost, short day length, and icy roads and sidewalks. The harsh climate characteristics of cities located in cold regions limit urban life for the residents during winters. Therefore, the role of urban planners is essential to design an urban microclimate which lessens the discomfort of winters, although it is a challenging task. A comfortable microclimate in urban spaces increases the outdoor spending time (Beyer, Szabo et al. 2016).

The specific characteristics of cold regions lead planners to develop a special design approach for cold regions. Pressman (1995) suggests that planners are required to rediscover and emphasize 'naturally-derived' solutions to problems of living in winter cities (Pressman 1995). Widespread studies have been conducted considering the relationship found between climate and energy efficiency. Terjung (1966) offered a method to bioclimatic division of United States, in which four physiological and psychological reactions of man to temperature, relative humidity, wind chill, and solar radiation are considered. Givoni (1998) specified comfort zone and different bioclimatic conditions in relation with two elements of temperature and relative humidity. In this research, mean of maximum temperature and minimum of relative humidity were used to determine bioclimatic conditions and building construction requirements.

Kaviani and Alijani (2005) used Becker equation to prepare summer and winter bioclimatic map for north and south of Iran. In their article, they prepared Iran bioclimatic map using Terjung (1966) method and evaluating 25-year statistics of 48 synoptic and 106 climatic stations. Jahanbakhsh and Babapour Basseri (2003) determined human bioclimatic stimulations range in Tabriz. Then, he studied thermal conditions considering effective temperature, defined thermal requirement calendar of the city, and finally, specified comfort range as varying from 6 to 12ºC. Khalili, Farnoud et al. (2011) measured energy requirement of different months considering temperature of cold or warm days using Olegi and Givoni models.

Climate-sensitive design is an urban planning concept that focuses on the relationship of climate, the built environment and people (Eliasson, Knez et al. 2007, Sanborn 2017). It is also known as bioclimatic urban design or climate responsive design. The interaction of these three (climate, the built environment and people) is very important to understand since determines how people use outdoor spaces. Formerly, the priority in urban designing was given to indoor spaces due to their economic importance. The public non-built spaces between buildings were often considered as "leftover" spaces that formed unconsciously (Culjat and Erskine 1988). For this reason, climatology has been largely ignored in the history of modern city development. For instance, modern cities in North America from downtown Toronto, Canada to Phoenix, Arizona share very similar geometry characteristics such as building spacing, street orientation and dimension, and housing styles, despite their drastically different climates (Bosselmann, Arens et al. 1995).

With the advance of climate-sensitive design in urban development throughout the 1980s and 90s, city planners intended to use climate-sensitive approached in order to lessen drawback of cold climate such as snow, darkness and cold (Culjat and Erskine 1988). In response to this growing awareness in North America, the Livable Winter Cities Association (now called the Winter Cities Institute) was started in 1982 to share information amongst northern cities through publication of relevant material and the organization of conferences.

The British/Swedish architect, Ralph Erskine, is well-known for his contribution in architecture and design in northern latitude places. His works on interaction of people and climate in design and architecture was an inspiration for the resurgence of this Winter City awareness. In terms of cold region city planning he advised that: “Here houses and towns should open like flowers to the sun of spring and summer but, also like flowers, turn their backs on the shadows and the cold northern winds, offering sun-warmth and wind-protection to their terraces, gardens and streets” (Erskine 1968).

Erskine, as an architect and city planner, believed that despite of forms of buildings and other urban environments, it would be important to design and plan cities in order to improve comfort sensation of people; “only by such methods can arise a personal and indigenous Alaskan, Canadian, Scandinavian or Northern Russian tradition” (Erskine 1968). Nature can be the best source of inspiration for climate-sensitive design, as suggested by Pressman (1995). He believes that nature and climate vary so widely from place to place, it is difficult to offer prescriptions to designers (Pressman 1995). As a result, climate-sensitive design offers general rules rather than specific prescriptions for the built form.

It is of great importance for city planners to understand which factors and parameters influence the urban microclimate and comfort of residents. In other word, it is required to investigate how different parameters such as air temperature, humidity and urban form impact thermal sensation. For this purpose, the first step is to quantify thermal sensation. During the history of urban development, many thermal indices are developed such as predicted mean vote

(PMV), physiologically equivalent temperature (PET) (Matzarakis and Mayer 1997, Matzarakis, Mayer et al. 1999), standard effective temperature (SET) (Fobelets and Gagge 1988), outdoor standard effective temperature (Out_SET) (Spagnolo and De Dear 2003), and universal thermal climate index (UTCI) (Fiala, Havenith et al. 2012, Havenith, Fiala et al. 2012, Jendritzky, de Dear et al. 2012). Each of these indices defines a thermal comfort range in which a human is not exposed to the thermal stress. In studies on thermal comfort in urban areas, researchers investigate the effect of each factors on a selected thermal index. Although, the literature on studying thermal comfort in cold regions is limited, many studies are dedicated to investigate the microclimate and human comfort of urban areas in hot climates. Johansson (2006) studied the influence of urban geometry on outdoor thermal comfort by comparing an extremely deep canyon and a shallow street canyon in Fez, Morocco. PET index was used in this work for thermal comfort assessment. Results indicated that deep canyon is comfortable in summer, however, the shallow canyon is more likely to access the solar light in cool winters, and therefore is more comfortable. Krüger, Minella et al. (2011) studied the effect of some urban parameters such as street configuration, buildings height and their attributes on outdoor thermal comfort and air quality in Curitiba, Brazil. In their study, the sky view factor (SVF) was used as urban geometry indicator. The influence of geometry features of a compact mid-rise high-latitude city (Gothenburg, Sweden) were investigated on outdoor comfort condition (Thorsson, Lindberg et al. 2011). PET index was used to quantify the outdoor comfort. The results showed that open areas are warmer than adjacent narrow street canyons in summer, but cooler in winter. Many other studies used PET index in order to investigate the effect of urban geometry on outdoor thermal comfort (Johansson and Emmanuel 2006, Ali-Toudert and Mayer 2007, Taleghani, Kleerekoper et al. 2015).

Vegetation also has an important effect of urban climate and human outdoor comfort. Shashua-Bar, Pearlmutter et al. (2011) studied the influence of trees and grass on human thermal stress in hot and dry regions. In this study, the index of thermal stress (ITS) is used to quantify the pedestrian thermal stress. It was indicated that vegetation may make a substantial contribution to human thermal comfort. Vegetation reduces long-wave emission from courtyard surfaces and limits the amount of solar radiation reflected from them. Alexandri and Jones (2008) showed that presence of green walls and green roofs decreases temperature is urban canyons. The effect of shading on outdoor thermal comfort is studied in Taiwan by Lin, Tsai et al. (2012). They used SVF to characterize urban geometry. Also, PET is used as a thermal index, while RayMan model is employed to calculate PET index. It was noted in the paper that, although sufficient shading should be provided to improve thermal comfort in summer, outdoor space planning should avoid excessive shading since Taiwanese have poor tolerance of cold temperature in winters. Therefore, in creating shaded areas, the thermal requirements of residents as well a local climate characteristics must be considered. Thorsson, Lindberg et al. (2011) compared thermal condition in a park and a square in north-east of Tokyo, and showed that the park was on average 1.1ºC cooler than the square.

Ali-Toudert and Mayer (2006) studied the effect of building height to street width (H/W), and orientation of street canyons on outdoor thermal comfort in hot and dry climate using PET index. The results revealed that the distribution of PET index at street ground depends on H/W ratio and street orientation.

1.2 Problem statement

Urban life in cities located in cold regions is impacted by certain characteristics of the cold climate. Long and harsh winters minimize the outdoor spending time, limit recreational activities, and increase energy consumption in these cities. Therefore, creating comfortable outdoor microclimate which encourages people to stay outside during winter months is a key component of urban development in these cities. The necessity of climate-sensitive urban design practice to promote socializing in winter, leads to the following research questions: How are climate-sensitive design principles incorporated in cold climate cities? And whether the present physical features of built environment are compatible with climate sensitive design principles. Answering these questions will provide insight into the possible methods and processes that can aid incorporation of climate-sensitive design principles into municipal processes.

1.3 Objectives

The main objective of this study is to understand the relationship between physical form of cities in cold climate region and outdoor thermal comfort sensation during winter months. It mainly focuses on physical features of built environment in Tabriz, one of the coldest climate cities in Iran. Urban form and geometry in two different districts of Tabriz are analyzed, and their role in providing a comfortable microclimate is compared. The first district is located in a historic neighborhood, Kabud Mosque. This neighborhood is one of the oldest districts of Tabriz. The early urban development in this area is not well-documented, and it has been devastated by several earthquakes during its history. The present-day urban form of Kabud Mosque neighborhood is evolved from Qajar dynasty era (1785 to 1925) where the city was the traditional residence for the crown princes. The second district is located in Valiasr neighborhood, a wealthy neighborhood at eastern part of Tabriz. The neighborhood is constructed during the last decade of the Pahlavi dynasty era (1964–1979). Although the general urban form such as street size and orientation of the neighborhood has remained the same over the period of time, most of its buildings are reconstructed or renovated. The two selected districts have different physical features including height and shape of the buildings, size and orientation of streets, and vegetation. This study considers whether physical features of two selected districts of Tabriz are compatible with the cold climate conditions. In this direction, the effect of sky view factor as an indicator of urban physical form is studied on outdoor thermal sensation. Based on thermal classification report of Tabriz by Hejazizadeh et al. (2015), Tabriz has five cold months. The mild climate in remaining months prevents human thermal stress, therefore, thermal comfort evaluation is limited to only five cold months in this thesis. Furthermore, due to the author's limitation to travel to Tabriz to acquire more data on the selected sites, this thesis calculates and compares thermal comfort in only two target points using the available resources. One target point is situated in the historic Kabud Mosque neighborhood, and the second point is in Valiasr neighborhood. The purpose of this study is to provide an explanatory study to guide planners and municipalities to create comfortable microclimate in urban spaces in cold-climate cities.

1.4 Methodology

The research on urban planning can be classified into two main groups: explanatory and change-oriented. The main aim in an explanatory research is to answer the 'what' and 'how' types of questions. In the first place, it uses the knowledge in the field to describe and understand a phenomenon. Then, it questions 'why does it work?' (Aken 2004). In other word, explanatory research is defined as an attempt to connect ideas to understand cause and the effect of a phenomenon. On the other hand, change-oriented research, also be called design-oriented research, focuses on developing knowledge that leads to a change. The change-oriented type of research seeks for a mechanism that can affect or change a certain 'context' (Aken 2004).

In this thesis, an explanatory research is employed to investigate the effect of climate sensitive planning strategies on outdoor environment comfort in cold climate region. Two districts in Tabriz, a cold city in Northwest of Iran, are selected in order to study how different urban geometries in two districts influence the outdoor thermal comfort. To analyze the outdoor thermal comfort, a quantitative method is used in which the thermal comfort is quantitated using a thermal index, Universal Thermal Climate Index (UTCI). UTCI is calculated using RayMan model based on different input parameters such as air temperature, wind speed and urban geometry. RayMan Pro 1.2, a free software that implements RayMan model is used. Furthermore, AutoCAD and 3DMax software programs are used to describe and visualize the selected sites and existing built condition.

1.5 Thesis outline

Chapter 1 provides the background on outdoor thermal comfort and climate-sensitive urban planning. In addition, problem statement and methodology are described in this chapter.

In Chapter 2, outdoor thermal comfort is explained in detail. Then some thermal indices that mostly used in literature to evaluate thermal comfort are listed and described briefly. Among listed thermal indices, UTCI is employed in this thesis in thermal comfort assessment. Therefore, a thorough description of this thermal index is provided in Section 2.3. Chapter 2 also provides description of RayMan model which is used in this study to calculate UTCI. Finally, the input for the RayMan model or in the other word, the design parameters that affect the outdoor thermal comfort are listed and explained.

Chapter 3 starts with details about metrological and geographical characteristics of Tabriz, Iran. Then two sites in Tabriz that are selected for the thermal analysis are described. AutoCAD and 3DMax visualization are provided to simulate the existing condition of the sites. These visualizations are also used to obtain some input parameters of the thermal analysis. At the end, based on metrological and geographical characteristics of Tabriz, and urban geometry of the selected sites, the thermal analyses of two locations are performed and the results are compared.

