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Analysis of the Impact of Urban Building Blocks Orientation on Outdoor Thermal Comfort in Winter Cities Using ENVI-met

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Abstract

The increase in urbanization, building density in cities, and the excess of hard surfaces exacerbate the urban heat island effect, negatively impacting outdoor thermal comfort. It is anticipated that not only the abundance of structures but also the orientation of building blocks in space affects thermal comfort. In this study, four different orientation scenarios "0°, 45°, 90°, 135°" were analyzed using the ENVI-met 5.6.1 software model. The newly developed settlement area Yıldızkent, located in the development axis of the city center of Erzurum, was chosen as the study area. The study concluded that the street orientation at a 45° angle was the most suitable scenario in terms of thermal comfort for both winter and summer months. In this scenario analysis, a 1.0°C PET improvement for winter months was determined, positively affecting thermal comfort. It was determined that the orientation of building blocks has an impact on thermal comfort.

Keywords: *Building blocks, orientation, ENVI-met 5.6.1, cold climate, outdoor thermal comfort.*

Kış Kentlerinde Yapı Bloğu Yöneliminin Dış Mekân Termal Konfor Üzerine Etkisinin ENVI-met ile Analizi

Öz

Kentleşmenin artması kentlerdeki bina yoğunluğu, sert zemin fazlalığı kentsel ısı ada etkisini arttırmakta ve bu da dış mekan termal konforu olumsuz yönde etkilemektedir. Sadece yapı fazlalığı değil aynı zamanda yapı bloklarının mekandaki yönlenmesinin de termal konforu etkilediği öngörülmektedir. Yapılan bu çalışmada ENVI-met 5.6.1 yazılım modeli kullanılarak 4 farklı açıda yönelim senaryosu "0°, 45°, 90°, 135°" çalışılmıştır. Çalışma alanı olarak Erzurum kent merkezinde gelişme aksında yer alan, yeni yerleşim yeri Yıldızkent tercih edilmiştir. Çalışma sonucunda 45° açılı cadde yöneliminin hem kış hem yaz ayı için termal konfor açısından en uygun senaryo olduğu tespit edilmiştir. Bu senaryo analizinde kış ayları için 1.0 C°'lik bir PET iyileşmesi olduğu ve termal konforu olumlu yönde etkilediği belirlenmiştir. Yapı bloğu yönlenmesinin termal konfor üzerinde etkisi olduğu belirlenmiştir.

Anahtar kelimeler: *Yapı blokları, yönelim, ENVI-met 5.6.1, soğuk iklim, dış mekân termal konfor.*

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1. Introduction

Climate change has become a crisis manifesting itself globally today. In addition to climate change, cities also experience the urban heat island (UHI) effect, a localized increase in air temperature (Oke, 2002; Oke et al., 2017; He et al., 2021; Menteş et al., 2024). The urban heat island is defined as the temperature difference between urban and rural areas (Salvati & Kolokotroni, 2023). The rise in temperature is more pronounced in urban areas due to factors such as building density, the prevalence of hard surfaces, the placement and orientation of buildings, the direction of wind, and the lack of green spaces (Yılmaz et al., 2018; Yılmaz et al., 2022; Potchter et al., 2022). Especially in summer, the absorption and reflection of heat on hard surfaces make the urban heat island effect more noticeable (Salvati et al., 2019). Global warming has led to more frequent and intense extreme heat events, with prolonged heat waves threatening the sustainable development of urban areas and human societies. Between 2001 and 2020, global surface temperatures increased by 0.99°C compared to the period from 1850 to 1900 (IPCC, 2021). Global warming has become a major issue for cities (He et al., 2021; Yılmaz et al., 2023).

There are numerous studies and software developed to improve outdoor thermal comfort. Since 2017, a total of 165 thermal indices have been developed to address this issue (De Freitas & Grigorieva, 2017). A review study determined that in the last five years, simulation software was used in 77% of studies aimed at improving outdoor thermal comfort, with Physiological Equivalent Temperature (PET)-ENVI-met being the preferred choice (Tsoka et al., 2018). Alternative scenario applications have shown that outdoor thermal comfort conditions can be improved with designs that consider the natural features of the space (Blazejczyk et al., 2012; Santamouris, 2020; Jamali et al., 2021).

Urban environments also affect wind speed and direction. The roughness of the urban surface reduces wind speed by 20% to 30% and increases turbulence intensity by 50% to 100% when moving from rural to urban areas (Ghiaus et al., 2005). By changing the free-flow speed over buildings, the reduction in average wind speed at pedestrian level is even higher, reaching up to 60% in densely urban areas (Orme et al., 1998; Palusci et al., 2022). The shape of the building and the geometric features of its surroundings (i.e., the ratio of street width and length to the height of buildings), street designs (Yılmaz et al., 2017) affect the airflow around buildings in cities, altering the potential for natural ventilation in buildings (Mei et al., 2017; Xie et al., 2020). The varying solar radiation depending on street and avenue orientation was tested in simulations with a 12° southeast orientation. The results showed that, particularly in high-rise east-west oriented buildings, the orientation resulted in a temperature increase on the northern façades, with the orientation increasing the ambient temperature by an average of 0.5°C during the winter period (Yavaş & Yılmaz, 2019).

The thermal environment of a street block is influenced by factors such as the Sky View Factor (SVF), street orientation, street aspect ratio, and other factors (Watson & Johnson, 2010). SVF explains the impact of the spatial pattern of urban street canyons on the urban physical environment from an energy transfer perspective; it is an important quantitative index for defining urban geometry. Today, scientists generally agree that SVF is a significant parameter affecting the microclimate, night heat island effect, thermal comfort, and air pollution in urban areas (Li et al., 2020; Cui et al., 2023). Various simulations using the ENVI-met software have analyzed alternative street canyon structures (Ali-Toudert & Mayer, 2006-2007; Acero et al., 2021; Sun et al., 2022), the relationship between building block orientations within urban spaces and thermal comfort (Song et al., 2023; Salameh et al., 2024; Sadeghian et al., 2024), and the impact on energy consumption (Peng et al., 2020).

