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Research Paper

Investigating Outdoor Thermal Comfort in Various Street Patterns (Case Study: A Neighborhood in the Historical Context of Tabriz)

Saber Sabouri [1*], Niloufar Alinasab [2]

[1,2] *Department of Architecture and Urban Design, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran*

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Abstract
Nowadays, due to rapid urbanization, People can't participate in outdoor activities. On the other hand, environmental issues such as climate change and heat stress have caused thermal dissatisfaction for users. In this regard, studying outdoor environments becomes crucial. In the present historical context, lack of responsive urban layout consequences not only morphological problems but also causes thermal dissatisfaction during the passages. The present study aims to find the responsive layout pattern for providing an approximate outdoor thermal comfort based on local criteria and limitations in summer and winter; which requires the minimum intervention in the current context. In this regard, we intend to represent three basic street patterns (Linear, Grid, and Circular) as alternative designs and attempt to localize them with the current urban layout. For analyzing the prototypes, we used Envi-met Beta software to compare the average amount of climatic factors, orientation, and H/W ratio for the alternatives. In addition, the PMV factor (=Predicted Mean Vote Model) was used as a measurement index of outdoor thermal comfort. According to the outcomes, the Radial pattern with dominant NE-SW oriented passages prepares adequate solar energy in the winter. Also, it could balance the high radiation during the summer, whereby provides optimal thermal satisfaction in both hot and cold seasons.

Keywords: *Building façades, Energy-efficiency, High-rise buildings, Energy simulation, Energy reduction, Cold-dry climate.*

1. INTRODUCTION

Nowadays, according to the importance of social interaction among people, outdoor thermal comfort should be highly considered. Unfortunately, during the past decades, neglecting people's need in the urban spaces, doing activities, and communicating with other people, have caused harmful effects on their physical and mental health. Therefore, the possibility of their presence in urban spaces must be considered (Biddle et al., 2021; Gibson et al., 2015). In this regard, shopping centers and economic hubs of cities, such as historical Bazaars in traditional cities, have a strong potential to attract people and create livability (Einifar et al., 2019). For instance, Iranian Bazaars were not only characterized based on buying and selling but also played a substantial role in shaping social and cultural activities (Assari et al., 2011).

In cold and tropical climates, due to lack of thermal comfort, outdoor trading was not possible; thus, indoor markets were fundamental. Also, in the past, buildings and especially markets had been designed indigenously with local materials and structures. Consequently, thermal comfort in different seasons was provided. But as time goes on, modernity has reshaped the form of cities and consequently increased environmental and climatic problems. So, providing a solution to reform the historical identity and thermal comfort for pedestrians must be considered.

1.1. Theoretical Framework

The concept of thermal comfort refers to the mental feeling of satisfaction with the temperature of the environment. Various parameters could affect thermal comfort; including four main climatic factors -temperature,

* *Corresponding author: s.sabouri@tabrizu.ac.ir*

wind speed, thermal radiation, and humidity- (Chen et al., 2020), physiological factors (type of clothing and amount of activity) (Fanger, 1973), and psychological factors. The sense of thermal comfort is different among people, and it's challenging to satisfy everyone (ASHRAE Standard 55, 2004). Also, morphological factors (such as the height of buildings, width, and orientation of passages, the density of buildings, vegetation, and materials) affect the person's thermal sensation as well. In this regard, passages are the most common parts of the outdoor environment, which play a significant role in people's life. The basic types of streets which form the neighborhood layouts are known as Linear, Grid, and Radial. These patterns, depending on the requirements of each region, have altered or incorporate other patterns over time (Marshall, 2004). For instance, Stephen Marshall divided these patterns into three primary categories and combined them as shown in Fig 1. It is also possible to employ numerous modes of street patterns. In the present study, we will use these three basic patterns to retrofit our case study in morphological and climatic aspects.

Abbreviations	
PMV	Predicted Mean Vote
H/W	Height to width ratio
AO	Axes Orientation
Mrt	Mean Radiant Temperature
Rh	Relative humidity
W.S	Wind speed
T	Air Temperature
Act	Actual site

2. LITERATURE REVIEW

The first studies about the relevance between micro-climate and urban design were published by Olgyay (1963), Oke (1987), and Givoni (1991). In recent decades, extensive researches about the relation between thermal comfort and urban design factors have been accomplished (Table 1). According to the outcomes, physical parameters, such as height to width ratio (H/W), axes orientation (AO), and neighborhood layout configurations (NLC), have a significant effect on the thermal comfort in various climates without mechanical equipment demands (passively). Extensive studies indicate a strong relationship between urban forms and thermal comfort factors like gained solar radiation and wind speed (Britter & Hanna, 2003; Hachem et al., 2011; Kakon & Mishima, 2012; Sanaieian et al., 2014; Taleghani et al., 2015; Yilmaz et al., 2021; Zakhour, 2015). Also, investigations about the relationship between height to width ratio and thermal comfort show that higher H/W ratio during the summer season and lower ratio in the winter could provide appropriate thermal comfort, due to the gained solar radiation through the streets (Ali-Toudert & Mayer, 2006a; Bourbia & Awbi, 2004; Bourbia & Boucheriba, 2010; Johansson, 2006).

Other studies about the relationship between axis orientation and thermal comfort demonstrate that E-W oriented streets provide inappropriate thermal comfort (Yin et al., 2019), whereas NE-SW and NW-SE oriented streets provide appropriate thermal comfort for pedestrians during summer and winter (Ali-Toudert & Mayer, 2006b, 2007).