Chapter 4 contains concluding remarks on thermal analysis of selected sites in Tabriz, and provides some design-based suggestion to promote outdoor thermal comfort in cold-climate cities.

CHAPTER 2

THERMAL COMFORT EVALUATION

2.1 OUTDOOR THERMAL COMFORT

Urbanization is believed to be responsible for climate instability and inconstancy (Oke 1988). Cities changes their own climate, and as reported by Oke (1988), there is a 12 °C (54 °F) difference between urban and rural temperatures at the night time. The microclimate of urban spaces affects daily pedestrian traffic and different outdoor activities, and thus generally the urban livability (Beyer 2016). For this reason, the assessment of microclimate has been gained popularity among city planners over the past few decades. In order to promote the use of outdoor spaces and the quality of urban life, urban planners are intended to create spaces that satisfy people. Among many factors that determine the people's satisfaction on use of outdoor spaces, the thermal comfort is an important one. Thermal comfort is defined by ANSI/ASHRAE Standard 55 (ASHRAE 2004) as condition of mind that expresses satisfaction with the thermal environment. Evaluating thermal comfort is a complex task since it is influenced by several parameters such as urban form and geometry, urban density, vegetation, etc. From an urban planner's viewpoint, it is of great importance to determine how outdoor characteristics influence people's thermal sensation. It is also worth to mention that besides the metrological factors such as air temperature and wind speed, biological factors such as weight, race, gender and also clothing may affect the human thermal sensation. Many thermal indices have been developed to link all these factors and evaluate the human thermal satisfaction. In the following section some of these indices are explained.

2.2 Thermal indices

The assessment of outdoor thermal comfort is a growing topic in bioclimatic research. Thermal indices are developed to assess the thermal environment and to describe heat exchange between the human body and the surrounding environment. In the last 100 years, more than 150 different thermal indices have been derived in order to quantify the thermal comfort (De Dear, Brager et al. 1998, Jendritzky, de Dear et al. 2012, de Freitas and Grigorieva 2015). Many of these indices referred as "simple thermal indices" or "simple thermal models" only consider few parameters such as air temperature, wind speed and humidity in assessing thermal comfort (Landsberg 1972, Epstein and Moran 2006, Parsons 2014). Therefore, these indices are not reliable in thermal assessment in complex conditions for example when urban form influence the thermal state. On the other hand, some thermal indices are derived based on energy balance of the human body for thermal comfort studies. This section gives a brief description of some mostly used simple and energy-based thermal indices.

2.2.1 Simple indices

Simple thermal indices mainly consider only two or three meteorological variables in thermal comfort evaluation. For example, they do not consider human body factors such as metabolic rate and clothing insulation in their equation.

- *Equivalent temperature* (TEK): defines as a temperature in which all containing vapor of air is condensed (in constant air pressure).
- *Effective temperature* (ET): established to provide a method of determining the relative effects of air temperature and humidity on comfort.
- *Wind chill temperature* (WCT): defines an equivalent environment of which the cooling power is identical to that of the actual, windy environment.
- *Wet-bulb-globe-temperature* (WBGT): emerged from the "corrected effective temperature" (CET) comprised the weighting of dry-bulb temperature, natural (unaspirated) wet-bulb temperature, and black globe temperature.
- *Humidity index* (Humidex): describes how hot the weather feels to the average person, by combining the effect of heat and humidity.

The list of simple indices, their required variable and corresponding equation is provided in Table 2.1.

Table 2.1. The variables used to infer a thermal comfort quantity. T = air temperature (°C), VP and E = vapor pressure (hPa), RH= relative humidity (%), v = wind speed (m s−1) (Farajzadeh, Saligheh et al. 2015).

Index	Input variables	Formula
Equivalent temperature (TEK)	T, E	$TEK = T + 1.5\,E$
Effective temperature (ET)	T, RH, V	$ET = 37 - \dfrac{37 - T}{0.68 - 0.0014RH + \dfrac{1}{1.78 + 14V^{0.75}}} - 0.29T * (1 - 0.01RH)$
Wind chill temperature (WCT)	T, V	$WCT = 13.12 + 0.6215T - 11.37V^{0.16} + 0.3965TV^{0.16}$
Wet-bulb-globe temperature (WBGT)	T, VP	$WBGT = 0.567T + 0.393VP + 3.94$
Humidex	T, VP	$Humidex = T + 0.5555\ (VP - 10)$

2.2.2 ENERGY-BASED INDICES

The limitation in using the simple indices in thermal comfort assessment led to emerging more advanced methods based on human body energy balance. In addition to the meteorological parameters such as air temperature or humidity, these indices also evaluate the effects of climate conditions and thermo-physiological values in order to describe the effects of the thermal environment on humans.

- *Physiologically Equivalent Temperature* (PET) is defined based on the Munich energy balance model for individuals" (MEMI) (Mayer and Höppe 1987). PET is equivalent to the air temperature at which the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Mayer and Höppe 1987). PET is defined in a typical indoor setting (without wind and solar radiation).

In PET calculation, the following assumptions are made: The reference clothing insulation value is selected as 0.9 clo (Mayer and Höppe 1987). The basic metabolic rate is 86.5 W. For a light activity, a work metabolic rate of 80 W should be added to the basic metabolic. Mean radiant temperature was equivalent to the air temperature ($T_{mrt} = T_a$). Air velocity was set to 0.1 m/s. Water vapor pressure was set to 12 hPa (approximately equivalent to relative humidity of 50% at T_a = 20°C). The reference person is set as height: 1.75 m, weight: 75 kg, age: 35 years, and sex: male (Matzarakis, Mayer et al. 1999, Farajzadeh, Saligheh et al. 2015).

Table 2.2. Physiological equivalent temperature PET for different grades of thermal perception and physiological stress; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo, according to (Matzarakis and Mayer 1997).

PET (°C)	**Thermal perception**	**Grade of physiological stress**
< +4	Very cold	Extreme cold stress
+4 – +8	Cold	Strong cold stress
+8 – +13	Cool	Moderate cold stress
+13 – +18	Slightly cool	Slight cold stress
+18 – +23	Comfortable	No thermal stress
+23 – +29	Slightly warm	Slight heat stress
+29 – +35	Warm	Moderate heat stress
+35 – +41	Hot	Strong heat stress
≥ +41	Very hot	Extreme heat stress

Note: Data for different PET grades from Matzarakis and Mayer (1997).

- *Standard Effective Temperature* (SET) is defined as the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing the standard clothing for the activity concerned, has the same heat stress (skin temperature T_{sk}) and thermoregulatory strain (skin wettedness, w) as the actual environment. SET uses skin temperature and skin wettedness as the limiting conditions. The values for T_{sk} were derived from a two-node model of human physiology (Fobelets and Gagge 1988).

- *Physiological Subjective Temperature* (PST) represents the subjective sensation persons in the thermal environment derives from signals of cold and/or warm receptors in the skin and in the nervous system. Thermal effects of the environment are expressed through mean radiant temperature formed under clothing (inner T_{mrt}). PST is defined as the temperature formed around the skin surface, under clothing, after an interval of 15–20 min of adaptation to maintain homoeothermic. PST indicates the effect of environmental factors and of specific physiological responses to the thermal stimuli. It is applicable in a wide range of environmental conditions, although this index is limited to wind speeds lower than 22 m/s (Blazejczyk, Epstein et al. 2012).
- *Subjective Temperature* (STI) is an index that illustrates the thermal load subjectively felt by an individual, which results from the ambient environment before the activation of adaptation processes. It depends on both ambient conditions (temperature, solar radiation, wind, and humidity) and the heat exchange in the individual's environment. STI represents the thermal load formed in the air layer surrounding the outer layer of clothing. The thermal impacts of environment are expressed by means of radiant temperature. The physiological response of an organism is represented by the net heat storage (Blazejczyk 2005).
- *Universal Thermal Climate Index* (UTCI) is defined as an equivalent ambient temperature (°C) of a reference environment, providing the same physiological response of a reference person as the actual environment (Jendritzky, de Dear et al. 2012). The calculation of the physiological response to the meteorological input is based on a multi-node model of

human thermoregulation (Fiala, Havenith et al. 2012), which is associated with a clothing model.

UTCI is defined as the air temperature (T_a) of the reference condition causing the same model response as actual conditions. UTCI was developed in 2009 by virtue of international co-operation between leading experts in the areas of human thermo-physiology, physiological modelling, meteorology and climatology. In this study, UTCI is used in order of study the effect of physical structure of urban spaces on outdoor thermal comfort because UTCI is newly developed index and is more sensitive to the changes in all ambient stimuli (air temperature, solar radiation, humidity, and wind speed) (Blazejczyk, Epstein et al. 2012). A detailed description of UTCI is provided in Section 2.3.

2.3 Universal Thermal Climate Index (UTCI)

UTCI is defined as "the isothermal air temperature of the reference condition that would elicit the same dynamic response (strain) of the physiological model" than the actual environment (Jendritzky, de Dear et al. 2012). UTCI also follows the concept of an equivalent temperature. The meteorological conditions are compared to a reference environment with 50% relative humidity, calm air and mean radiant temperature (T_{mrt}) being equal to air temperature (T_a) (Blazejczyk, Epstein et al. 2012). The comparison is performed on basis of a heat transfer model (Fiala, Havenith et al. 2012). In contrast to other indices, physiological parameters cannot be set in UTCI. Besides the self-adapting clothing insulation, a permanent walking speed of 4 km/h (1.11 m/s) and an internal heat production of 135 W/m^2 are assumed (Jendritzky, de Dear et al. 2012). UTCI includes a clothing model that automatically adapts to the current conditions (Havenith, Fiala et al. 2012). UTCI is not, like PT or PET, calculated directly. Due to its extremely high complexity, and thus, high computational effort, UTCI cannot be calculated for most studies. It can only be approximated using a regression equation that was abbreviated from sample calculations performed by computing centers (Fiala, Havenith et al. 2012, Jendritzky, de Dear et al. 2012). The regression function makes the calculation of UTCI computationally cheap, but it also leads to a very narrow range for the input parameters it accepts. Only the meteorological parameters T_a (°C), V_P (hPa), v (m/s), and T_{mrt} (°C) can be set. All physiological parameters are considered to be determined automatically. Limitations for the applicability due to the restriction for T_a of -50.0°C to +50.0°C, as well as for the valid range of wind speed ranging from 0.5 m/s to 17.0 m/s, are to be expected. This can lead to unreliable results in heat stress conditions with high T_a and low wind velocity (Fröhlich and Matzarakis 2016). The increase in T_a by 2 °C does not seem to increase UTCI (Fröhlich and Matzarakis 2016). Other uncertainty is to be expected due to vapor pressure of the reference environment, which is limited to 20.0 hPa (Jendritzky, de Dear et al. 2012). Within the accepted range, UTCI is very sensitive to wind speed (Chen and Matzarakis 2014, Fröhlich and Matzarakis 2016). Besides T_a, T_{mrt} strongly influences UTCI (Chen and Matzarakis 2014, Fröhlich and Matzarakis 2016).

Table 2.3. Thermal stress classification for UTCI (Blazejczyk, Jendritzky et al. 2013).

UTCI (◦C)	**Thermal Stress Category**
≥ +46	Extreme heat stress
+38 – +46	Very strong heat stress
+32 – +38	Strong heat stress
+26 – +32	Moderate heat stress
+9 – +26	No thermal stress
0 – +9	Slight cold stress
-13 – -0	Moderate cold stress
-27 – -13	Strong cold stress
-40 – -27	Very strong cold stress
< -40	Extreme cold stress

Note: Data for different UTCI grades from Note: Data for different PET grades from Matzarakis and Mayer (1997).

Mean Radiant Temperature, T_{mrt} (°C) is one of the most important input parameters for all sophisticated thermal indices applied in human-biometeorology. It is an equivalent surface temperature that summarizes the effect of all the different short-and longwave radiation fluxes (Kántor and Unger 2011, Chen, Lin et al. 2014). T_{mrt} is defined as the surface temperature of a perfect black and equal surrounding environment, which leads to the same energy balance as the current environment (Fanger, Højbjerre et al. 1974).