From the studies related to street angles and ENVI-met: Ali-Toudert & Mayer (2006) investigated both the aspect ratios and orientations of streets in Algiers, which has an arid climate, to determine which are more suitable for thermal comfort. The study found that higher street height-to-width ratios and orienting the street in a NE-SW or NW-SE direction provided better thermal comfort conditions. Achour-Younsi & Kharrat (2016), in their study using the ENVI-met model in Tunisia, examined the impact of street canyon geometry and orientation on outdoor thermal comfort in the city. They determined that having the street oriented NW not only aligned with the prevailing wind direction but also facilitated air flow through the street, making it the most suitable orientation for thermal comfort.

Yılmaz et al. (2016), in their study in Dadaşkent, Erzurum, investigated the impact of different street orientations on thermal comfort during the winter months. They found that the NE-SW oriented street was the most suitable for winter outdoor thermal comfort, while the NS oriented street was the least suitable. Mutlu et al. (2018) examined the impact of street angles on thermal comfort in an area with various orientations in Erzurum. They analyzed angles of 0°, 22.5°, 45°, and 67.5° separately for the winter months and determined that the 45° oriented street provided the best thermal comfort.

The research area in Erzurum, located in a cold climate region according to the Köppen and Flee (1954) criteria, experiences extremely harsh winter conditions (Kottek et al., 2006). Erzurum has the potential to become a significant brand city due to its historical background and winter tourism opportunities. The city, which hosted the 2011 Winter Olympics, has substantial infrastructure facilities for winter tourism. With its two universities and a large number of students, outdoor thermal comfort is crucial in the city. Erzurum has approximately 650 hectares of urban renewal and transformation areas. Therefore, studies conducted for each micro-area are considered highly valuable.

In Erzurum, known for its cold climate, residential fuel consumption is the primary source of pollutant gas emissions. The heavy reliance on fossil fuels during the winter months exacerbates air pollution (Yılmaz et al., 2021). According to the 2020 World Air Quality Report, Turkey ranked 46th out of 106 countries, and Erzurum was highlighted as one of the top three cities with the highest air pollution levels in Turkey (WAQR, 2020).

These studies aim to develop design criteria that will improve outdoor thermal comfort and facilitate the creation of more comfortable living spaces. In this context, a neighborhood in the Yıldızkent area, which began developing after the 2000s, was selected. Within this neighborhood, a regular building block with existing structures was identified. Microclimate data from the study area were recorded using a device. The ENVI-met 5.6.1 software, used for simulation analyses in thermal comfort studies, was employed to analyze this building block. The study investigated the optimal orientation angle for building blocks in cold climate regions. Thus, the research sought to answer the question, "What orientation angle should building blocks have to improve outdoor thermal comfort conditions in cold climate cities?"

2. Material and Method

The city of Erzurum, one of the coldest cities in Turkey and situated at the highest elevation, was selected as the study area. Green space system scenarios with various proposals were implemented at the urban scale in the chosen study area. The coordinates of the study area are 39°54'19.77"N and 41°15'57.29"E. The selected study area is located in the Hüseyin Avni Ulaş neighborhood, specifically the Zabıta unit, which is part of the Palandöken district. Palandöken Municipality has a total population of 175,920, while the population of the neighborhood encompassing the study area is 46,118 (Anonymous, 2023).

The Zabıta station is located in the Yıldızkent area of Palandöken Municipality. A 514m x 480m area within this region, which includes residential complexes, was selected as the study area. The Zabıta station was chosen to be in the exact center of this area (Figure 1).

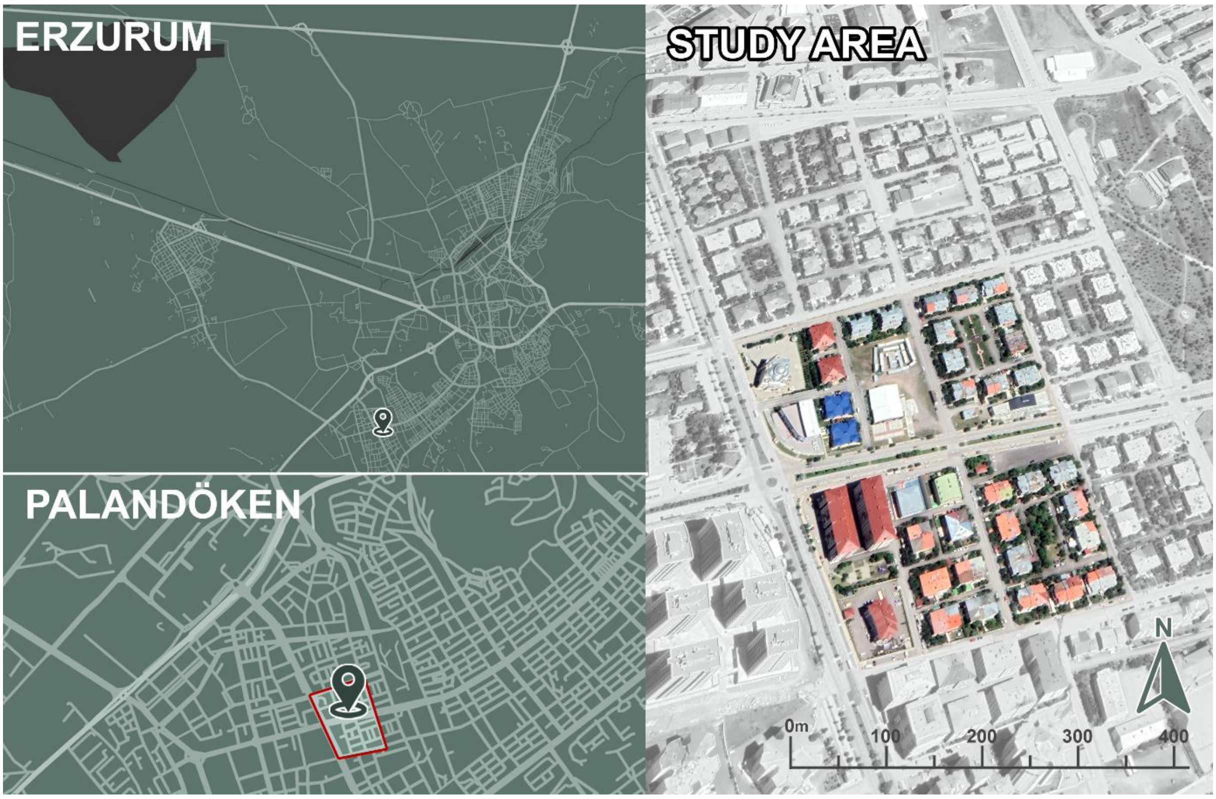

Figure 1. Location of the Yıldızkent study area and visual of the building block

Four different scenarios were created for the study area. The data for the areas positioned at four different angles within this building block were evaluated for both summer and winter months. The data include hourly air temperature (Ta-°C), humidity (RH-%), wind speed (m/s), Mean Radiant Temperature (Tmrt), and Physiological Equivalent Temperature (PET).