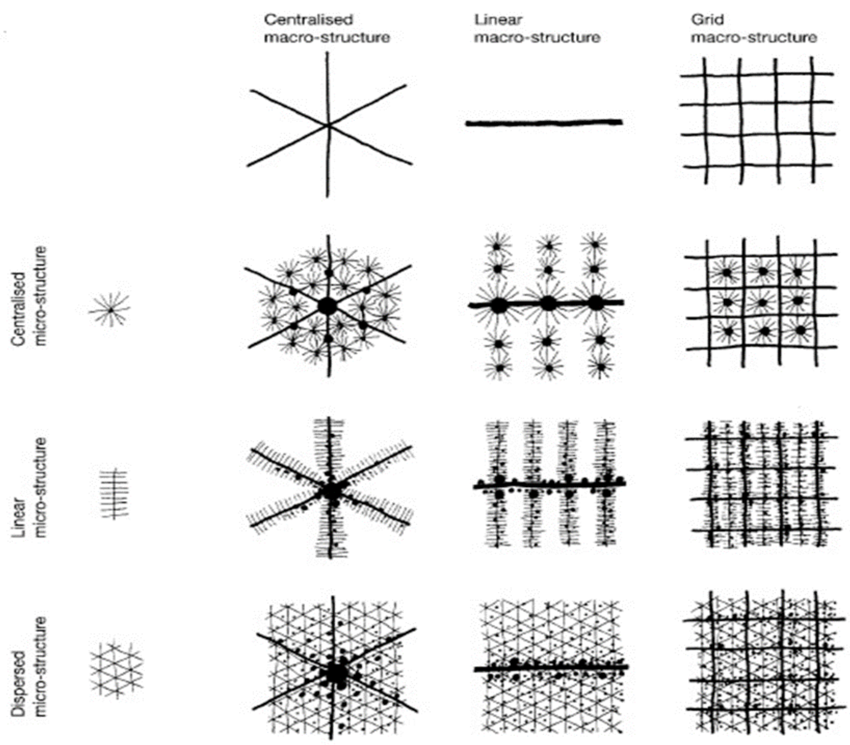

Fig 1. Incorporation of Basic Network Patterns in Three Different Scales (Marshall, 2004)

Table 1. Investigations about the Relationship between Morphological Factors and Thermal Comfort

Researcher	Morphological Parameters	Climatic Parameters	Survey Method
(Ali-Toudert & Mayer, 2006b)	H/W, Orientation	Air temperature, MRT, wind velocity	Numerical modeling (ENVI-met)
(Johansson, 2006)	H/W, SVF, Orientation	Air temperature, MRT, Humidity, wind speed	Measurement instruments
(Bourbia & Boucheriba, 2010)	H/W, SVF, Orientation	Air ambient temperature, MRT	Measurement instruments
(Kakon & Mishima, 2012)	FAR (floor-area-ratio), Height of buildings, SVF	Solar Radiation, Air Temperature, MRT	Numerical modeling (ENVI-met)+RayMan
(Middel et al., 2014)	SVF, mean Height of buildings, Surface Albedo	Air temperature, surface temperature, Wind speed	Numerical modeling (ENVI-met)
(Monam & Rückert, 2013)	Height and dense of buildings, Materials	Air temperature, Vapor pressure, Wind velocity, MRT	Numerical modeling (ENVI-met)+ Ecotect
(Zakhour, 2015)	H/W, SVF	Air temperature, surface temperature, relative humidity, MRT, Wind velocity	Numerical modeling (ENVI-met)+Measurement instruments
(Xuan et al., 2016)	D/H, FAR, SVF	surface temperature, relative humidity, MRT, Wind velocity	Estimating methods (Nakamura)+ software DUTE
(Yin et al., 2019)	H/W, canyon type, layout configurations, canyon axis, orientation	Air temperature, MRT, wind velocity	Measurement instruments + Numerical modeling (ENVI-met)

3. MATERIALS AND METHODS

3.1. Background

Tabriz is located at 38.09 degrees North latitude and 46.2 degrees East longitude. Also, it's one of the most important economic and historical centers in Iran. Fig 2 presents the central context of Tabriz, which consists of ancient museums, historic gates, and the Grand Bazaar. Tabriz's Grand Bazaar has performed economic and social roles, with numerous corridors, and about 8,000 shops, and in 2010 it was registered as the world's historic market on the UNESCO World Heritage List. The main characteristic of the Bazaar was not just shopping, but it was a public place with social, educational, and religious functions (Ebrahimi et al., 2013). But with the advent of modernity, streets became expanded, and the interconnection among different spaces of the historical context was disrupted. Darayi Street is one of the main roads that splits the two sides of the Bazaar. The street was established in 1965, and despite the active transportation role, it caused physical disruption between both sides of the historical context (Hashempour et al., 2018). Some other problems in the Bazaar context including traffic congestion, interference between pedestrians and vehicles, and disruption of activities subsequently cause other issues including noise and air pollution, the heat islands in the summer, and the lack of thermal comfort.

After observing the field and conducting interviews with local people, we realized that most of the thermal dissatisfaction during the passages are related to the morphological problems. We also considered the restriction and criteria of the historical context. Since the old gates of the city are ringed around the historic core, the inner region of these gates includes the following specific criteria:

- Permissible materials in the historical context are bricks, cement, and plaster.
- The maximum height allowed for construction in this area is around two floors.
- The permitted land-uses are residential, commercial, service, and parking.

3.2. Envi-met Software

In the current study, we used Envi-met Beta software (Bruse & Fleer, 1998) for analyzing the selected area. Envi-met is a three-dimensional software that provides various possibilities for modeling, simulating, and analyzing urban microclimates. Fig 3 demonstrates the Envi-met workflow.

The initial step in the present study was to model the current site in the spaces area; after importing data about the height of buildings, materials, and the soil types, we merged other climatic information of Tabriz (validated by Weather Data by Location | EnergyPlus). Finally, we analyzed the simulation results in the LEONARDO area and illustrated them as images or charts. In the present study, due to the lack of thermal comfort in summer and winter, January 17, 2018, was selected as the coldest day of winter for the simulation, and August 10, 2018, was chosen as the hottest day of summer, respectively.

For setting the simulation time, the presence of people in outdoor places was determined for three different hours in the morning, noon, and evening, respectively, for both seasons. Eventually, due to the maximum outdoor activity, 12:30 pm was selected as the simulation time (Fig 4). Table 2 represents the important information of modeling and simulation.