2.4 RayMan model

The RayMan model has been developed at the Chair for Environmental Meteorology of the Albert-Ludwigs-University Freiburg for urban climate studies. RayMan is a micro-scale model that used to calculate the mean radiant temperature and different thermal indices. As discussed in Section

2.2, these thermal indices can be used for the quantification of thermal conditions (thermal comfort, cold stress and heat stress) for different climates and regions. RayMan calculates radiation fluxes in simple and complex environments (Matzarakis, Rutz et al. 2007) which allows it to calculate T_{mrt} as an important input parameter in the calculation of thermal bio-meteorological indices such as UTCI and PET.

RayMan is time-independent, and its calculations are performed at the single bio-meteorological state. RayMan requires some input parameters including:

- Air temperature
- Air humidity
- Wind speed
- Topology
- Obstacles
- Sky view factor (SVF)

Mean radiant temperature T_{mrt} can be calculated based on global radiation or cloud coverage. RayMan can calculate and visualize the following parameters and indices:

- Sun shine duration
- Sun paths or sun orbit
- Shadow
- Global radiation
- Mean radiant temperature (T_{mrt})
- Predicted Mean Vote (PMV)

- Physiologically Equivalent Temperature (PET)
- Standard Effective Temperature (SET)
- Perceived Temperature (PT)
- Universal Thermal Climate Index (UTCI)

Figure 2.1 shows RayMan Pro 2 software that implements RayMan model. This thesis uses RayMan Pro 2 to calculate UTCI in two target points during specific times in 2017-2018 winter.

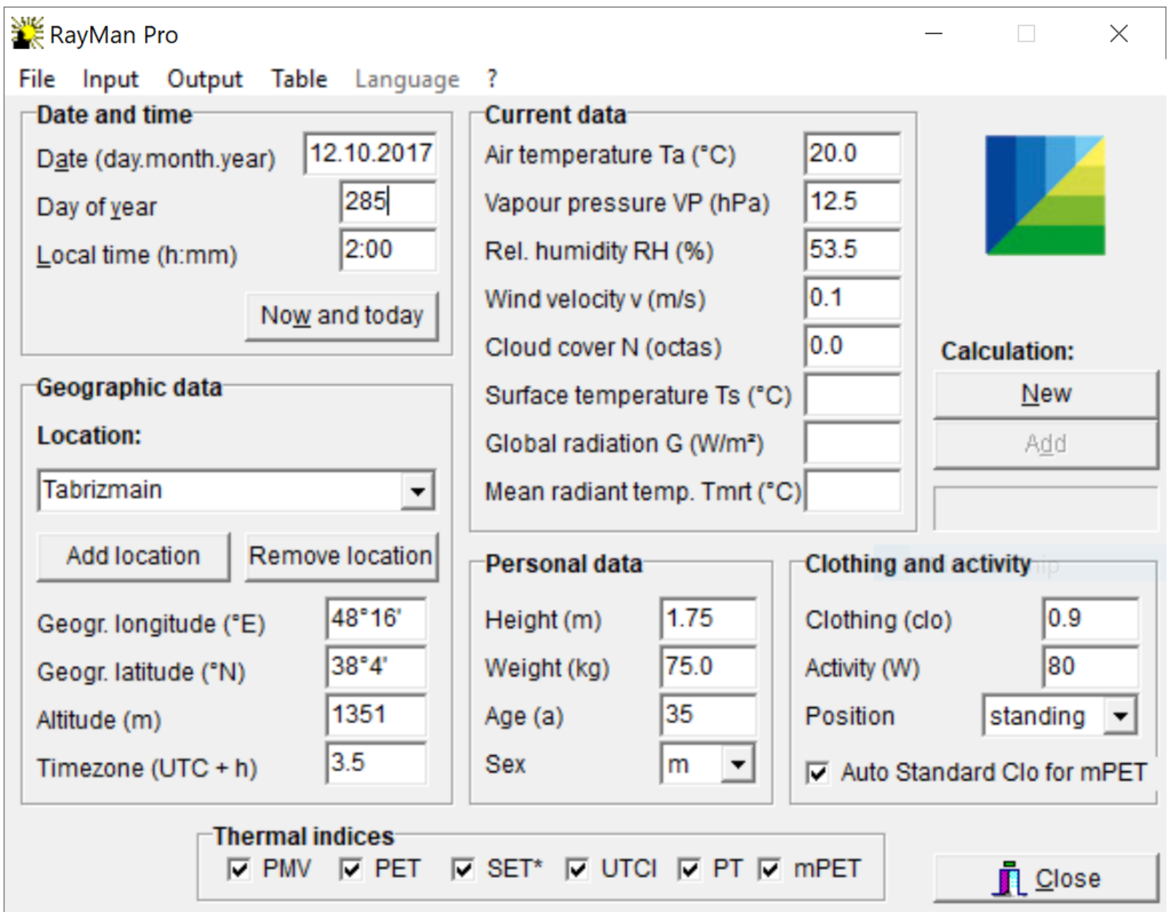


Figure 2.1. Main menu of RayMan Pro 2 software.

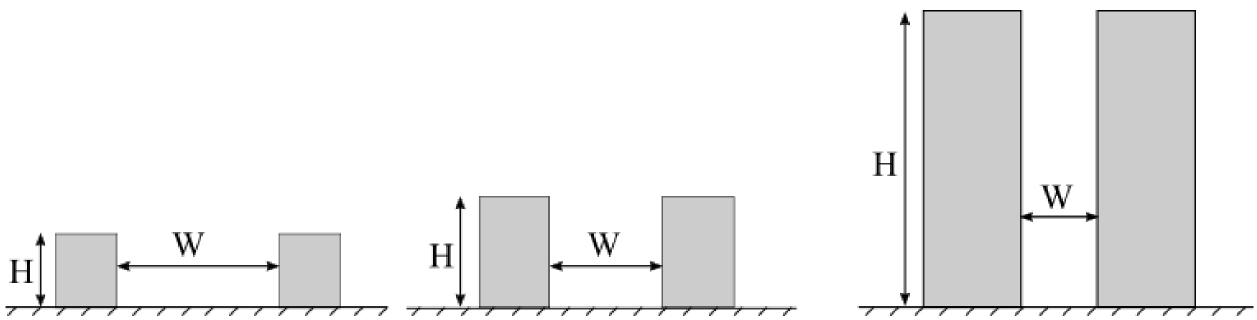
2.5 Design based factors

Urban microclimate has an important role of future development of a city. Urban microclimate controls the outdoor comfort, then people are intended to spend more time on outdoor spaces. Therefore, comfort in urban spaces helps to increase satisfaction of residents, then economy and development of the city. Besides the metrological factors such as air temperature and humidity in urban microclimate, physical form of the urban built environment is a determinant. This study focuses on the effect of physical structure of buildings on outdoor thermal comfort in urban environment. The thermal index, UTCI, is used to quantify the outdoor thermal comfort. Therefore, the aim of this study is to understand how physical characteristics of cities impacts the UTCI calculations.

Milosovicova (2013) summarized the design-based factors that influence outdoor thermal comfort in urban areas. These factors are listed as urban geometry, density, land use, city size and water surfaces. There are many factors that form the configuration of cities, such as building height, street width, street orientations (or street design), building volume and surfaces and etc. All these factors can be considered as urban geometry. Among urban geometry related factors, this thesis investigates the effects of building height to street width (H/W) and the sky view factor (SVF) on outdoor thermal comfort are studied. Since the selected districts are both residential areas, the effect of specific land use are neglected. In this regard, vegetation is only considered providing shading and also influencing wind speed. It is worth to mention that the effect of city size is excluded due to lack of reliable explanation about the relation of city size and the urban climate (Dursun[1] and Yavas 2015). Finally, Tabriz is not a coastal city and there is no major natural or artificial water surfaces close to the city, therefore, this factor is also excluded.

2.5.1 BUILDING HEIGHT TO STREET WIDTH (H/W) RATIO

H/W ratio is an important factor in determining urban microclimate, in which H and W stand for building height and street width, respectively. H/W ratio is an indicator showing how much sunlight and radiation reaches the street ground and heats the air near the ground (Milosovicova 2013). When there is no building around, H/W is zero. It means that all sunlight and insolation is absorbed by the ground. The state in which H/W = 0.5 is called “shallow street canyon” (See Fig. 2.2 a). With H/W = 1.0, the street canyon is called “uniform street canyon” (See Fig. 2.2 b). In this street canyon state, radiation hits other buildings and the ground and is absorbed near the ground level (Milosovicova 2013). When H/W > 4 in high density areas, the radiation cannot reach the ground level and the absorption stays high above the ground level. This state is called a “deep street canyon” (See Fig. 2.2 c). A higher H/W ratio decreases the heating of the urban environment. However, on the other hand, restricts the release of heat into the atmosphere at night. Therefore, the cooling of the urban environment at night is slowed down for a higher H/W ratio (Milosovicova 2013, Shishegar 2013). Shishegar states that the quantity of solar energy absorbed by the street surfaces is affected by the H/W ratio. Although, the effect of H/W ratio on urban heat island has been investigated in a number of studies, there is no clear answer for the appropriate H/W ratio of urban canyon. For example the range of 0.4-0.6 is suggested by Emmanuel (2005), as the optimal values of H/W ratio keep minimal heat in summer and enhance it in winter. However, some factors such as seasonal impacts, vegetation and anthropogenic heat production are not considered in the obtaining optimal H/W ratio by Emmanuel.



(a) H/W = 0.5 (b) H/W = 1 (c) H/W > 4

Shallow street canyon Uniform street canyon Deep street canyon

Figure 2.2. Different street canyon forms based on H/W ratio. Note: the schematic figures are plotted by the author.

2.5.2 SKY VIEW FACTOR (SVF)

One important factor in urban heat island investigations is Sky View Factor (SVF). SVF is defined as the ratio of visible sky at a point in space and a hemisphere centered over the analyzed location (Oke 1988). In a simple word, SVF is the ratio of visible sky that can be seen from a location in the urban space to whole sky dome that contains both visible and obstructed sky as seen in Figure 2.3. SVF is a dimensionless values ranges between 0 and 1 and determines the radiation budget and accordingly the energy absorbed by the street ground. At a point where the SVF = 1, there is no obstacle to block the sky from view (Lin, Tsai et al. 2012). It means that neither reflected short-wave radiation, nor additional long-wave radiation is received. If there is an obstacle blocking parts of the sky view, the SVF will be smaller than 1. SVF = 0 represents a location in which the entire sky is blocked from view by obstacles. In this case the energy budget (in terms of flux) can in this case be considered ideal, there is no short-wave reflection and there is no long-wave nocturnal interference (Oke 1988).

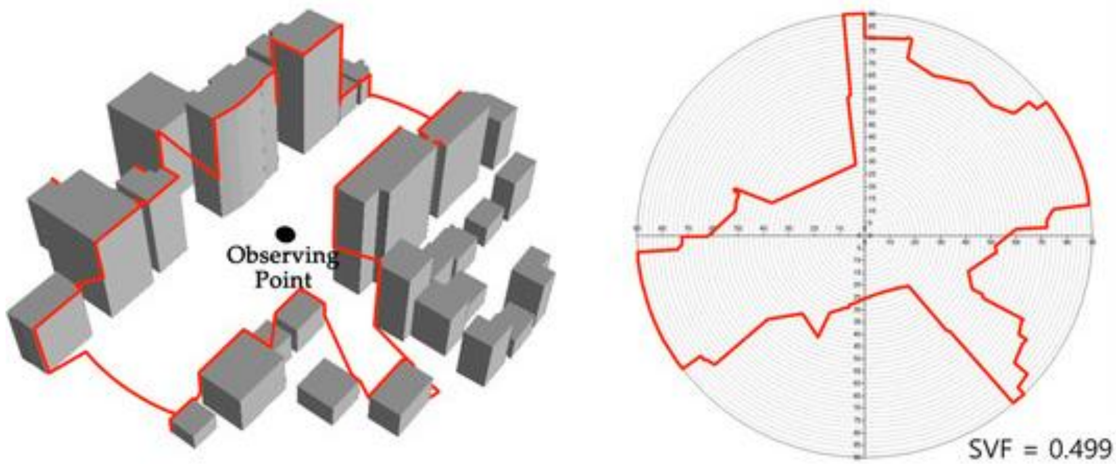


Figure 2.3. Street view factor (SVF) definition. Note: the figure is reprinted from Park, Ha et al. 2017.