2.1. ENVI-met Scenarios

Four scenario designs were produced with different angles of building block orientations. The scenarios generated along with the existing condition are as follows:

Scenario 1: The building block orientation has an angle of 0°.

Scenario 2: The building block orientation has an angle of 45°.

Scenario 3: The building block orientation has an angle of 90°.

Scenario 4: The building block orientation has an angle of 135°.

Microclimate Data Measurement: A measurement device was installed in the garden of the Zabıta Building, which is determined to be publicly owned in the Yıldızkent settlement area. The recording device of this apparatus was placed inside the Zabıta Building and connected to electricity. The device is protected by an iron cage against potential hazards. Its calibration was performed in collaboration with a meteorological engineer from the manufacturing company (established under TÜBİTAK 1001-TOVAG project number 119O479) (Figure 2).

For the study area, the annual climate data collected by the Davis Vantage Pro-2 for the hottest and coldest days of 2021 were first recorded. According to the collected climate data, the coldest day was determined to be January 22, 2021, while the hottest day was July 21, 2021.

Figure 2. Measurement of microclimate data within the study area

The 24-hour climate data for these identified days were obtained and used for analysis in the ENVI-met program (Table 1). The current status of the study area was drawn in the ENVI-met 6.5.1 version program, and analyses at four different angles were conducted for these days.

Table 1. Data used in the ENVI-met 6.5.1 program

Location	Yıldızkent Settlement Area	
Climate Type	Mountain Ecosystem	
Simulation Time	January and July	
Total Simulation Duration	24 hours per alternative	
Spatil Resolution	2m x 2m x 2m	
Area Size	257m x 240m x 36m	
Model Angle	…	
	22.01.2021	**21.07.2021**
Basic Meteorological Inputs	Unshaded	Unshaded
Wind Speed (m/s)	0.18	0.6
Wind Direction (°)	234.37 °	225.0 °
24-Hour Air Temperature	+	+
24-Hour Relative Humidity	+	+
Lowest Air Temperature (°C)/h	-19.7 °C / 07:00	17.1 °C / 05:00
Highest Air Temperature (°C)/h	-10.4 °C / 14:00	32.6 °C / 16:00
Lowest Humidity	%68 / 14:00	%13 / 16:00
Highest Humidity	%84 / 07:00	%58 / 23:00
Sky View Factor	Open	Open

2.2. ENVI-met 5.6.1 Software

ENVI-met is a three-dimensional, non-hydrostatic microclimate model developed to calculate and simulate climate variables in urban areas, with a grid resolution ranging from 0.5 to 10 meters. Developed by Michael Bruse in 1993, it is a small-scale atmospheric adaptation capable of simulating surface air in an urban environment with up to 250 grids from a single building. The model takes into account total radiation, including direct, reflected, and diffuse solar radiation as well as long-wave radiation. By utilizing the laws of fluid dynamics and thermodynamics, it models the evolution of climate variables measured within the study area throughout the day. The ENVI-met model integrates the effects of buildings, orientation angles, vegetation, surface characteristics, soils, and climatic conditions to compute the state of the atmosphere (Bruse & Fleer 1998; Bruse, 1999).

To run a simulation, the user needs to create two files. The first is a field input file in *.INX format that contains all the necessary physical information about the area to be simulated. This file includes information about the dimensions of the simulation, building sizes and placements, materials of various surfaces, roads, vegetation, etc. The second is a *.SIM file that contains the climatic data at the start of the simulation and shows the results on the timeline. Climate data (temperature, humidity, wind speed, and direction) collected from mobile measurements or a fixed meteorological station are required to initiate a simulation in the ENVI-met 5.6.1 software and are stored in a *.SIM file. Practically, the minimum and maximum grid sizes for ENVI-met are 0.5x0.5 meters and 10x10 meters, respectively. The grid size varies depending on the required level of detail (Qaid & Ossen, 2015; Faragallah & Ragheb, 2022; Guo et al., 2023).

In this study, the building block in the area of the station, with dimensions of 514m x 480m, was analyzed using the ENVI-met 5.6.1 model. Each grid in the simulations represents a 2m x 2m area. The model consists of 2m grids in the Z direction, with the model height ending at 36 meters. The field input file (.INX) has 257 x 240 x 36 (x * y * z) grid cells, with a grid size of 514 x 480 x 72 meters and thus an area size of 246,720 m².

2.3. ENVI-met 5.6.1 Software Model Validation

In the study, the accuracy of the ENVI-met program's scenarios was assessed by comparing the data used in the program with the results obtained. This comparison was performed through accuracy analysis. The accuracy analysis compared the predicted data with observed data using R^2 (coefficient of determination), RMSE (root mean square error), MBE/MAE value, and d (agreement index). This validation method, developed by Willmott (1982), uses specific formulas for analysis. The MBE/MAE value should be between 0 and 1. A value of 1 or close to 1 indicates the accuracy of the model. In the analysis, high values of the agreement index (d) and coefficient of determination (R^2) represent the agreement of the data (Qaid et al., 2016; Yılmaz et al., 2021; Ertem Mutlu & Yılmaz, 2024).

For the current situation, when evaluating the measured and simulated air temperature data for the winter months, the R^2 value was 0.8129. A high R^2 value close to 1 indicates that the data agreement is high. The d value was 0.71, which, being close to 1, indicates the reliability of the simulation (Ertem Mutlu, 2023) (Figure 3).