NOTE: In the current study, due to the focus on morphological issues, vegetation, canopy, and cloud cover are not considered as the variables.

• PMV (Predicted Mean Vote)

ENVI-met also includes a simple bio-meteorological model to predict the thermal comfort inside the model area. Based on Fanger's model (Fanger, 1973), the PMV (predicted mean vote) relates the energy balance of the human body to the personal comfort feeling of persons exposed to the corresponding climates. The PMV is one of the best-known Biomet models which could be applied for indoor and outdoor environments (Honjo, 2009; Jendritzky & Nübler, 1981). According to Bruse (Bruse & Fleer, 1998), the validity of PMV is approved globally, and the results are related to the climatic factors (air temperature, wind speed, thermal radiation, and humidity) and physiological factors (type of clothing and amount of activity) of any region. Normally, the PMV scale is defined between -4 (very cold) and +4 (very hot). For calculating the PMV in the Biomet area, personal human parameters were set for a typical person. Also, the vertical range is calculated for up to 1 meter height, due to the pedestrian's activity area.

Fig 2. Introducing the Case Study

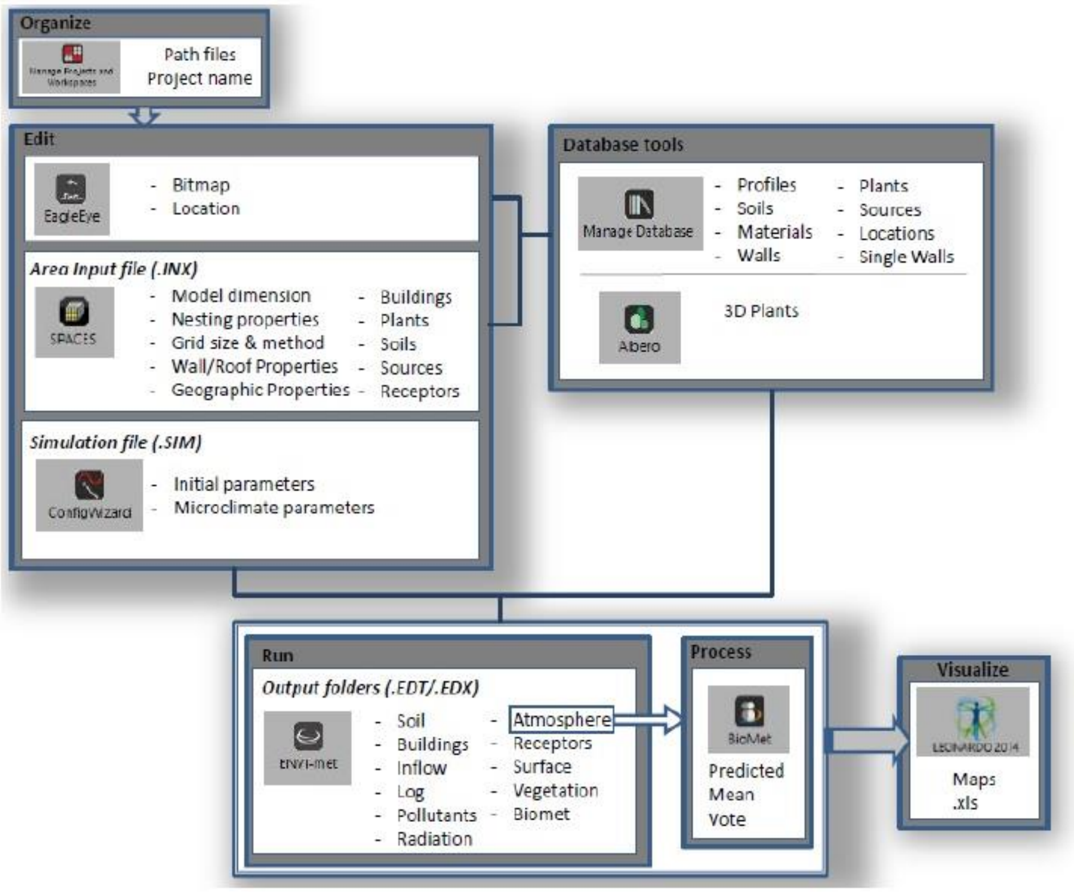

Fig 3. Envi-met Workflow (Chatzinikolaou et al., 2018)

Table 2 Simulation and Modeling Properties

Simulation model size	428 x 440 x 15	
Number of grids	144 x 148 x 25	
Size of grid cell	3 x 3 x 1	
Geographic location	38.08, 46.27	
Nesting grids	6 m	
Reference time zone	Tehran +03:30	
	Winter	Summer
Simulation date	Jan 17, 2018	Aug 10, 2018
Simulation time	12:30 pm	12:30 pm
Wind direction (deg)	90	90
Wind speed (m/s)	3	1.3
Min temperature (°C)	0	14.4
Max temperature (°C)	3.3	30.6
Min Humidity (%)	70	20
Max humidity (%)	84	51

Fig 4. Amount of People's Outdoor Activity during Three Different Times of a Day

3.3. Design Process

In the present design, the current situation of the site plays a decisive role in selecting the appropriate type of intervention for the street network. We combined existing context and global networking patterns; then we tried to localize these patterns. In the next step, we came up with a general outline about the location and grading of the passages, the valuable buildings, width, and orientations of the pathways (Fig 5). Accordingly, the maximum height of the buildings in the design pattern is 6 meters, and two types of height to width ratios are 1:2 and 1:1 in the local streets, with a width of 12 and 6 meters. Ultimately, we reached three design alternatives. For accurate pattern measurement, through the short passages, three receptors have been located at the beginning, middle, and end of the short passages. Also, more than four receptors are set in the longer passages. As mentioned before, in the present study, the effects of the trees and canopy were not considered.