2.5.3 BUILDING VOLUME

Building volume is another important factor in urban geometry category that influence the urban microclimate. It is essential to obtain the most appropriate building form in terms of climate sensitive urban design. Milosovicova (2013) states that building with larger surfaces, are more likely to absorb solar radiation. Therefore, multi-unit buildings are most preferable due to their small proportion of walls and roofs. Buildings with these characteristics are most likely to avoid multiple sunlight reflections and solar radiation absorption, as well as the emittance of heat from buildings through walls.

2.5.4 Street orientation

Another feature of urban geometry that has impact on urban microclimate is street orientation. Street orientation directly influences airflow, solar exposure of open areas and buildings, solar access inside and outside the buildings, and urban ventilation as well as the potential for cooling of the urban system (Emmanuel 2005, Herrmann and Matzarakis 2010, Shishegar 2013). Street orientation is an important factor in determining thermal comfort. In designing streets, seasonal changes need to be considered. In summer, street should provide protection from the sun. On the other hand, it should maximize sun access during the winter months.

Street orientation also plays an important role in air flow regime of the street. The effect of orientation of a street canyon on airflow and wind speed depends on the wind direction with respect to the street orientation direction. When the wind is parallel to the street canyon, a channelization effect is created, therefore, winds tend to be channeled and accelerated through the canyon. When wind is perpendicular to the street canyon, a vertically rotating wind flow is created with a centered primary vortex inside street canyons. In this case, three airflow regimes are defined based on the aspect ratio of H/W (Figure 2.4). In the increasing order of aspect ratio these flow regimes are: isolated roughness flow, wake interference flow and skimming flow. The total number of vortices made and their intensities depends on many factors. In isolated roughness flow, there is no interaction between windward and leeward flows. The wake interference flow regime is produced by increasing H/W ratio. For higher values of H/W ratio, a skimming air flow regime is produced in which the airflow in the street canyon is isolated from the urban air flow above the average height of canyon buildings. In this case a circulatory vortex is created as seen in Fig. 2.4 (c).

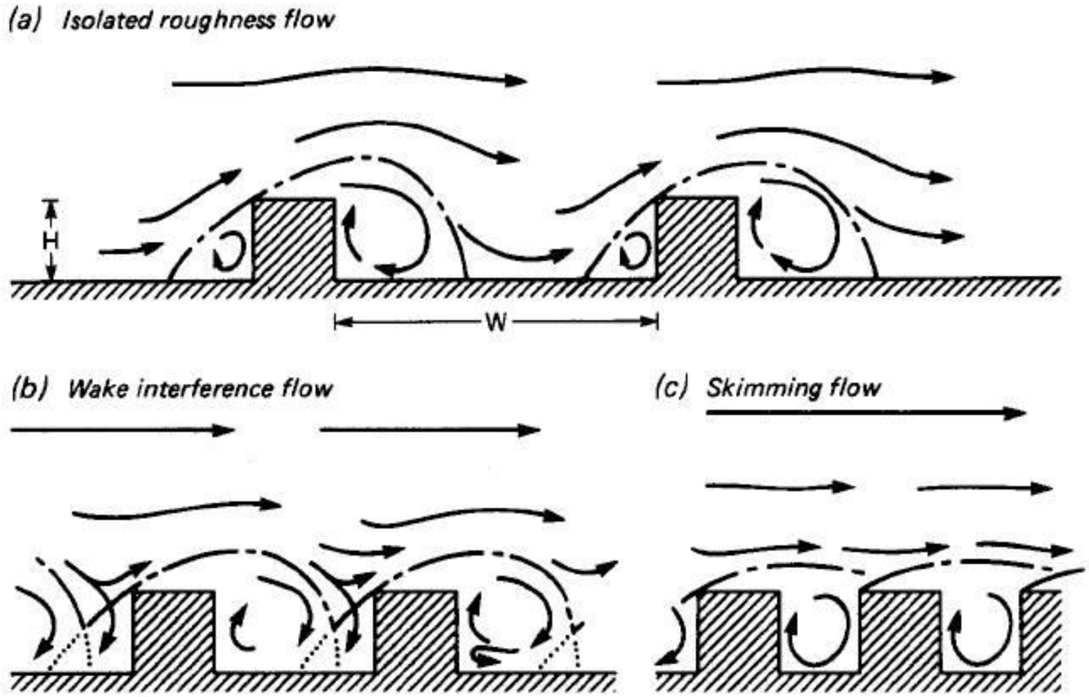
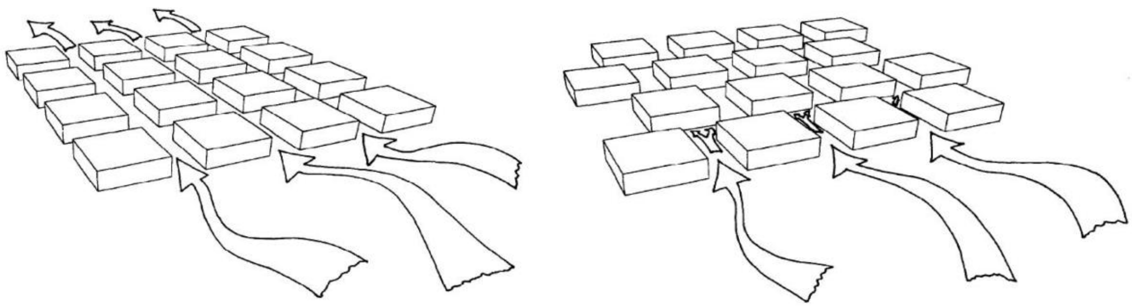


Figure 2.4. Three different wind regimes defined by Oke (1988) by increasing H/W ratio. Note: the figure is reprinted from Oke (1988).

Planners can employ design strategies in urban geometry to change urban airflow. For example, a few blocks of high-rise towers may decrease or increase the airflow based on the wind direction and urban form. Accordingly, the temperature can be increased or decreased. Also, straight and parallel streets increase the wind speed, while winding streets slow down the wind (Milosovicova 2013, Shishegar 2013).



(a) (b)

Figure 2.5. Effect of street orientation of urban airflow, (a) Straight and parallel streets improve airflow into and within a city, (b) Narrow and winding streets make airflow slow. Note: the figure is reprinted from Shishegar 2013.

In cold regions, it is essential to maximize the sunlight that reaches to the street ground. As reported in the literature (Herrmann and Matzarakis 2010, Milosovicova 2013), the north-south oriented street is the most appropriate state. However, lower temperatures are observed in east-west oriented urban canyons. It is also important to note that minimizing wind speed in cold climate by street planning strategies can improve outdoor thermal comfort. This can be done by designing wide urban canyons perpendicular to the wind direction in order to reduce the wind speed (Givoni 1998).

CHAPTER 3

ANALYSIS AND RESULTS

3.1 CASE STUDY: TABRIZ, IRAN

Tabriz is the most populated city in Iranian Azerbaijan located in Northwest of Iran. Iranian Azerbaijan is a historical region in northwestern Iran that borders Iraq, Turkey, the Nakhchivan Autonomous Republic, Armenia, and the Republic of Azerbaijan (See Figure 3.1). Tabriz, the largest economic hub and metropolitan area in Northwest Iran, is a historical city and was chosen as the capital of several rulers including Ilkhanate (Mongol) dynasty (1265 A.D.), Ghazan Khan (1295 A.D.), Qara Qoyunlu dynasty from 1375 to 1468 (A.D.) and then during the Ag Qoyunlu within 1468–1501 (A.D.). Finally, it was capital of the Iranian Empire in the Safavid period from 1501 (A.D.) until their defeat in 1555 (A.D.). During the Qajar dynasty, Tabriz was used as residence center of Iranian Crown Prince (1794–1925 A.D.) (Werner 2000).

Tabriz, the present capital of East Azerbaijan province, located in the Quru River valley, between long ridges of volcanic cones in Sahand and Eynali mountains. The latitude for Tabriz is 38.4 and the longitude is 46.16. Tabriz's area is about 2,356 km^2 (910 sq. mi) and the city's elevation ranges between 1,350 and 1,600 meters (4,430 and 5,250 ft.) above sea level. According to Iran census in 2016, the population of Tabriz in over 1.73 million (Statistical census of Iran 2016).

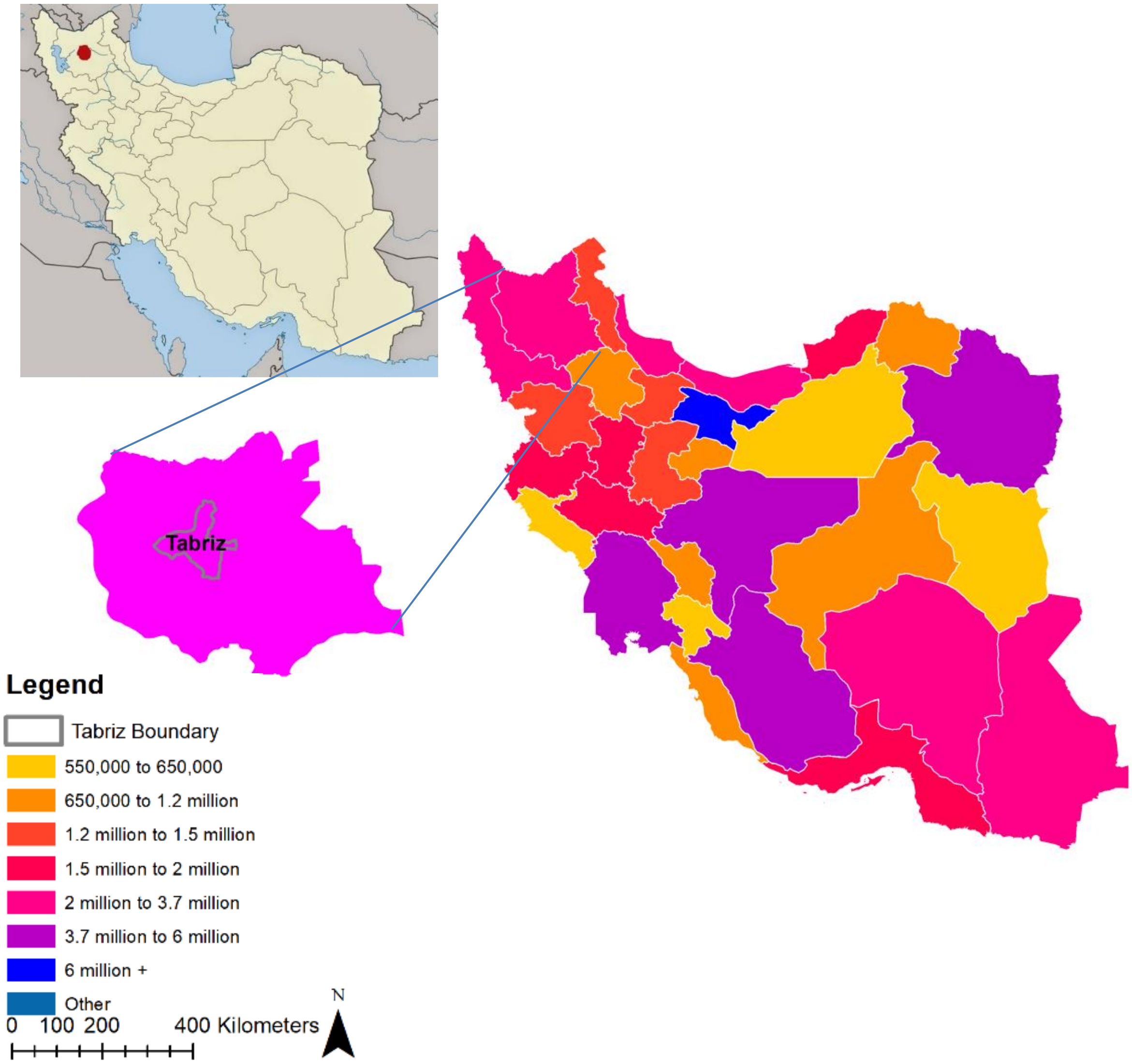


Figure 3.1. Location of Tabriz, the capital of East Azerbaijan province, in Iran, and the population map of Iran. Note: the figure is provided by the author using ArcGIS.