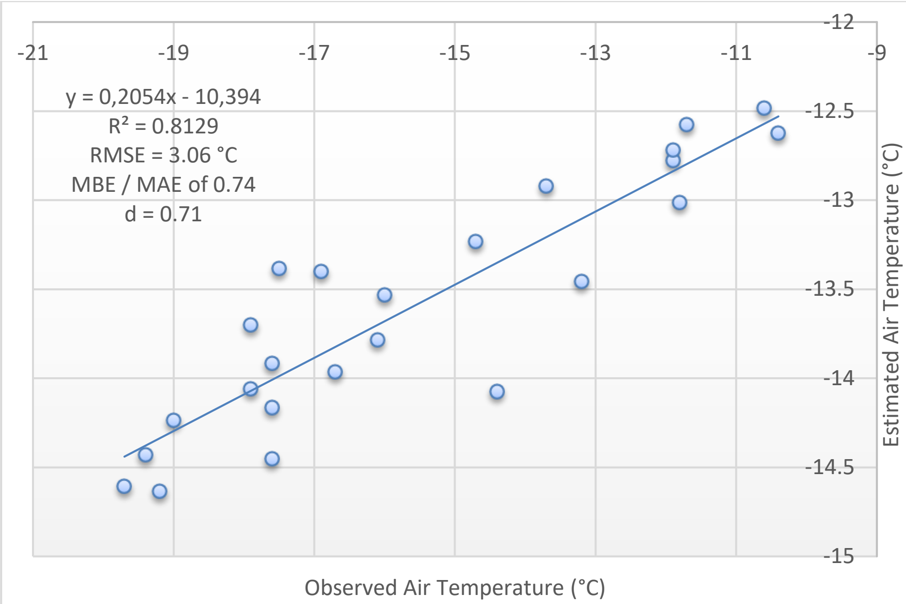

Figure 3. Scatter plot of predicted and observed air temperature data for winter accuracy analysis (Ertem Mutlu & Yılmaz, 2024)

For the summer months, the accuracy analysis of the current situation resulted in an R^2 value of 0.92. This high R^2 value shows that the data agreement is very high. The d value was 0.90, indicating the reliability of the simulation (Figure 4).

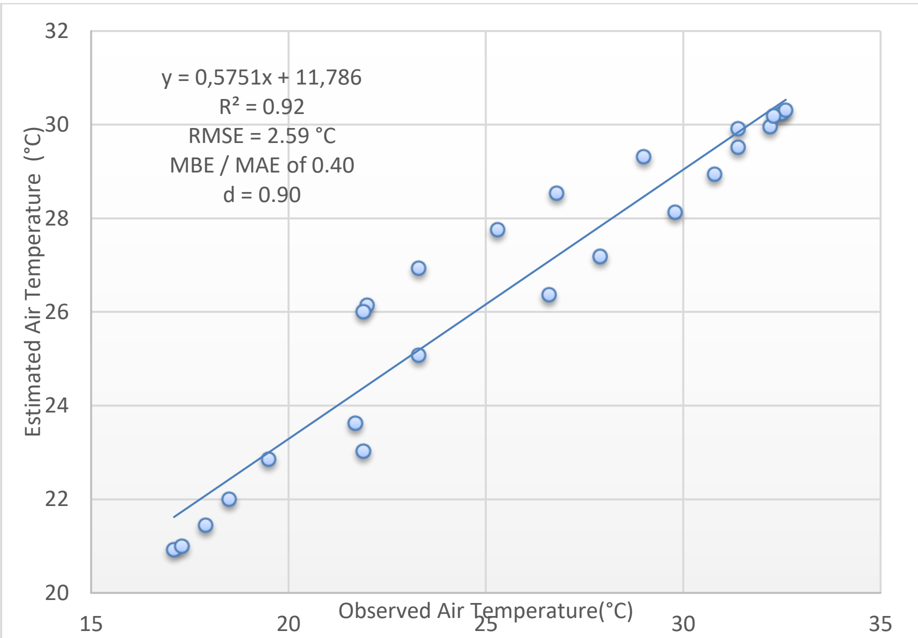

Figure 4. Scatter plot of predicted and observed air temperature data summer month accuracy analysis (Ertem Mutlu & Yılmaz, 2024)

According to the results, the ENVI-met software has been well validated with these data, and the study can be conducted using the software outputs. The meanings of the abbreviations in the formula 1 (Battista et al., 2016) are as follows:

d: Agreement index [–]

MAE: Mean Absolute Error [–]

MBE: Mean Bias Error [–]

ND: Number of data points analyzed [–]

Ō: Mean of the observed variable

Oj: Observed variables for each j instance

Pj: Model-predicted variables for each j instance

$$d = 1 - \left[\frac{\sum_{j=1}^{N_D} \left[(P_j - \bar{O}) - (O_j - \bar{O}) \right]^2}{\sum_{j=1}^{N_D} \left(|P_j - \bar{O}| + |O_j - \bar{O}| \right)^2} \right] \qquad (1)$$

$$MBE = \frac{\sum_{j=1}^{N_D} (P_j - O_j)}{N_D}$$

$$MAE = \frac{\sum_{j=1}^{N_D} |P_j - O_j|}{N_D}$$

3. Research Findings and Discussion

Within the Yıldızkent residential area, which extends to the north-northwest of Erzurum city center and the foothills of Mount Palandöken, four different ENVI-met analyses were performed on the identified building block. The analyses, conducted for both summer and winter months, were evaluated separately in terms of air temperature (°C), relative humidity (%), wind speed (m/s), Mean Radiant Temperature (Tmrt), and Physiological Equivalent Temperature (PET) for different orientation angles.

3.1. Analysis of Current Conditions for Summer and Winter Months

For the analysis of the current conditions of the area, the existing trees have been drawn to scale. A total of 868 plant species have been used in the area. Analyses for both summer and winter months have been conducted.