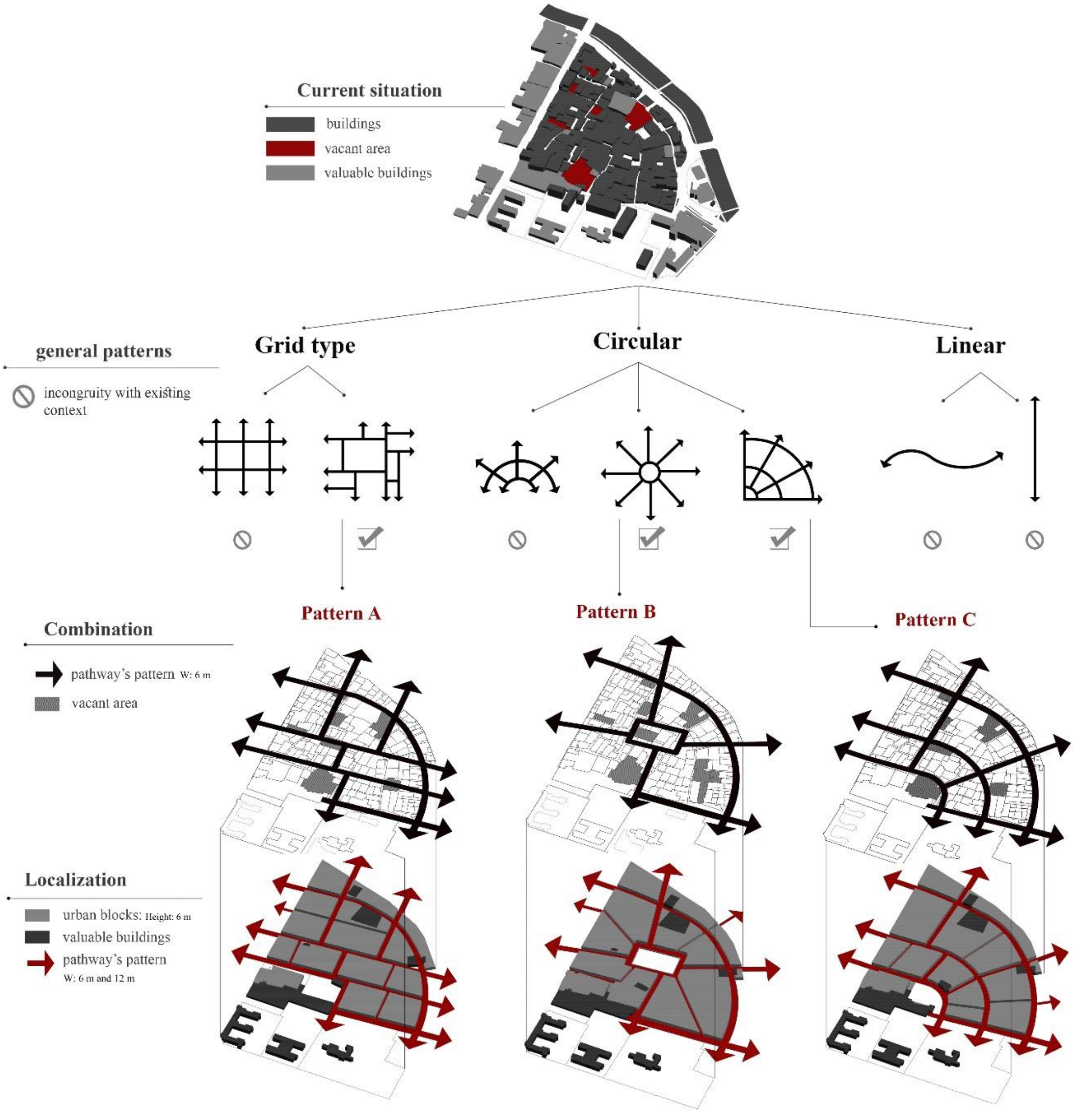

Fig 5. Design Process (Combination and Localization of the Current Area with the Mentioned Patterns)

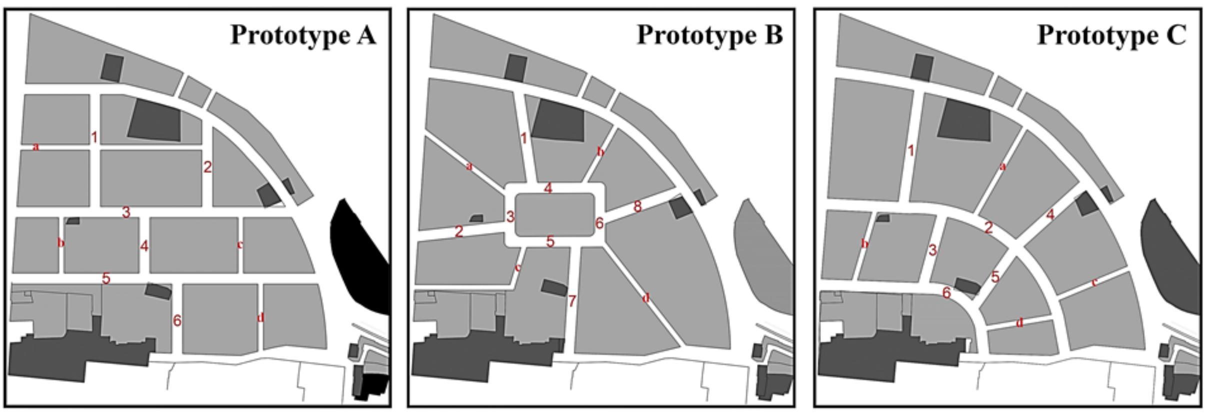

Fig 6. Exact Plans of the Prototypes

4. RESULTS AND DISCUSSION

Tabriz has a mid-latitude steppe/semi-arid cold climate. The Koppen Climate Classification subtype for this climate is "BSk" (Tropical and Subtropical Steppe Climate). Accordingly, the city suffers from thermal dissatisfaction during the year. For addressing the problem, firstly we simulated all the mentioned alternatives in the hot season. For analyzing the results, we used the PMV factor as an index to measure people's outdoor thermal satisfaction within the passages. In the following, we debate the analyzed climatic parameters in three categories (layout patterns, average orientation, and H/W ratio).