3.2 CLIMATE SPECIFICATION

Generally, Iran's climate can be divided in four types: 1) Moderate and humid climate (Caspian Sea coast in the North), 2) Cold climate (Mountainous area in the West), 3) Hot and dry climate (Central plateau), and 4) Hot climate (South Coast of Iran). The detailed description of Iran's climate is provided in Figure 3.2 including sub-groups of Very cold, Cold, Moderate/rainy, Semi moderate/rainy, Semi-arid, Hot/dry, Very hot/dry, Hot/humid. As seen in the figure, Tabriz is situated in the cold climate.

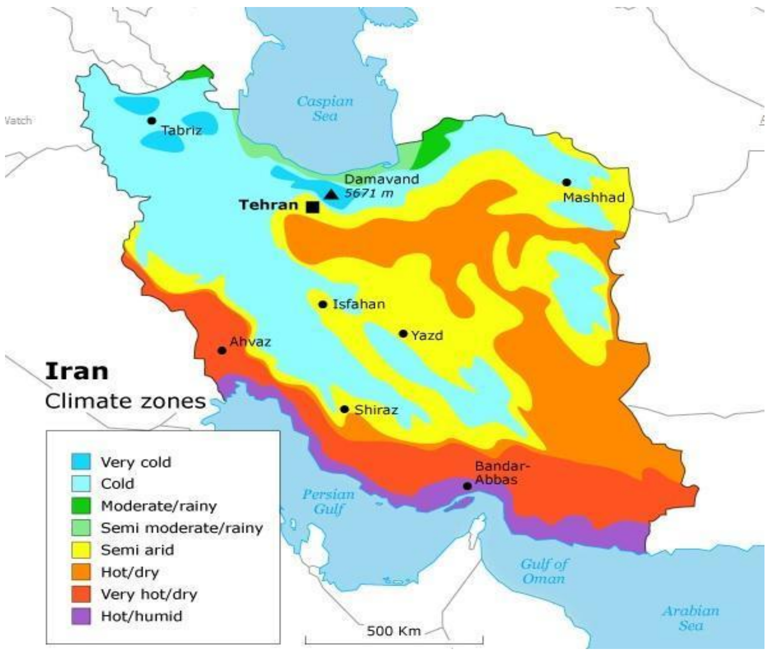


Figure 3.2. Climate zones in Iran. Note: the figure is reprinted from fanack.com 2016.

East Azerbaijan is located in a mountainous region, that about 40 percent of its area is covered by mountains. About 28 percent is covered by hills and the rest areas are plains. Generally, East Azerbaijan is situated in a cold and dry climate zone, however, due to topographical variety, it contains many sub-climates. This area is subjected to cold Northern and Siberian winds, and humid winds from Black Sea, Meditation Sea and Atlantic Ocean. In addition, the climate of East Azerbaijan is influenced by local winds which formed from physical elements of area such as high mountains, Caspian Sea and Urmia Lake. The minimum average temperature in this area is -3 ºC, and the annual average rainfall is between 250 to 300 mm. Tabriz, the capital of East Azerbaijan, has a cold and dry climate where the annual average rainfall is 285 mm. Due to the city's high elevation, it has long cold winters and moderate summers.

Jean Chardin (1643 - 1713), French traveler, in his ten-volume book *The Travels of Sir John Chardin* states "Tabriz climate is cold and dry, and cold weather lasts for a long time. Mount Sahand in south of Tabriz is seen to be covered of the snow for over a period of nine months a year." Solar radiation in this area is very low during winters. Winters are harsh, long and very cold, so that the grounds are icy for several months. Winter starts from mid-November and lasts until March. Rainfall is low in summer and high in winter in the form of snow.

Temperature

The average temperature data of Tabriz in a seventeen-year period is illustrated in Table 3.1. It shows Tabriz's winter is very long and that contains about 5 months (November-March) Cold weather begins from November, intensifies during December, January and February, and lasts until March. The average number of frost days in these five months are 3, 9, 24, 29 and 13, respectively.

Table 3.1. Monthly average temperature data of Tabriz during January 2000 - December 2017 (www.weatheronline.co.uk 2018).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Max (°F)	36.1	40.8	51.1	62.6	73	83.8	91	90.9	82.9	69.3	53.6	41.4
Max (°C)	2.3	4.9	10.6	17.0	22.8	28.8	32.8	32.7	28.3	20.7	12.0	5.2
Min (°F)	21.7	25	33.1	42.8	51.3	59.7	66.7	66.4	58.1	47.1	35.8	26.8
Min (°C)	-5.7	-3.9	0.6	6.0	10.7	15.4	19.3	19.1	14.5	8.4	2.1	-2.9

Note: Data for monthly average temperature of Tabriz from www.weatheronline.co.uk 2018.

Humidity

The average relative humidity rate during different months shows that the relative humidity increases by reducing temperature in October (See Table 3.2). The least relative humidity occurs at summer (July and August) with the average relative humidity of 36%.

Table 3.2. Monthly average relative humidity data of Tabriz during January 2000 - December 2017 (www.weatheronline.co.uk 2018).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Relative humidity (%)	72	69	61	56	50	40	36	36	39	51	65	71

Note: Data for monthly average relative humidity of Tabriz from www.weatheronline.co.uk 2018.

Precipitation

The physical location of Tabriz valley, the high mountains that surrounds the city and a cold front from the Northwest have influences of precipitation in Tabriz. The cold front streams from Europe (with air high pressure) in winter, crosses Mediterranean Sea and Black Sea zones (with lower air pressure) and brings a lot of moisture to Azerbaijan area. High mountains absorb the moisture and cause rain or snow. In Tabriz, precipitation starts from September at a moderate level, and intensifies in March to reach its highest level in April and May. The seventeen-year average participation results show that March, April and May with 45.0 mm, 56.6 mm and 50.1 mm, respectively, are months with the highest precipitation (Table 3.3). On the other hand, July and August have the least precipitation with 10.6 mm and 5.3 mm, respectively.

Table 3.3. Monthly average precipitation data of Tabriz during January 2000 - December 2017 (www.weatheronline.co.uk 2018).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Prec. (in)	0.866	0.953	1.575	2.031	1.618	0.646	0.22	0.13	0.311	0.886	1.067	0.87
Prec. (mm)	22.0	24.2	40.0	51.6	41.1	16.4	5.6	3.3	7.9	22.5	27.1	22.1

Note: Data for monthly average precipitation of Tabriz from www.weatheronline.co.uk 2018.

Wind

The study on airflow direction in the city of Tabriz in a seventeen-year period reveals that local winds are presents with different directions and intensities. Table 3.4 presents the percentages of wind based on its direction. It reveals that winds from the East and the North-East are the main airflows in Tabriz. These flows have the most intensity comparing to other airflows.

Table 3.4. Wind direction percentage in Tabriz (www.weatheronline.co.uk 2018).

Wind direction	**Percentage**
North	8 %
North-East	24 %
East	31 %
South-East	6 %
South	3 %
South-West	9 %
West	13 %
North-West	6 %

Note: Data for wind direction percentage in Tabriz from www.weatheronline.co.uk 2018.

Airflows from the West and the South-West have lower speed, while airflows from the North, South, South-East and North-West have very low speed (See Figure 3.3 and Table 3.5). A seventeen-year period airflow investigation shows that East and North-East airflows have the highest wind speeds (equals to 18.2 and 16.8 km/h, respectively). The wind speed in the South-West and West directions is 12.0 and 9.0 km/h, respectively.

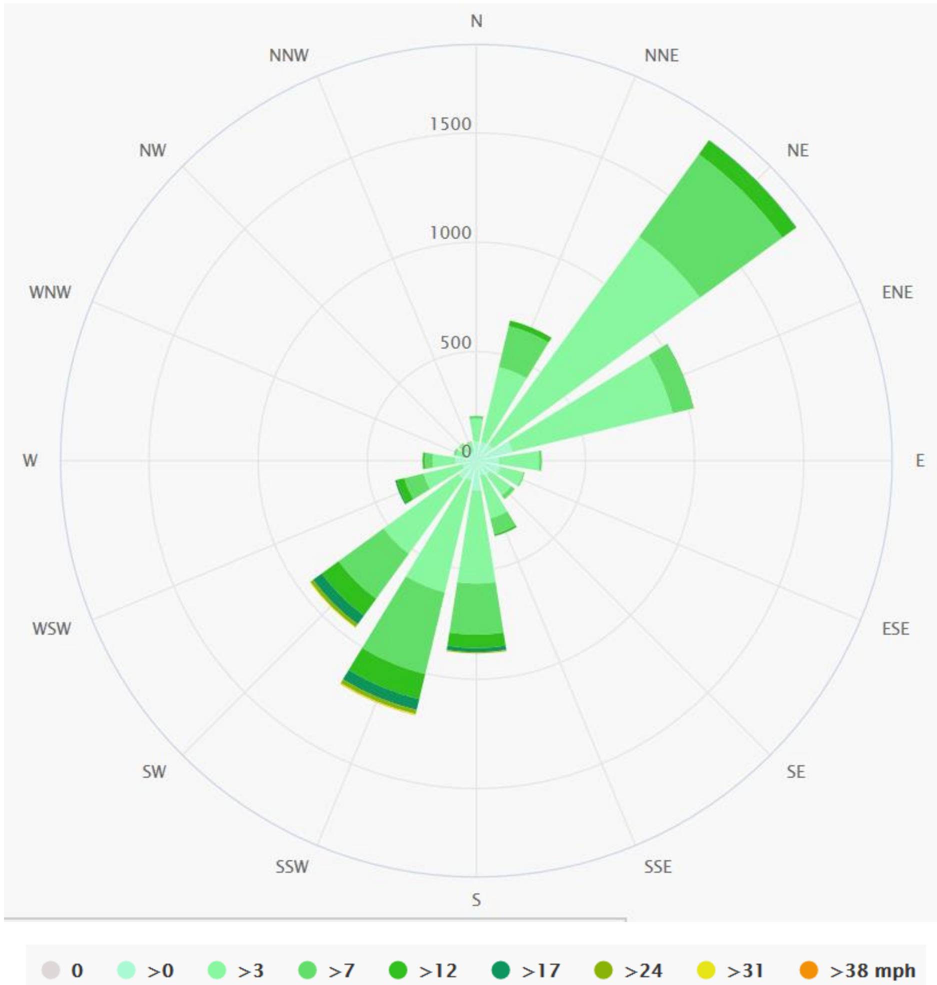


Figure 3.3. Wind rose map for Tabriz. Note: the figure is reprinted from www.meteoblue.com.

Table 3.5. Monthly average wind speed data of Tabriz during January 2000 - December 2017 (www.weatheronline.co.uk 2018).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Wind Speed (km/h)	9.4	10.9	13.5	13.8	14.3	15.6	18.1	16.2	13.0	10.7	9.4	8.9

Note: Data for monthly average wind speed of Tabriz from www.weatheronline.co.uk 2018.

Air Pressure

Air pressure is almost uniform in Tabriz during the year. The air pressure measurement results during 1976 to 1981 shows that the maximum average air pressure in Tabriz was 5.864 (mbar) in 1977 and the minimum average air pressure was 5.792 (mbar) in 1979.

Sunshine

Latitude is a determining factor in sunshine duration. The average sunshine hours from 2000 to 2017 is provided in Table 3.6. The average daily sunshine hours is 7.66 hours (January 2000 - December 2017).

Table 3.6. Average daily hours of sunshine data of Tabriz during January 2000 – December 2017 (www.weatheronline.co.uk 2018).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Hours of Sunshine	4.06	5.22	5.792	6.69	8.66	11.14	11.37	10.89	10.04	7.46	6.01	4.41

Note: Data for monthly average daily hours of sunshine of Tabriz from www.weatheronline.co.uk 2018.

3.3 Site Analysis: Blue Mosque Neighborhood and Valiasr Neighborhood

Two different districts of Tabriz is selected in this study to investigate the effect of urban form and geometry on outdoor thermal comfort. In this section, the physical characteristics of these districts are presented. The first district is located in a historical neighborhood, Kabud Mosque Neighborhood. This neighborhood is one of the oldest districts of Tabriz. The early urban development in this area is not well-documented, and it has devastated by several earthquakes during its history. The present-day urban form of Kabud Mosque Neighborhood is evolved from Qajar dynasty era (1785 to 1925) where the city was the traditional residence for the crown princes. The second district is located in Valiasr Neighborhood, a wealthy neighborhood at eastern part of Tabriz. The neighborhood is constructed during the last decade of the Pahlavi dynasty era (1964–1979). Although the general urban form such as street size and orientation of the neighborhood is remained the same over the period of time, most of its buildings are reconstructed or renovated. The locations of these two neighborhoods are shown in Figure 3.4. Furthermore, these figures represents the location of two points (A in Kabud Mosque Neighborhood and B in Valiasr Neighborhood). Thermal analysis will be performed in these two points in Section 3.4.