Looking at the winter analysis of the current conditions, the minimum air temperature was -12.5 °C, the maximum was 16.2 °C, and the average air temperature was 1.9 °C. In terms of humidity data, the minimum was 9.7%, the maximum was 144%, and the average was 76.9%. Regarding wind speed, the minimum was 0 m/s, the maximum was 0.15 m/s, and the average was 0.07 m/s. For the Mean Radiant Temperature (Tmrt) data, the minimum was -13.9 °C, the maximum was 20.5 °C, and the average was 3.3 °C. In the Physiological Equivalent Temperature (PET) data for winter, the minimum temperature was 2.6 °C, the maximum temperature was 13.9 °C, and the average was 8.3 °C.

Looking at the summer analysis of the current conditions, the minimum air temperature was 20.7 °C, the maximum was 33.1 °C, and the average air temperature was 26.9 °C. In terms of humidity data, the minimum was 14.4%, the maximum was 38.8%, and the average was 26.6%. Regarding wind speed, the minimum was 0 m/s, the maximum was 1.2 m/s, and the average was 0.6 m/s. For the Mean Radiant Temperature (Tmrt) data, the minimum was 38.3 °C, the maximum was 64.8 °C, and the average was 51.6 °C. In the Physiological Equivalent Temperature (PET) data for summer, the minimum temperature was 36.5 °C, the maximum temperature was 57.4 °C, and the average temperature was 47 °C.

3.2. Thermal Comfort Analysis of the Building Block in the "0° Angle Position"

When analyzing the winter conditions of the building block at the 0° position, the air temperature was found to have a minimum of -12.5 °C and a maximum of 16.2 °C. No variability was observed in air temperature compared to the current conditions. In terms of humidity data, the minimum was 9.7%, the maximum was 144.3%, and the average was 77%. The maximum value increased by 0.3 compared to the current conditions, which also raised the average value by 0.15. Looking at wind speed data, the minimum was 0 m/s, the maximum was 0.18 m/s, and the average was 0.09 m/s. While the minimum remained unchanged for the winter, the maximum increased by 0.3 m/s compared to the current conditions. The Mean Radiant Temperature (Tmrt) data showed a minimum of -14.1 °C, a maximum of 20.3 °C, and an average of 3.1 °C. In the winter analysis compared to the current conditions, the minimum and maximum temperatures decreased by 0.2 °C. For the Physiological Equivalent Temperature (PET), the winter minimum was -2.8 °C, the maximum was 9.4 °C, and the average was 3.3 °C. Compared to the current conditions, the minimum temperature in winter decreased by 5.4 °C, and the maximum decreased by 4.5 °C.

When looking at the summer analysis at the 0° position, the minimum air temperature was 20.7 °C and the maximum was 33.3 °C. While the minimum temperature remained unchanged compared to the current conditions, there was a 0.2 °C increase in the maximum temperature. In terms of humidity data, the minimum was 14.4%, the maximum was 38.8%, and the average was 26.6%. No changes were observed for the summer conditions compared to the current state. For wind speed data, the minimum was 0 m/s, the maximum was 1.44 m/s, and the average was 0.7 m/s. The minimum remained unchanged, while the maximum increased by 0.28 m/s compared to the current conditions. Looking at the Mean Radiant Temperature (Tmrt), the minimum was 38.4 °C, the maximum was 65.1 °C, and the average was 51.8 °C. Compared to the current conditions, the minimum increased by 0.1 °C, and the maximum increased by 0.3 °C. For the Physiological Equivalent Temperature (PET), the minimum was 33.2 °C, the maximum was 52.9 °C, and the average was 43 °C. Compared to the current conditions, the minimum decreased by 3.3 °C, and the maximum decreased by 4.5 °C.

3.3. Thermal Comfort Analysis of the Building Block in the "45° Angle Position"

The study area was positioned at a 45° angle, and this condition was analyzed for both summer and winter months. When looking at the winter analysis at the 45° position, the air temperature had a minimum of -12.4 °C and a maximum of 16.2 °C. Compared to the current conditions, a 0.1 °C increase was observed in the minimum temperature, while no variability was noted in the maximum temperature. In terms of humidity data, the minimum was 9.7%, the maximum was 143.1%, and the average was 76.4%. The minimum value remained unchanged compared to the current conditions, while the maximum value decreased by 0.9. For wind speed data, the minimum was 0 m/s, the maximum was 0.14 m/s, and the average was 0.07 m/s. The minimum remained unchanged for winter conditions, while the maximum decreased by 0.01 m/s compared to the current conditions. The Mean Radiant Temperature (Tmrt) showed a minimum of -8.3 °C, a maximum of 5.9 °C, and an average of -1.2 °C. In the winter analysis compared to the current conditions, the minimum temperature increased by 5.6 °C, while the maximum decreased by 14.6 °C. For the Physiological Equivalent Temperature (PET), the minimum was 3.6 °C, the maximum was 14.3 °C, and the average was 9 °C. Compared to the current conditions, the minimum temperature increased by 1 °C, and the maximum increased by 0.4 °C.

When examining the summer analysis at the 45° position, the minimum air temperature was 20.7 °C, and the maximum was 33.1 °C. No variability was observed in air temperature compared to the current conditions. In terms of humidity data, the minimum was 23.9%, the maximum was 40.5%, and the average was 32.2%. Compared to the current conditions, the minimum increased by 9.5, and the maximum increased by 1.7 for the summer months. For wind speed data, the minimum was 0 m/s, the maximum was 0.94 m/s, and the average was 0.5 m/s. The minimum remained unchanged, while the maximum decreased by 0.22 m/s compared to the current conditions. The Mean Radiant Temperature (Tmrt) had a minimum of 38.3 °C, a maximum of 64.8 °C, and an average of 51.6 °C. No changes were observed compared to the current conditions. For the Physiological Equivalent Temperature (PET), the minimum was 36.4 °C, the maximum was 57.5 °C, and the average was 47 °C. Compared to the current conditions, the minimum decreased by 0.1 °C, while the maximum increased by 0.1 °C.