4.1. Layout Patterns

- ***Summer Season***

Wind Speed

The results of the simulation for wind speed illustrate that the average wind speed through the passages for the actual site (act), patterns A, B, and C are 0.48m/s, 0.55m/s, 0.53m/s, and 0.50m/s, respectively (Figure 7). During August, the prevailing wind direction is 90deg from the East, which makes the E-W oriented passages contain maximum wind speed comparing other orientations. Therefore, pattern A, which has the highest rate of E-W oriented passages, obtains the maximum amount of average wind speed through the passages. In contrast, the current site (act) and pattern C, which consist of dominant NE-SW and NW-SE oriented passages, receive a low rate of wind speed.

Mean Radiant Temperature

Based on studies about the mean radiant temperature, pattern C, the current site (act), and pattern A with 64.3 ° C, 64.1 ° C, and 63.1 ° C have the highest radiation temperature, respectively. Pattern B with dominant NW-SE oriented passages has the lowest radiation temperature (58.7 ° C). Consequently, the most remarkable result to emerge from the data is that the E-W and NE-SW oriented passages obtain the highest amount of solar energy during the hot season (Fig 7).

The acceptable way to reduce the disadvantages of mean radiant temperature during the hot season is to use the canopy within passages. In this research, the canopy factor was not considered.

Relative Humidity

An appropriate level of relative humidity during the hot seasons helps to moderate the air temperature. Wind speed and mean radiant temperature are the main climatic factors affecting relative humidity. According to Fig 7, in pattern A, higher mean radiant temperature and wind speed evaporate the existing moisture, thereby reduce it to 26.8%. In pattern B, despite the low mean radiant temperature, the presence of wind speed reduces relative humidity. Finally, in pattern C, despite the high mean radiant temperature, lower wind speed modifies conditions and keeps moisture during the passages. According to the results, the relative humidity of all the alternatives is higher than the current condition (act).

Air Temperature

Air temperature is closely related to the other climatic components. For instance, by increasing the amount of moisture and reducing the received radiation, the air temperature can be significantly decreased. In this study, the air temperature of the alternatives doesn't have any significant difference. But considering the impact of other climatic factors, the air temperature of pattern A is the highest at 26.94 ° C. The temperatures of current condition (act), patterns B and C, are 26.38 ° C, 26.37 ° C, and 26.23 ° C, respectively (Fig 7).

Thermal Comfort

According to *Fig 8* and *Fig 9*, pattern C provides more thermal satisfaction than the current condition (act), patterns A and B; that is relevant to the climatic factors. For instance, the E-W oriented passages receive a high amount of solar energy, which subsequently causes a noticeable rising in the amount of air temperature and reducing the relative humidity. Consequently, pattern A with a high rate of N-S oriented passages provides less thermal satisfaction. The existence of NE-SW and NW-SE oriented passages in patterns B and C, help to balance the climatic components through the passages and improve the outdoor thermal comfort. To sum up, the comparison between each pattern and the current condition (act) represents that pattern C obtains better thermal circumstances. In contrast, pattern A has a minimum amount of thermal comfort.

- ***Winter Season***

In the climate of Tabriz, cold months last longer. Therefore, we should scrutinize the importance of thermal comfort during this season as well as the summer. In this regard, adjusting the climate factors such as wind speed, mean radiant temperature, and relative humidity could affect outdoor thermal satisfaction. In the following sections, we will discuss the investigated climatic parameters in the winter for the alternatives.

Wind Speed

The high rate of wind speed along the passages reduces people's thermal satisfaction in winter. During January, the wind direction is from the East (90 degrees). Therefore, patterns with dominant E-W passages have the highest amount of wind speed. For instance, pattern A has a wind speed of 0.93 m/s which is higher than the wind speed in the current condition (act), patterns B and C with wind speeds of 0.88 m/s, 0.87 m/s, and 0.77 m/s, respectively. This situation could cause thermal dissatisfaction within the passages (Fig 10).

Mean Radiant Temperature

In contrast to the summer season, in winter, the more sunlight could be gained, the more desirable condition people feel along the streets (Mehdizadeh Saradj & Maleki, 2014). The obtained results about the mean radiation temperature along the passages in Fig 10 indicate that pattern C with 30.62 ° C, causes more favorable conditions than patterns A and B with the mean temperature of 20.35 and 23.51 °C, respectively. Also, the MRT of the current situation is 25° C, which indicates that pattern C could be an appropriate alternative to reach outdoor thermal comfort. Consequently, we could remark that the NE-SW-oriented passages could earn more solar energy during the cold season.

Relative Humidity

The high level of relative humidity in winter is a significant feature of Tabriz's climate. Weak sunlight and cold winds prevent evaporation and adjust the moisture. According to Fig 10, in pattern A, the efficient combination of the wind speed and the solar energy in the E-W-oriented passages reduces the relative humidity comparing other patterns along the passages. In contrast, the high amounts of NW-SE-oriented passages with a high H/W ratio in pattern B could decrease the solar access, and subsequently, relative humidity becomes increased.

Air Temperature

In the winter, controlling the wind speed and air humidity, as well as improving solar energy, can improve the air temperature and thermal comfort. According to the reached results from Fig 10, we could find that the current condition (act) suffers from low air temperature during the cold season. Significantly, all of the alternatives could modify the current circumstance. Since the E-W-oriented passages are well-irradiated, in pattern A, the combination of powerful wind speed and sunlight could control the relative humidity and help to moderate the air temperature. Also, pattern C with a temperature of 3.63 ° C is more desirable than pattern B, with a temperature of 3.55 ° C.