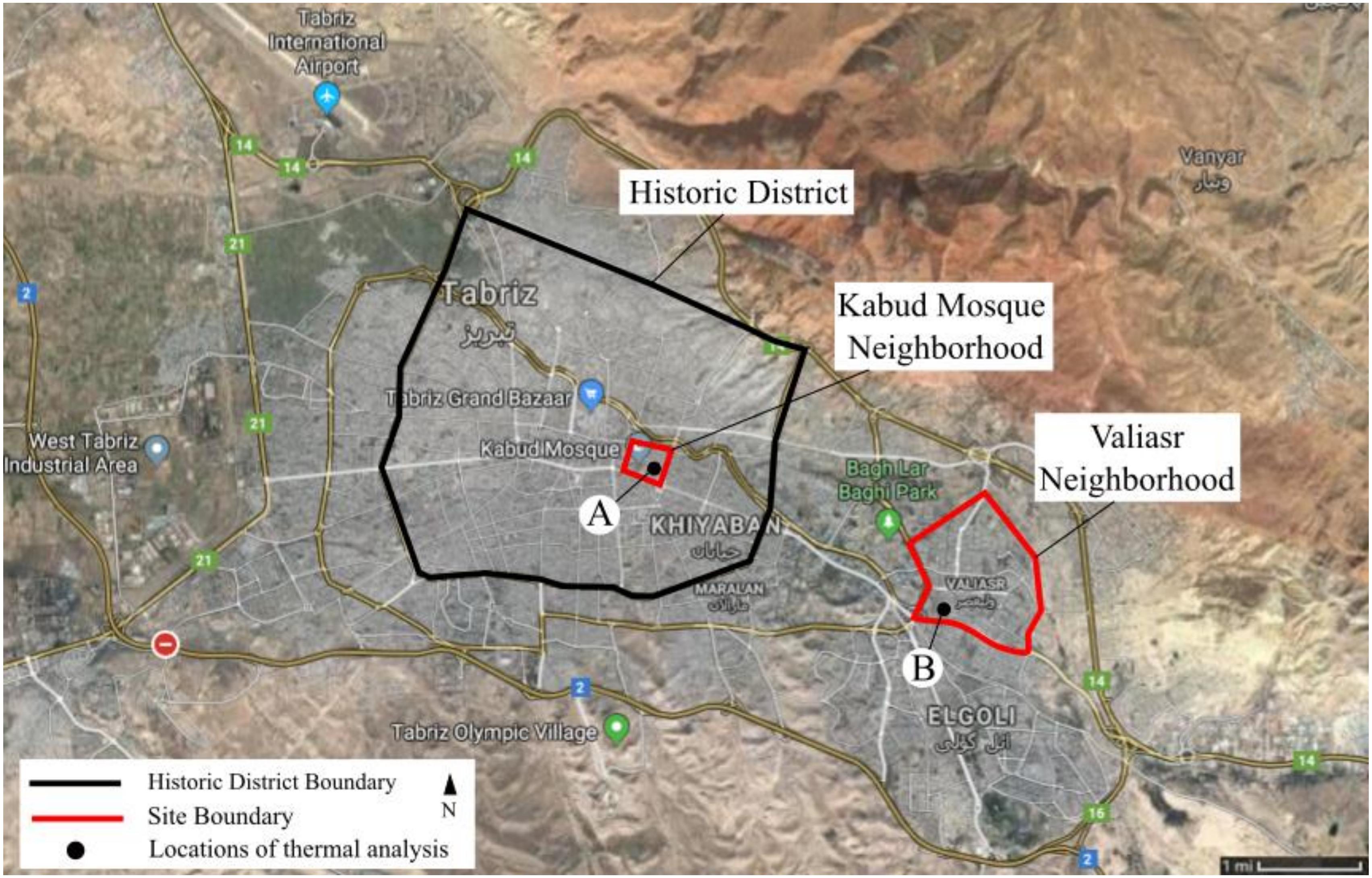


Figure 3.4. Location of Kabud Mosque and Valiasr neighborhoods in the city of Tabriz.
Note: Tabriz satellite view is taken from https://www.google.com/maps.

The two selected districts have different physical features including height and shape of the buildings, size and orientation of streets, and vegetation. Figure 3.5 illustrates the position of point A in Kabud Mosque Neighborhood. As seen in this Figure 3.5 (b), the buildings around point A, are low-rise and mainly have two-three stories. The street width and the average building height values for this neighborhood is provided in Figure 3.5 (c). The H/W ratio for this neighborhood approximately equals to 0.6. Therefore, based on definition presented in Section 2.5.1, this canyon can be categorized into the Shallow Street Canyon group.

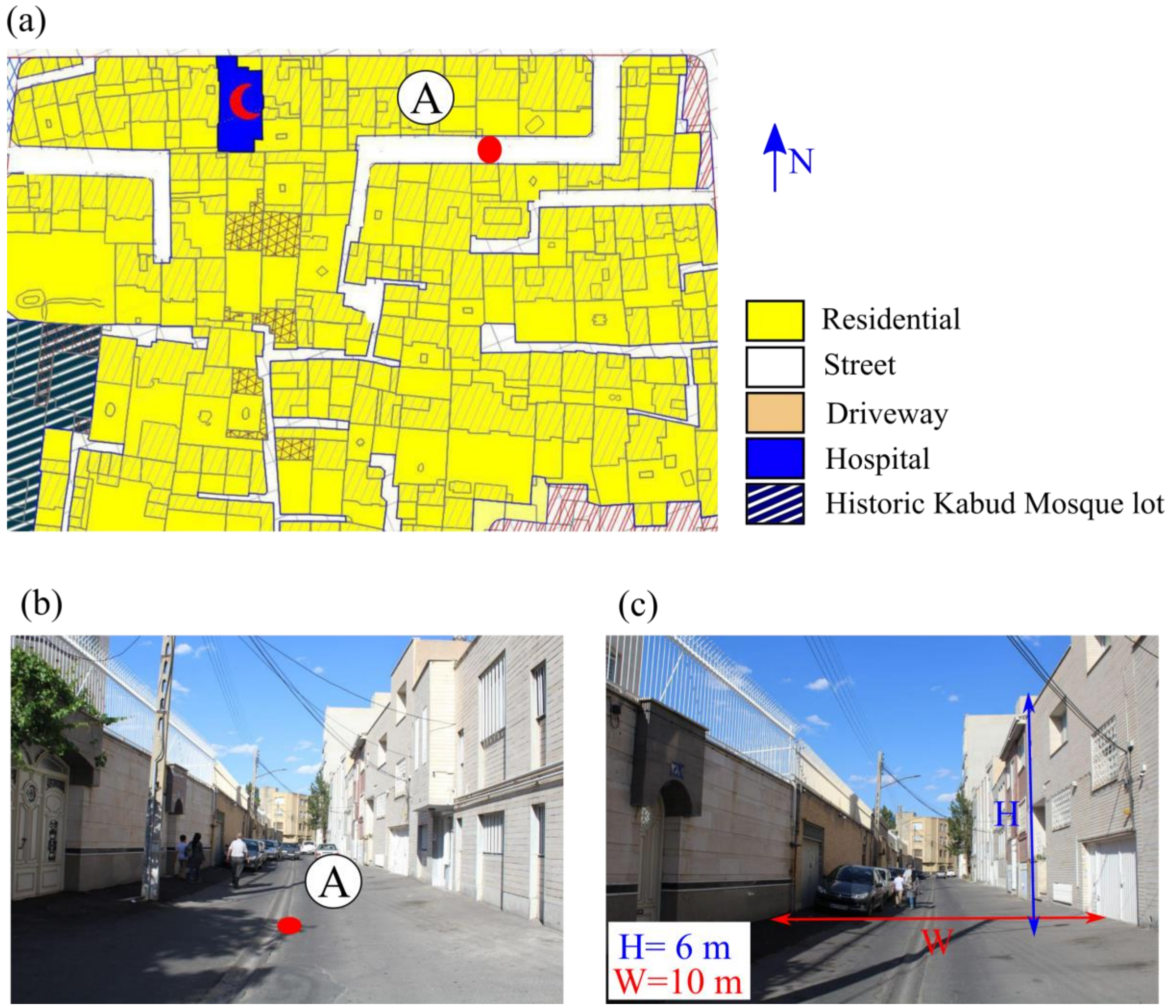


Figure 3.5. a) The location of point A in Kabud Mosque neighborhood, b) A photo of the target point, and c) Obtaining street width (W) and building height (H). Note: AutoCAD modeling and photos are provided by the author.

The 3D modeling of the neighborhood is represented in Figure 3.6. The location of the target point A also is illustrated in these plots. Figure 3.7 also presents some photos of historic buildings in this neighborhood.

Figure 3.6. 3D modeling of Kabud Mosque neighborhood. Note: 3DMax models are provided by the author.

Figure 3.7. Photos of some preserved historic buildings in Kabud Mosque Neighborhood. Note: photos were taken by the author.

The target point B is located in Valiasr neighborhood and is used in order to study thermal comfort in this wealthy neighborhood of Tabriz. Figure 3.8 (a) and (b) illustrate the location of point B in this neighborhood. Furthermore, a view of the sky seen from the target point B is provided in Figure 3.8 (c). As seen in this figure, building of this neighborhood are high-raised with six to eight stories. The H/W ratio for this area can be calculated with the information provided in Figure 3.8 (d). The high H/W ratio (H/W > 2.5) suggests that this street canyon is a Deep Canyon as discussed in Section 2.5.1. Figure 3.8 is also provides 3D modeling of Valiasr neighborhood around the target point B.