3.4. Thermal Comfort Analysis of the Building Block in the "90° Angle Position"

For the winter analysis at the 90° angle, the air temperature showed a minimum of -12.6 °C, a maximum of -10.2 °C, and an average of -11.4 °C. Compared to the current conditions, the minimum temperature decreased by 0.1 °C, while the maximum temperature experienced a significant drop of 26.4 °C. In the humidity analysis, the minimum was 70.3%, the maximum was 145%, and the average was 107.7%. Compared to the current conditions, the minimum increased by 60.6, and the maximum increased by 1. Rüzgar hızı data indicated a minimum of 0 m/s, a maximum of 0.15 m/s, and an average of 0.07 m/s. There were no changes compared to the current conditions. For the Mean Radiant Temperature (Tmrt), the minimum was -14 °C, the maximum was 20.5 °C, and the average was 3.25 °C. In comparison with the current conditions, the minimum temperature decreased by 0.1 °C, while no changes were observed in the maximum temperature. For the Physiological Equivalent Temperature (PET), the minimum was 2.6 °C, the maximum was 13.5 °C, and the average was 8.1 °C. Compared to the current conditions, the minimum temperature remained unchanged, while the maximum decreased by 0.4 °C.

In the summer analysis at the 90° angle, the air temperature showed a minimum of 30 °C, a maximum of 33.3 °C, and an average of 31.7 °C. Compared to the current conditions, there was a 9.3 °C increase in the minimum temperature and a 0.2 °C increase in the maximum temperature. For the humidity analysis, the minimum was 14.4%, the maximum was 25.4%, and the average was 19.9%. Compared to the current conditions, there was no change in the minimum value, but the maximum decreased by 13.4. Wind speed data indicated a minimum of 0 m/s, a maximum of 0.93 m/s, and an average of 0.5 m/s. There were no changes in the minimum value, while the maximum decreased by 0.23 m/s. For the Mean Radiant Temperature (Tmrt), the minimum was 38.4 °C, the maximum was 65.2 °C, and the average was 51.8 °C. Compared to the current conditions, the minimum increased by 0.1 °C, and the maximum increased by 0.4 °C. For the Physiological Equivalent Temperature (PET), the minimum was 36.4 °C, the maximum was 57.5 °C, and the average was 47 °C. Compared to the current conditions, the minimum temperature decreased by 0.1 °C, while the maximum increased by 0.1 °C.

3.5. Thermal Comfort Analysis of the Building Block in the "135° Angle Position"

In the winter analysis at the 135° angle, the air temperature recorded a minimum of -12.5 °C, a maximum of -9.9 °C, and an average of -11.2 °C. Compared to the current conditions, there was no change in the minimum temperature, while the maximum temperature experienced a significant decrease of 26.1 °C. For humidity, the minimum was 70.4%, the maximum was 144.6%, and the average was 107.5%. In comparison to the current conditions, the minimum increased by 60.7, and the maximum increased by 0.6. Wind speed data indicated a minimum of 0 m/s, a maximum of 0.15 m/s, and an average of 0.07 m/s, showing no changes compared to the current conditions. The Mean Radiant Temperature (Tmrt) was recorded at a minimum of -8.4 °C, a maximum of 6.3 °C, and an average of -1.1 °C. Compared to the current conditions, the minimum temperature increased by 5.5 °C, while the maximum decreased by 14.2 °C. For the Physiological Equivalent Temperature (PET), the minimum was 3.9 °C, the maximum was 8.9 °C, and the average was 6.4 °C. Compared to the current conditions, the minimum increased by 1.3 °C, while the maximum decreased by 5 °C.

In the summer analysis at the 135° angle, the air temperature showed a minimum of 30 °C, a maximum of 33.6 °C, and an average of 31.8 °C. There was a 0.3 °C increase in the minimum temperature and a 0.5 °C increase in the maximum temperature compared to the current conditions. For humidity, the minimum was 14.4%, the maximum was 25.5%, and the average was 20%. There was no change in the minimum, but the maximum decreased by 13.3 units compared to the current conditions. Wind speed data indicated a minimum of 0 m/s, a maximum of 1.21 m/s, and an average of 0.6 m/s. There were no changes in the minimum, while the maximum increased by 0.05 m/s. For the Mean Radiant Temperature (Tmrt), the minimum was 38.4 °C, the maximum was 64.9 °C, and the average was 51.7 °C, with a 0.1 °C increase in both minimum and maximum temperatures compared to the current conditions. For the Physiological Equivalent Temperature (PET), the minimum was 36.4 °C, the maximum was 57.5 °C, and the average was 47 °C, showing a decrease of 0.1 °C in the minimum and an increase of 0.1 °C in the maximum compared to the current conditions.

For the winter season, the maximum relative humidity at the 45° angle decreased by 0.9 units, indicating a positive outcome for thermal comfort (Figure 5). In the summer, the scenario with the best results for relative humidity was also the 45° angle position, where the minimum humidity was 9.5 units higher and the maximum was 1.7 units higher, positively affecting thermal comfort (Figure 6).