Thermal Comfort

Investigations about outdoor thermal satisfaction in Fig 11 and Fig 12 demonstrate that patterns C, A, and B, respectively, provide better thermal comfort than the current condition (act). It seems that the E-W and NE-SW-oriented passages provide more thermal satisfaction in winter. Thus, pattern C, with dominant NE-SW-oriented passages, receives an effective rate of radiation and wind speed; whereby, they help improve thermal satisfaction. By contrast, in pattern B, long NW-SE passages couldn't obtain adequate solar radiation, and consequently, the air temperature and thermal comfort become reduced along the passages

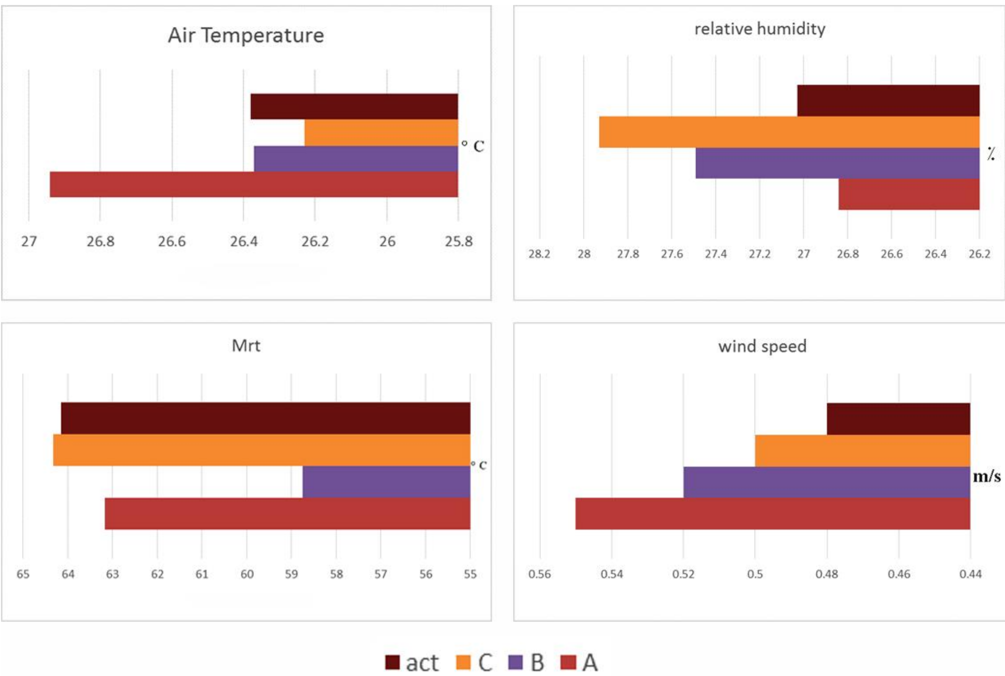

Fig 7. Correlations of Climatic Factors between the Current Situation and Designed Patterns in the Summer

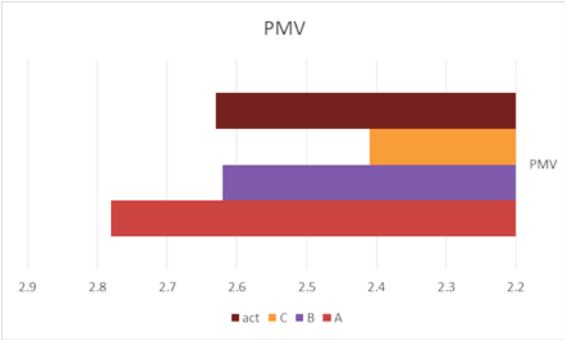

Fig 8. Correlations of PMV Factor among the Current Situation and Designed Patterns in the Summer

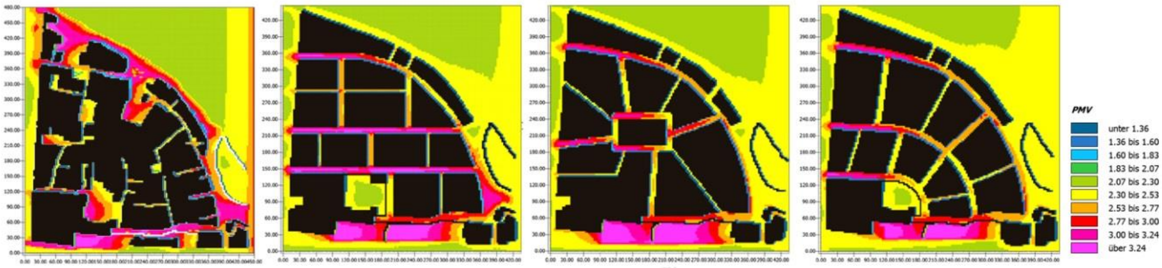

Fig 9. Comparing the Thermal Comfort among Designed Patterns and the Current Situation in the Summer