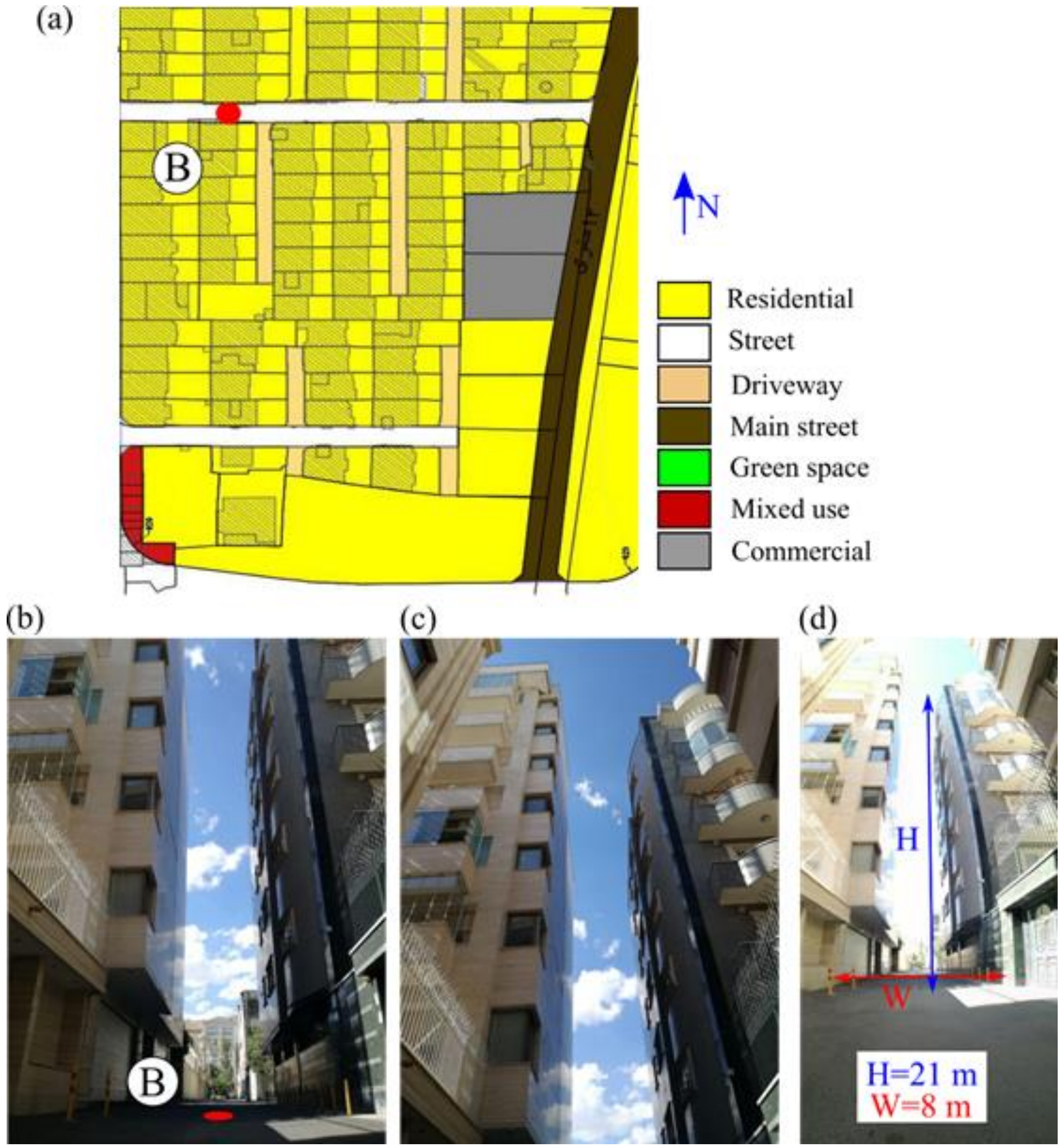
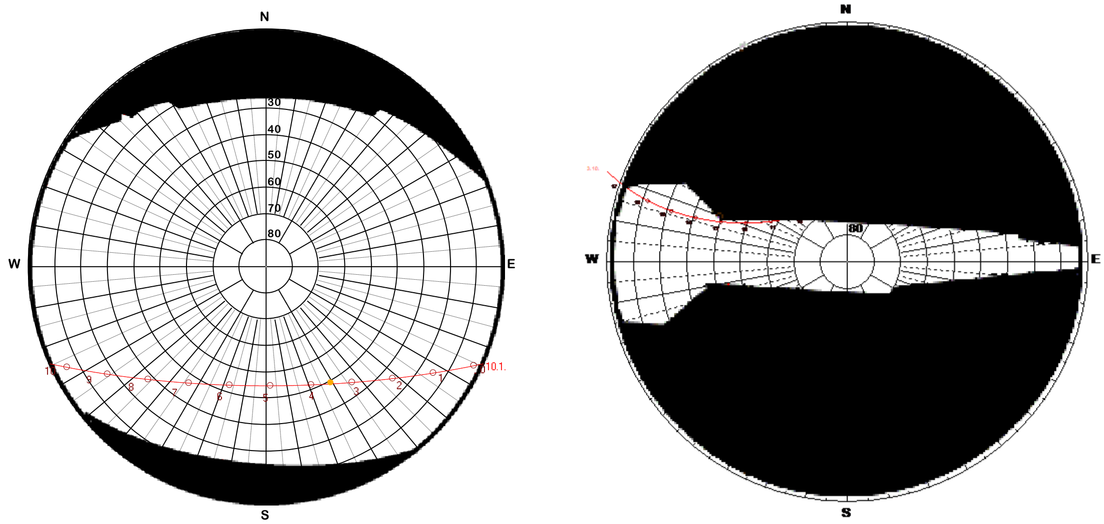


Figure 3.8. a) The location of point B in Valiasr neighborhood, b) A photo of the target point, c) Sky view at point B, and c) Obtaining street width (W) and building height (H). Note: AutoCAD modeling were created and photos were taken by the author.

Figure 3.9. 3D modeling of Valiasr neighborhood around the target point B. Note: 3DMax models were created by the author.

As discussed in Section 2.5.2, Sky View Factor (SVF) is an important parameter in determining outdoor thermal comfort. SVF is also important in calculating Universal Thermal Climate Index (UTCI) calculation in RayMan model. The RayMan Pro program is capable to calculate SVF using fisheye photos taken from the target point. The software's produced SVF figures for the selected target points are provided in Figure 3.10. Based on these figures, the SVF is calculated using the RayMan Pro software as 0.830 and 0.191 for points A and B, respectively. In other word, the horizon limitation for point A is 17.0%, and for point B is 80.9%.



(a) Sky view at point A (b) Sky view at point B

Figure 3.10. Sky views from point A and point B, using these figures, SVF is calculated as 0.830 for point A and 0.191 for point B. Note: Sky views are provided by the author using RayMan Pro 2.

In addition to SVF, there are some other parameters that influences the thermal comfort within the UTCI concept. These parameters are air temperature, relative humidity, vapor pressure, wind velocity, cloud cover, and mean radiant temperature. It is worth to mention that vapor pressure can be obtained for a given air temperature and the relative humidity. Therefore, it is not an independent parameter. In addition, if the mean radiant temperature is not given by the user in the RayMan software, the software can calculate this value. Therefore, for the current study, the main parameters are air temperature, wind speed, relative humidity and the SVF.

The SVF values comes from Figure 3.10. In addition, the air temperature and wind speed for any date (but selected hours) is available on Iran Meteorological Organization's website at http://www.irimo.ir/eng/. Tables 3.7-3.10 presents these values for 5 selected days in 2017-2018 winter collected from the Tabriz weather station. These days are Nov. 10 (2017), Dec. 10 (2017), Jan. 10 (2018), Feb. 10 (2018), and Mar. 10 (2018). In Meteorological Organization's website, the climate data are available for eight hours of 0, 3, 6, 9, 12, 15, 18, and 21 (UTC). Considering that Iran uses a Universal Time Coordinated (UTC) offset UTC+03:30, the climate parameters are available at 3:30, 6:30, 9:30, 12:30, 15:30, 18:30, 21:30, and 0:30 (Local time). Also note that since the hourly relative humidity is not available for Tabriz, therefore, the monthly average values of relative humidity provided in Table 3.2 are used in UTCI calculations. Finally, the geographic data of Tabriz are also required in RayMan modeling. Tabriz is situated in 38°04′N 46°18′E and its elevation is 1351.4 m.

Table 3.7. Climate parameters measured in Tabriz station on Nov. 10, 2017 (http://www.irimo.ir/eng/).

UTC	Local time	Temp. (ºC)	Pressure (hPa)	Wind speed (m/s)	Wind dir.
0	3:30	8	866.2	0	-
3	6:30	7	866.5	2	East
6	9:30	10	866.6	3	Southeast
9	12:30	13	865.7	5	North
12	15:30	13	865.1	4	West
15	18:30	9	865.7	0	-
18	21:30	9	866.3	3	East
21	0:30	7	866.0	3	Northeast

Note: Data for climate parameters of Tabriz from http://www.irimo.ir/eng/.

Table 3.8. Climate parameters measured in Tabriz station on Dec. 10, 2017 (http://www.irimo.ir/eng/).

UTC	Local time	Temp. (ºC)	Pressure (hPa)	Wind speed (m/s)	Wind dir.
0	3:30	-5	872.0	3	Northeast
3	4:30	-5	871.8	4	Northeast
6	9:30	-3	872.1	3	Northeast
9	12:30	2	871.1	1	East
12	15:30	2	870.2	0	-
15	18:30	-3	870.7	0	-
18	21:30	-4	870.5	3	Northeast
21	0:30	-5	870.2	2	Northeast

Note: Data for climate parameters for Tabriz from http://www.irimo.ir/eng/.

Table 3.9. Climate parameters measured in Tabriz station on Jan. 10, 2018 (http://www.irimo.ir/eng/).

UTC	Local time	Temp. (ºC)	Pressure (hPa)	Wind speed (m/s)	Wind dir.
0	3:30	-3	869.8	2	Northeast
3	4:30	-3	869.8	2	Northeast
6	9:30	0	871.0	1	East
9	12:30	5	870.6	3	West
12	15:30	6	869.6	3	West
15	18:30	0	869.5	3	North
18	21:30	0	870.0	3	Northeast
21	0:30	-2	870.0	2	East

Note: Data for climate parameters for Tabriz from http://www.irimo.ir/eng/.

Table 3.10. Climate parameters measured in Tabriz station on Feb. 10, 2018 (http://www.irimo.ir/eng/).

UTC	Local time	Temp. (ºC)	Pressure (hPa)	Wind speed (m/s)	Wind dir.
0	3:30	0	861.6	3	Northeast
3	4:30	-2	862.4	2	Northeast
6	9:30	5	863.5	2	Northeast
9	12:30	9	863.1	3	Northwest
12	15:30	10	861.7	4	West
15	18:30	6	862.6	3	North
18	21:30	4	863.6	2	East
21	0:30	1	864.3	4	Northeast

Note: Data for climate parameters for Tabriz from http://www.irimo.ir/eng/.

Table 3.11. Climate parameters measured in Tabriz station on Mar. 10, 2018 (http://www.irimo.ir/eng/).

UTC	Local time	Temp. (ºC)	Pressure (hPa)	Wind speed (m/s)	Wind dir.
0	3:30	3	858.5	2	Northeast
3	4:30	4	860.0	2	Southeast
6	9:30	7	861.2	2	Northwest
9	12:30	10	860.9	3	North
12	15:30	11	860.3	4	West
15	18:30	8	860.4	2	Northwest
18	21:30	6	861.4	2	East
21	0:30	5	861.8	0	-

Note: Data for climate parameters for Tabriz from http://www.irimo.ir/eng/.

3.4 RAYMAN MODELING RESULTS AND DISCUSSIONS

Figures 3.11-15 compares the UTCI values, obtained from RayMan model, in two different locations of Tabriz: Point A in historical Kabud Mosque neighborhood, and Point B in newly developed Valiasr neighborhood. Each figure is plotted from the data for eight different times of a day. UTCI ranges of thermal comfort is provided in Table 2.3, the figures are categorized based on these thermal stress ranges. Since this study focuses on winter days, only cold thermal stress sensations are included. It is important to note that air temperature, relative humidity and the wind speed are considered to be the same for both neighborhoods. The only parameters that makes the results differ from each other is the SVF.

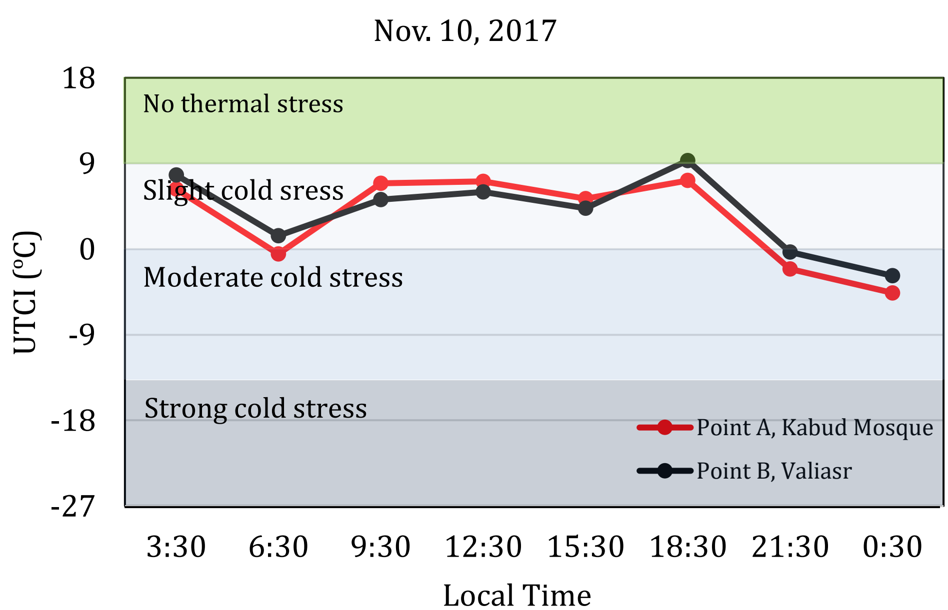


Figure 3.11. Comparison of UTCI values at points A and B on Nov. 10, 2017.