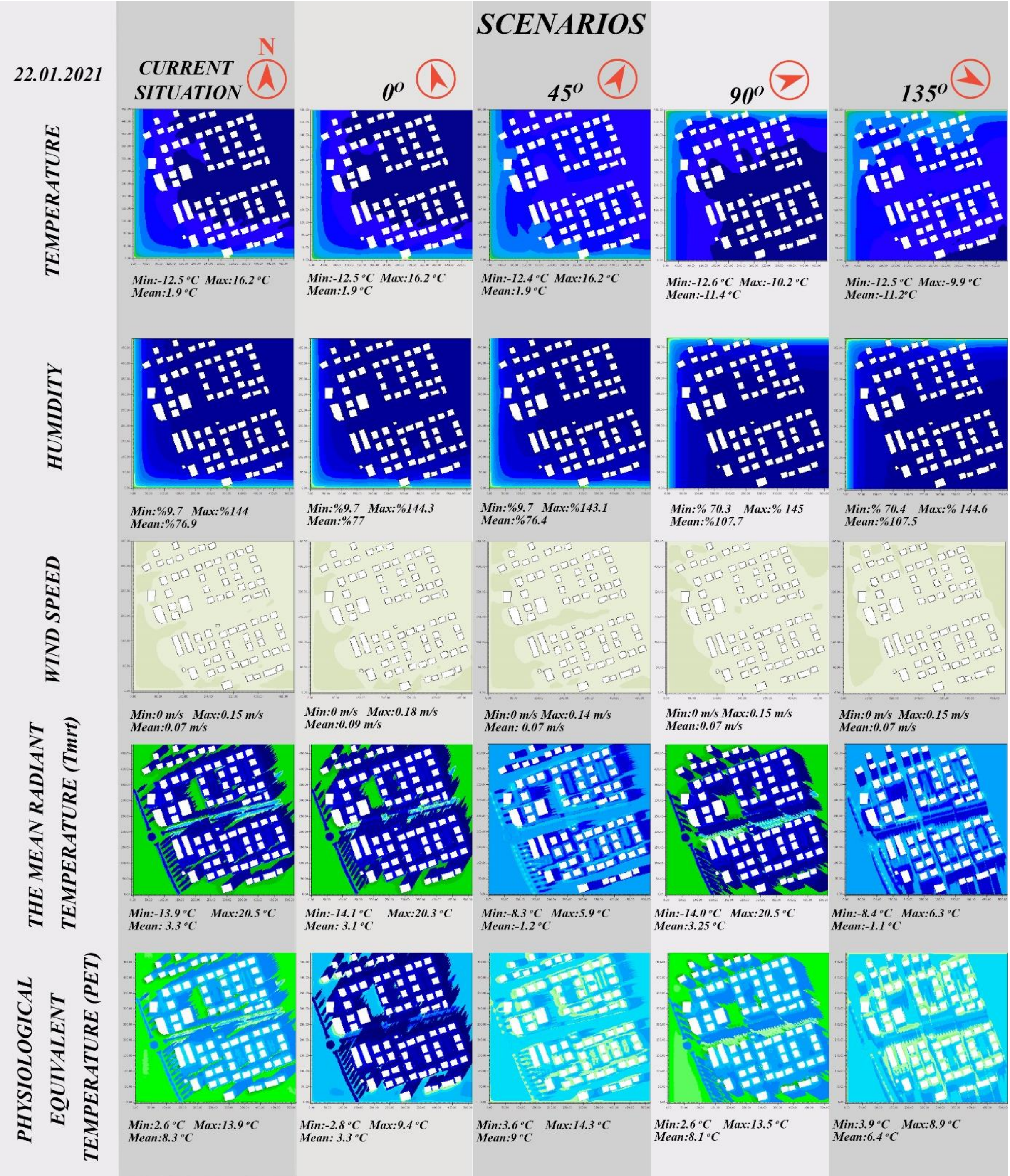

Figure 5. Winter analyses of building blocks at different angles

Figure 6. Summer analyses of building blocks at different angles

Looking at the *wind speed* data, the scenario that provides the best result for the winter months is the 45° angle scenario. While there is no change in the minimum, the maximum wind speed has decreased by 0.1 m/s. The low wind speed in winter makes the effect of cold weather less noticeable (Figure 5). For the summer months, the scenario that yields the best result is the 0° angle scenario. There is no change in the minimum, but the maximum wind speed has increased by 0.2 m/s. The high wind speed in summer creates a more comfortable environment in hot weather in terms of thermal comfort (Figure 6).

When examining the *Tmrt* analyses, no scenario has been identified that yields better results for winter compared to the current situation. On the contrary, Tmrt has decreased significantly at the 45° and 135° angles. This can be seen in Figure 5, where the colors are bluer. In Tmrt analyses for summer, no scenario has been identified that provides better results compared to the current situation (Figure 6).

Looking at the ***PET*** analyses, the scenario that yields the best result for winter is the 45° angle scenario. Compared to the current situation, the temperature has increased by 1 °C at the minimum and by 0.4 °C at the maximum. This has had a positive effect on thermal comfort (Figure 5). In summer PET analyses, the scenario that provides the best result is the 0° angle scenario. Compared to the current situation, the temperature has decreased by 3.3 °C at the minimum and by 4.5 °C at the maximum (Figure 6).

When analyzing the building blocks according to their angles, the scenario that provides the best thermal result for both summer and winter months is the one positioned at a 45° angle. While there are not many changes in angle variations for winter, the best thermal result for summer in terms of PET values has been found at a 0° angle. In other parameters, there have not been significant changes compared to the current situation for both winter and summer months (Table 1). The minimum and maximum values of the identified climate data for building blocks at different angles are presented in Table 2.

Table 2. Air temperature, relative humidity, wind speed, Tmrt, and PET analyses for winter and summer at different building block angles

Air Temperature (°C)				
	WINTER		**SUMMER**	
Scenarious	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Current situation	-12.5	16.2	20.7	33.1
0°	-12.5	16.2	20.7	33.3
45°	-12.4	16.2	20.7	33.1
90°	-12.6	-10.2	30.0	33.3
135°	-12.5	-9.9	30.0	33.6
Air Humidity (%)				
Scenarious	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Current situation	9.7	144	14.4	38.8
0°	9.7	144.3	14.4	38.8
45°	9.7	143.1	23.9	40.5
90°	70.3	145	14.4	25.4
135°	70.4	144.6	14.4	25.5
Wind Speed (m/s)				
Scenarious	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Current situation	0	0.15	0	1.2
0°	0	0.18	0	1.44
45°	0	0.14	0	0.94
90°	0	0.15	0	0.93
135°	0	0.15	0	1.21
The Mean Radiant Temperature (Tmrt) (°C)				
Scenarious	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Current situation	-13.9	20.5	38.3	64.8
0°	-14.1	20.3	38.4	65.1
45°	-8.3	5.9	38.3	64.8
90°	-14.0	20.5	38.4	65.2
135°	-8.4	6.3	38.4	64.9
Physiologically Equivalent Temperature (PET) (°C)				
Scenarious	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Current situation	2.6	13.9	36.5	57.4
0°	-2.8	9.4	33.2	52.9
45°	3.6	14.3	36.4	57.5
90°	2.6	13.5	36.4	57.5
135°	3.9	8.9	36.4	57.5

Based on the results of this study, the most suitable angle for thermal comfort is determined to be 45°. In a study conducted by Mutlu et al. (2018) in a different settlement area in Erzurum, the most suitable angles for air temperature in winter were found to be 45° and 0°. It was noted that the 45° angle is more favorable for thermal comfort in terms of benefiting from sunlight. De & Mukherjee (2016) investigated bioclimatic comfort by applying different angles in residential buildings and found that the best thermal comfort was achieved with a 30° angle. This angle was seen to improve thermal comfort by facilitating wind flow into the area. Additionally, in a study conducted by Yılmaz et al. (2018) in certain streets of Erzurum, the ideal street orientation was determined to be northeast-southwest. It was emphasized that each study area should be evaluated according to its own criteria.