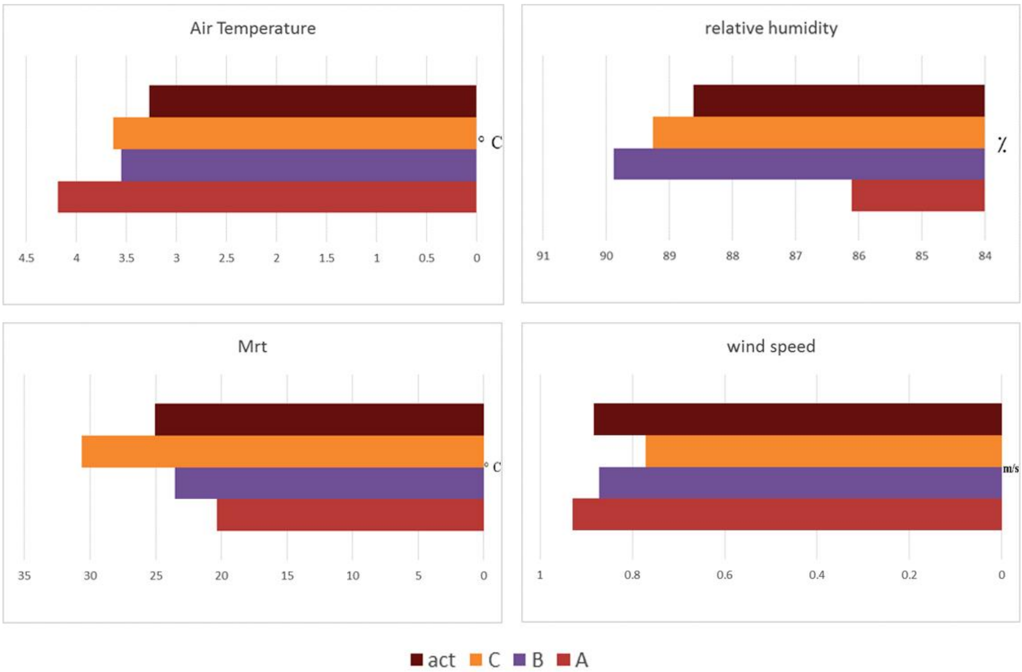

Fig 10. Correlations of Climatic Factors between the Current Situation and Designed Patterns in the Winter

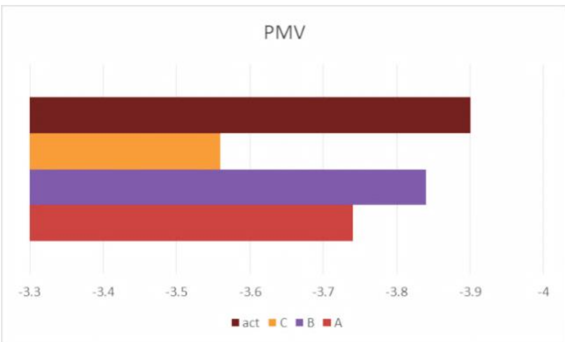

Fig 11. Correlations of PMV Factor among the Current Situation and Designed Patterns in the Winter

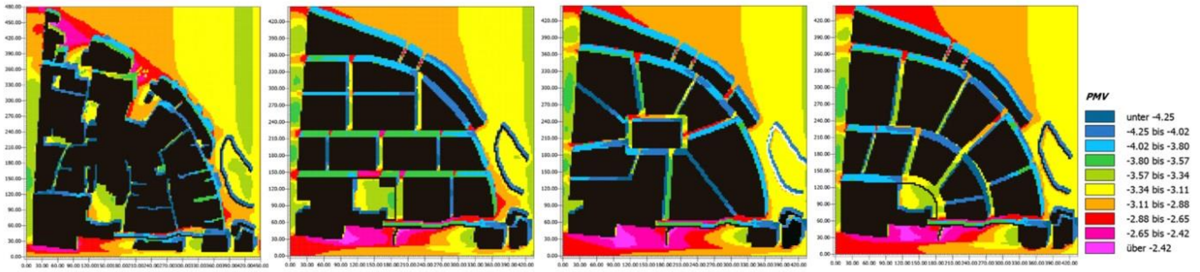

Fig 12. Comparing the Thermal Comfort among Designed Patterns and the Current Situation in the Winter

4.2. Passages Orientation

According to the obtained results, it seems that the effect of orientation on outdoor thermal comfort precedes other physical components such as density, H/W ratio, etc. Based on Fig 6, we have divided each passage into four main categories of orientation (E-W, N-S, NE-SW, NW-SE), and by examining the average of each group, we will discuss the optimal orientation in summer and winter.

• ***Summer***

Investigating the climatic components (Mrt, T, Rh, and W.S) in the four directions shows that the E-W-oriented passages have the highest radiation and wind speed and the lowest humidity in the summer. Thus, it can't provide sufficient comfort during these passages (Fig 13). The N-S-oriented pathways also have the minimum wind speed, with no significant difference in temperature, humidity, and radiation with NE-SW and NW-SE-oriented pathways. The NW-SE-oriented passages receive the lowest temperature and radiation levels. Also, they are similar in thermal comfort to the NE-SW-oriented pathways, which are more appropriate than E-W and N-S-oriented passages. Finally, the NE-SW-oriented passages, with the slightest difference from the NW-SE orientations, provide thermal satisfaction in the summer. To sum up, it's noticeable that the E-W passages cause more thermal dissatisfaction in the summer. In contrast, NE-SW and NW-SE are the most appropriate orientations. The result is consistent with previous studies.

• ***Winter***

The same investigations in the winter demonstrate that the E-W orientation contains a maximum amount of air temperature and wind speed and minimum relative humidity. Also, it provides an appropriate rate of thermal satisfaction after the NE-SW-oriented passages. The N-S orientation, despite a minimum amount of wind speed, has a low air temperature and thermal comfort. The NW-SE direction also receives the least radiation and makes the most undesirable thermal comfort during the passages. Finally, the NE-SW-oriented pathways, which obtain the highest radiation, provide the best thermal comfort compared to other orientations. To sum up, the results reveal that in the winter, NE-SW and E-W orientations obtain the highest thermal comfort, respectively (Fig 14).

4.3. H/W Ratio

The simulation results for the average of passageways with the ratio of 1:1 and 1:2 indicate that in the summer, the 1:1 ratio contains less radiation and temperature, and more humidity and thermal comfort. While in the winter, the 1:2 ratio provides the highest radiation and temperature, and better thermal comfort (Fig 15 and Fig 16).