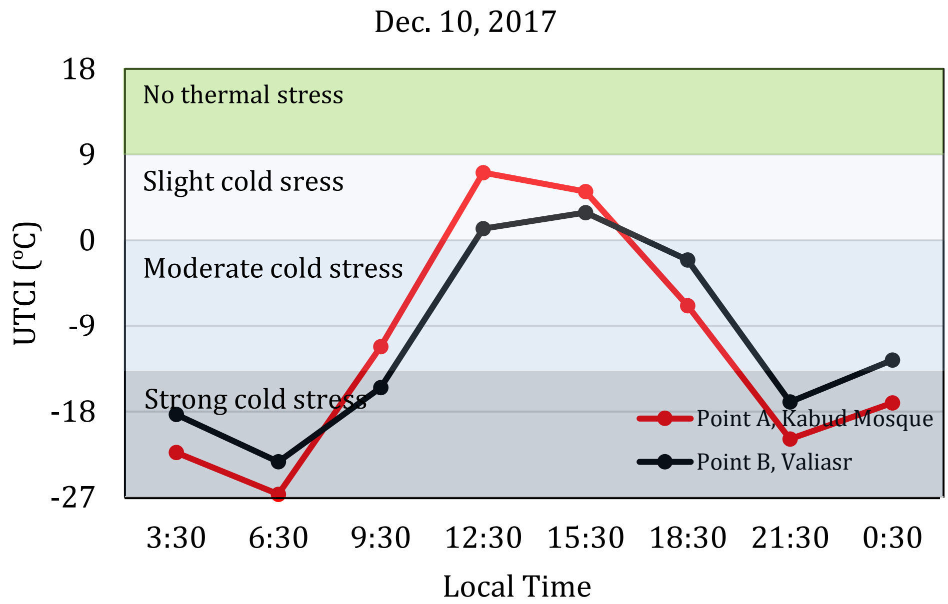


Figure 3.12. Comparison of UTCI values at points A and B on Dec. 10, 2017.

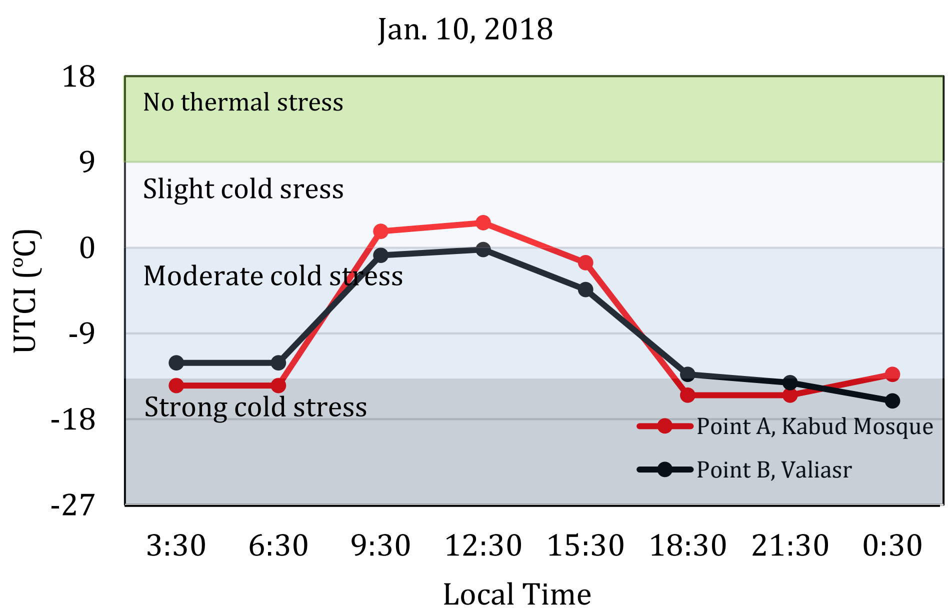


Figure 3.13. Comparison of UTCI values at points A and B on Jan. 10, 2018.

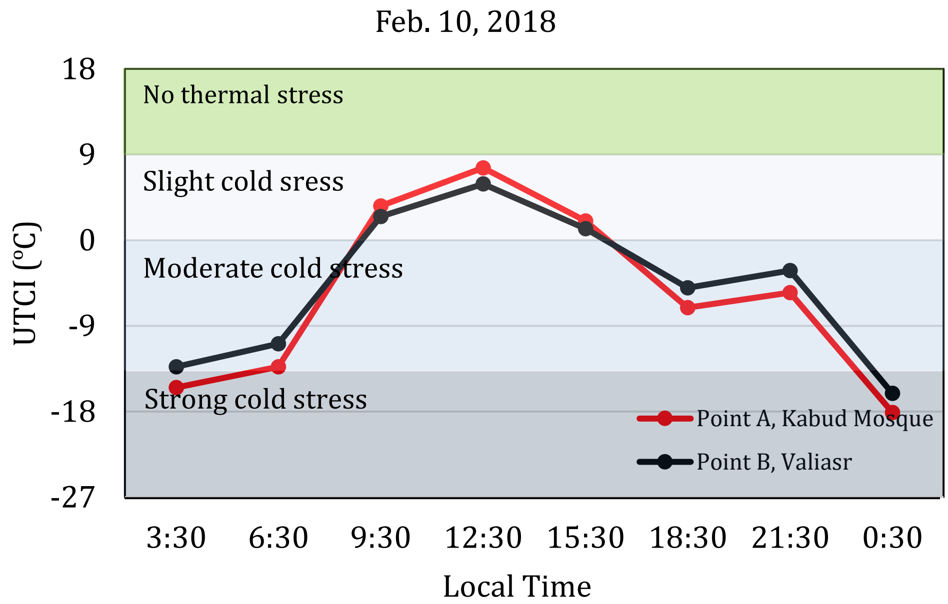


Figure 3.14. Comparison of UTCI values at points A and B on Feb. 10, 2018.

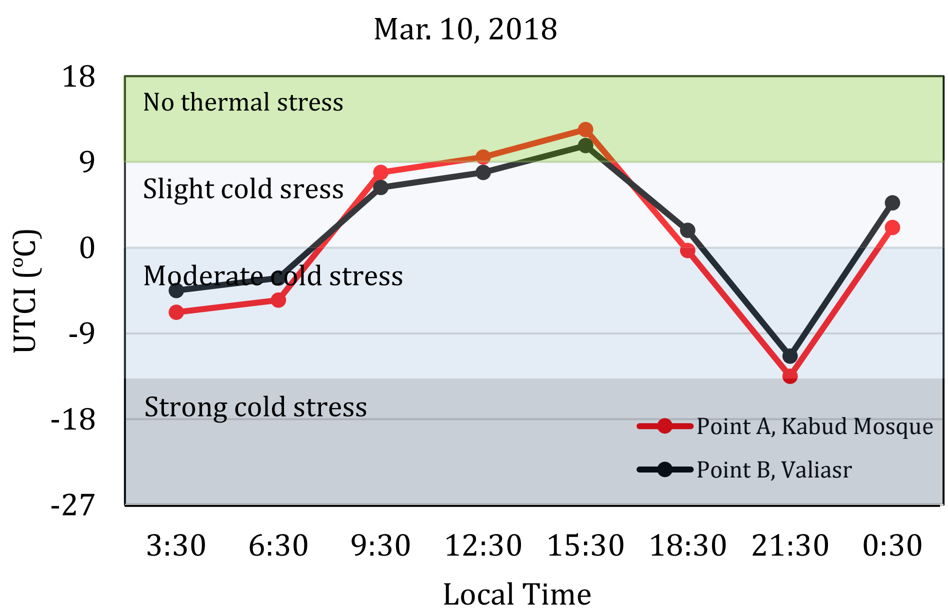


Figure 3.15. Comparison of UTCI values at points A and B on Mar. 10, 2018.

In order to interpolate the UTCI data results, it is beneficial to provide the sunrise and sunset times as seen in Table 3.12. For the winter dates selected in this study, the daytime is relatively short, about 10-11 hours.

Table 3.12. Sunrise and sunset data for the selected dates.

Date	Sunrise (hh:mm)	Sunset (hh:mm)
Nov. 10, 2017	6:52	17:10
Dec. 10, 2017	7:23	16:58
Jan. 10, 2018	7:33	17:15
Feb. 10, 2018	7:13	17:49
Mar. 10, 2018	6:39	18:19

Note: Data for sunrise and sunset in Tabriz from RayMan Pro 2.

Based on the daytime data provided in Table 3.12, two different patterns can be seen in UTCI results. In all eight dates, UTCI at point A (Kabud neighborhood) is higher than its value at point A (Valiasr neighborhood) for the daytime. The main reason is that point A has higher SVF (0.830) than point B (SVF at point B is 0.191). It means that point A has better access to the sun light, therefore, in the daytime, it gains more solar energy, and this leads to increase its thermal comfort sensation. On the other hand, during the night, UTCI is higher at point B. The SVF in point B is relatively high, this means there is high obstruction to the incoming and outgoing radiations. At point B, higher SVF prevents the neighborhood to lose energy at night by obstructing outgoing radiations from the ground surface to the sky. For this reason, the UTCI is higher at point B than point A at nights.

CHAPTER 4

CONCLUSIONS AND FUTURE WORKS

Providing a comfortable sensation for urban residents on their outdoor activities is one of the most important goals in urban developments. Especially in cold regions, the climate characteristics limits the outdoor activities, therefore, it is essential to use climate-sensitive strategies in order to promote outdoor thermal comfort in cold months. Many indices are defined to quantify the thermal comfort sensation. Among them, the recently developed Universal Thermal Climate Index (UTCI) gains popularity because it is valid in all climates, seasons and scales. Also, it is independent of person's characteristics (age, gender, specific activities and clothing etc.). This study utilizes the UTCI to analyze thermal comfort in two points of two different districts of Tabriz, one of the coldest cities in Iran. One district contains low-raise single family houses, while the other one contains multi-story buildings with relatively narrow streets. The physical characteristics of two neighborhoods influence the solar energy access and then thermal comfort in these areas. The study focuses of five days of Tabriz’s long winter. The UTCI is calculated using the RayMan model for both locations during the day. The results indicate that how physical features of the built environment can affect the thermal sensation, therefore, it is important for an urban planner and developer to design the urban space in order to promote the thermal comfort. This thesis investigated the effect of H/W ratio and SVF on thermal comfort. UTCI values are calculated for five days of 2017-18 winter in two target points selected in the historic and the newly developed neighborhoods. Nothing that target points are selected in west-east streets. In each target point, UTCI is calculated for eight different times during a day. The comparison of UTCI shows that, during the sunshine, UTCI at the target point belongs to the newly developed neighborhood is higher than its value at the target point of historic neighborhood. This suggests that physical form of the historic neighborhood promotes thermal comfort in cold months of Tabriz by increasing sun access to the ground.

The limitations associated with the present research can be listed as:

1. To compare thermal comfort in two neighborhoods of Tabriz, this thesis calculated UTCI at only one target point for each neighborhood. The UTCI value at the selected point may not represent outdoor thermal of respective neighborhood. At the time working on this thesis, the author was unable to travel to Tabriz to acquire data for more target points from each neighborhood.
2. This thesis only investigated thermal comfort in cold months, since the mild climate at the remaining months prevents any thermal stress to pedestrians.
3. Furthermore due to time limitation, this thesis calculated UTCI only for one day per cold month.
4. Data for air temperature and wind speed is only available for eight times a day.
5. The reported wind speed is measured at station. Presence of street canyon may amplify or weaken the air flow. Due to author’s lack of knowledge to quantify the effect of street canyon on wind speed, the author considered constant wind speed for two target points (as measured at the station).
6. The author did not have access to relative humidity data for the selected specific times. The only available relative humidity data provides the monthly average values. Therefore, the author used the monthly average value as relative humidity for a specific time.

Based on the listed research limitations, the future work may include the followings:

1. Collaborate with a local researcher to acquire data for some more target points in each neighborhood. This may lead to provide a UTCI map over the neighborhood and will increase the knowledge on effect of urban physical feature on outdoor thermal comfort.
2. Evaluate thermal comfort for all days of selected cold months. Also, thermal comfort evaluation is performed for 2017-18 winter. Since the climatic data is available in literature for seventeen years from 2000 to 2017, it is suggested to repeat the analysis for this period. These results would be more representative of normal weather.
3. Collaborate with an expertise in computational fluid mechanics to study the effect of street canyon and wind direction on the wind speed in the target point. The modified wind speed may result in accurate thermal comfort analysis.
4. Humidity is considered constant during the day. Investigate the variation of relative humidity during the day and study its effect of thermal comfort index.
5. Study the effect of asphalt and building materials on sun radiation.

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