This study has shown that street orientation affects the temperature and PET values of buildings, particularly during the summer months. The highest value obtained for winter was 14.3°C PET from the 45° simulation. In the scenario analysis, the building block with a 45° angle was found to have street orientations in the Northeast-Southwest and Northwest-Southeast directions. Similarly, in a study conducted for a similar area, it was determined that Northeast and Southwest orientations are more suitable for thermal comfort. The East-West orientation was less preferred due to a significant portion of building facades being in shadow during winter (Yavaş & Yılmaz, 2019). This suggests that paying attention to street orientation in new settlement areas will impact thermal comfort. In this research, the PET value for winter increased from 2.6°C in the current situation to 3.6°C in the 45° building block simulation, showing a 1.0°C improvement and positively affecting thermal comfort. A study has also shown that outdoor thermal comfort can be increased up to 2.0°C during winter with microclimate solutions obtained from the area and ENVI-met simulation analyses. Furthermore, it was emphasized that in North-South oriented streets, attention should be paid to the distances between buildings, and if possible, orientations towards the Southeast should be considered (Yavaş & Yılmaz, 2020). However, these studies may yield different results under various microclimate conditions, and numerous parameters influencing thermal comfort are also involved (Acero et al., 2021). A study conducted in a hot and arid city in Iran determined that the most suitable PET range is between 24.5°C and 29.8°C (Narimani et al., 2022). Therefore, simulations should be conducted for each development area to determine the most suitable conditions. It is emphasized that comparing values from different areas is not appropriate in this context (Morakinyo et al., 2019).

The highest wind speed for winter was found to be 0.18 m/s for the 45° angle block. This angle block also showed better PET values compared to other angle orientations. A similar study has determined that urban form and building density affect the thermal environment. Additionally, the thermal environment is influenced by humidity and wind speed (Huang et al., 2020). In terms of wind, in cities with cold climates, street orientations should be designed to align with wind directions to enhance the effect of prevailing northern winds. Especially in cities experiencing significant air pollution during winter, it is important to increase the impact of wind. Indeed, in this study, street orientations in building blocks with 45° and 135° angles correspond to long-term wind data of Erzurum city center (MGM, 2020). The highest PET value for winter was calculated as 3.9°C in the 135° angle block. For Erzurum city, it has been suggested to open air corridors parallel to the prevailing southwest and northwest wind directions on a macro scale.

Regarding humidity, the lowest maximum value of 143.1% for winter and the highest maximum value of 40.5% for summer were calculated for the 45° angle block. High humidity in summer and low humidity in winter have been found to be advantageous for thermal comfort in cold climate cities (Yin et al., 2021). It was determined that humidity and wind speed showed similar results in some scenarios and did not create significant changes. Indeed, a study found that surfaces in scenarios did not significantly affect wind speed up to a certain size (Yücekaya et al., 2022).

ENVI-met Model's Limiting Conditions: In ENVI-met simulation studies, it is possible to encounter restrictive issues. For Erzurum, where winters are typically snowy, the margin of error in simulation data is high (Liu et al., 2018; Ma et al., 2019; Yılmaz et al., 2021a). Additionally, the accuracy of the ENVI-met software decreases when wind speeds are below 1.0 m/s. This error during simulations is also explained within the ENVI-met software (ENVI-met Software, 2024). Some studies using ENVI-met have also noted that if wind speeds are less than 2.0 m/s, the software does not provide the desired results for wind analysis (Song et al., 2014; Acero & Arrizabalaga, 2018). Despite this, it is noted as one of the most widely used software models for outdoor thermal comfort studies (Salata et al., 2017;

Salameh et al., 2024). However, due to its limited options, the software is subject to scrutiny, and development and updates are ongoing (ENVI-met 5.6.1).

4. Conclusion and Suggestions

The study demonstrated that the orientation of building blocks affects outdoor thermal comfort values. ENVI-met scenario analyses were conducted for different orientations based on microclimate data collected throughout the year, including the hottest and coldest days. According to the analyses, the best outdoor thermal comfort was achieved with a 45° orientation for both summer and winter. In winter, an improvement of 1.0°C in thermal comfort was observed. The advantageous orientation was identified as the Northeast-Southwest and Northwest-Southeast directions for optimal thermal comfort.

This study shows that the orientation of building blocks influences air temperature and PET values during summer. This highlights the importance of considering street orientation in new development areas to affect outdoor thermal comfort. It was concluded that design criteria developed for cold climate regions may not be suitable for every settlement area and should be combined with locally specific data.

In winter, the highest wind speed of 0.18 m/s was found in the block with a 45° orientation. During summer, the building blocks with 45° and 90° orientations had the lowest wind speeds. However, the 45° oriented blocks had the highest humidity value at 32.2%. This is due to the dominant wind direction coming at an angle rather than parallel to main avenues and streets, preventing the existing vegetation from removing the moisture from the area. As a result, humidity levels reached their highest point. In contrast, the 90° oriented blocks had low wind speeds but managed to remove moisture from the area due to the dominant wind direction being parallel to the main avenue, resulting in the lowest humidity scenario. The dominant wind direction in building blocks is one of the most significant factors affecting humidity. This indicates that paying attention to the dominant wind direction in designs is crucial for thermal comfort.

The development of climate-sensitive design principles based on simulations and their guidance for future development planning decisions is considered a significant factor. For winter-centric cities like Erzurum, these urban design solutions aim to provide guidance during the implementation process.

For the city of Erzurum, sustainable designs and improvements in thermal comfort environments, which can be used as inputs in transformation areas, are of great importance. The ability of the city's population to live comfortably in winter conditions is directly related to the improvement of the city's thermal comfort values. Analyzing climate values with accurate methods and translating them into physical planning decisions is crucial for enhancing urban livability conditions, even in cities with extreme climate conditions.

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The first author contributed 80% and the second author contributed 20% to the article. The authors declare that there is no conflict of interest.

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