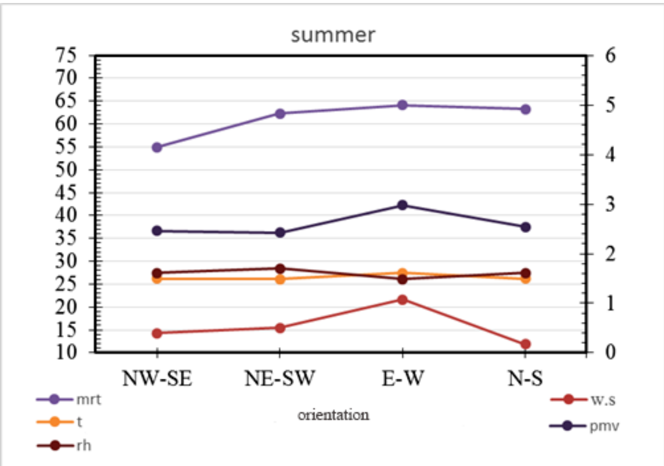

Fig 13. Correlations of Climatic Factors among Different Orientations in the Summer

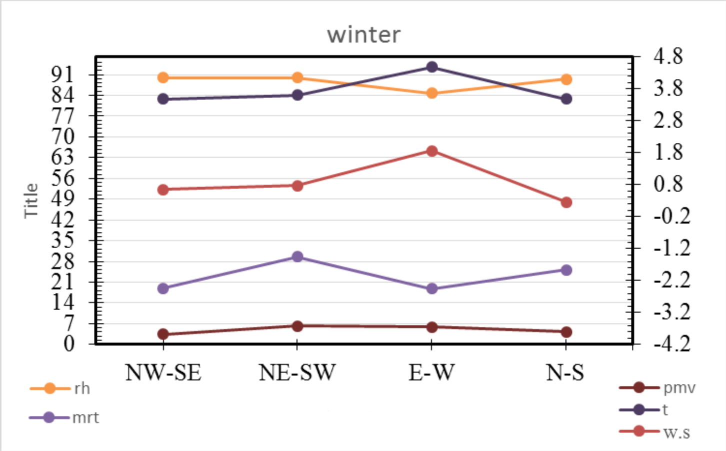

Fig 14. Correlations of Climatic Factors among Different Orientations in the Winter

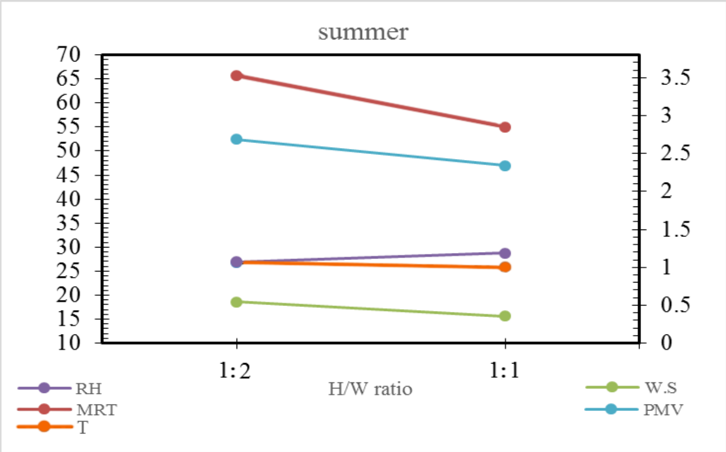

Fig 15. Comparison of PMV and Climatic Factors between Different H/W Ratios in the Summer

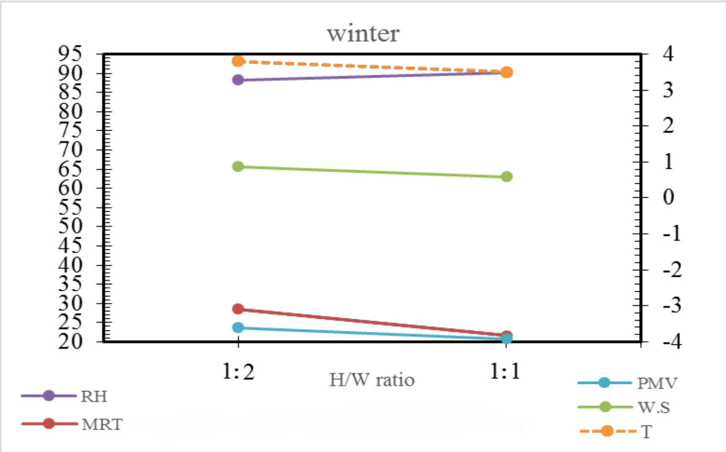

Fig 16. Comparison of PMV and Climatic Factors between Different H/W Ratios in the Winter

5. CONCLUSION

Urban layouts like other parts of cities play an important role in people's life, physically and mentally. In the present study, we attempted to improve outdoor thermal comfort by amending the morphological parameters, such as street networks, axis orientation, and H/W ratio in the historical layout of Tabriz. Three prototypes were established based on local criteria and limitations. The mentioned prototypes were simulated in Envi-met software, and the PMV factor was utilized as the outdoor thermal comfort index for evaluating the simulation outcomes. Consequently, the following highlighted points are achieved from the present study:

- The pattern with dominant NE-SW passages provides maximum thermal comfort both in the summer and winter.

• NE-SW and E-W orientations supply better thermal state and solar radiation during the cold seasons in the climate of Tabriz.

• NW-SE and NE-SW orientations could balance the solar radiation and improve the thermal circumstances during the hot seasons. This point is in line with previous findings (Ali-Toudert & Mayer, 2006b).

• The average H/W ratio in two types of passages demonstrates that the high amount of thermal comfort depends on the low range of the H/W ratio during the cold seasons. This point matches the prior findings (Johansson, 2006; Yin et al., 2019).

The highlighted results could be used as helpful guidelines for equivalent climate zones. Also, future works could concentrate on different locations, constructing different building heights and street widths, adding new layout patterns to find the most responsive circumstances, or assessing the chosen pattern on a detailed scale.

6. ACKNOWLEDGMENT

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AUTHOR (S) BIOSKETCHES

S. Sabouri., *Department of Architecture and Urban Design, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran*
Email*: s.sabouri@tabrizu.ac.ir*

N. Alinasab., *Department of Architecture and Urban Design, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran*
Email*: nfar.alinasab@gmail.com*

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