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Orginal Article

Thermal stress comfort in a contemporary housing district in a moderate climate zone, Lublin as a case study

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Abstract: Urban climate and its impact on the thermal comfort of residents are significant aspects in urban planning and the design of housing estates. The aim of this article is to investigate the temperature perception among residents in a contemporary residential area in Lublin during the hottest day, utilising an advanced computer simulation tool – the ENVI-met programme. A modern, densely built housing estate with no significant greenery was selected as a case study. General meteorological and spatial data were used for calibrating the housing estate model within the software. The housing estate model within the programme was calibrated using publicly available meteorological and spatial data, and computer simulations were conducted for Lublin's hottest day on 22 July 2022. Based on these simulations, the Universal Thermal Climate Index (UTCI) was calculated. The research results indicate that people experience moderate thermal stress in unshaded areas only at 4:00 pm, while in sunny locations, they experience strong to very strong heat stress throughout the day. This article underscores the importance of computer simulations in analysing the urban microclimate and provides insights into tools that can be used in urban planning and housing estate design processes, with the aim of creating more comfortable and environmentally friendly urban environments.

Keywords: climate change, housing estates, UTCI, ENVI-met

1. Introduction

Urban climate and its impact on residents' quality of life have become increasingly important considerations in the context of city development and the growing number of real estate investments. Urbanisation, especially in densely populated housing developments, can significantly influence the urban microclimate, which in turn has a profound impact on thermal comfort and residents' health [1]. In recent years, research into the influence of the urban climate on thermal comfort has been the subject of intensive scientific studies.

Extremely variable thermal conditions, such as summer heatwaves or cold winter days, can greatly affect the quality of life [2].

The United Nations Sustainable Development Goals, established in 2015 as a global agenda for the planet's future, are a key aspect in considering urban planning, housing estate design, and residents' quality of life [3]. Many real estate development companies strive to create sustainable communities and incorporate sustainable development aspects into their activities. Real estate developers, as key participants in the construction and development of housing estates, play a significant role in creating living spaces that impact residents' comfort and quality of life. In the context of Environmental, Social, and Governance (ESG) reporting, developers are increasingly attempting to address sustainable development aspects, both in the environmental, social, and governance areas [4].

Thermal comfort, as a category assessing residents' thermal sensations, is important in housing estates, influencing their quality of life, health, and overall comfort [5], [6]. Variations in ambient temperature have a considerable impact on residents' well-being and daily productivity, both during extreme heatwaves and cold periods [7]. Optimal building placement, green spaces, shading, water availability, well-implemented thermal insulation, and ventilation methods are crucial in minimising extreme thermal sensations and ensuring more comfortable living conditions in residential areas. Caring for thermal comfort not only contributes to improving residents' quality of life but also enhances the attractiveness and property value [8]. Modern, sustainable communities that adapt to thermal comfort needs are becoming increasingly desirable in society.

The aim of this article is to analyse residents' temperature perception in a modern housing estate and determine during which hours of the hottest day of the year they experience thermal comfort and when they undergo thermal stress in the neighbourhood space. The study was conducted on 22 July 2022, utilising an advanced computer simulation tool, the ENVI-met program. Based on simulations to explore perceived temperature, the Universal Thermal Climate Index (UTCI) was calculated. The research was conducted as a case study on a housing estate in Lublin, Poland.

1.1. Literature review

Urban climate and its impact on the thermal comfort of residents have become subjects of growing interest for researchers and urban planners worldwide. In recent years, numerous studies have focused on analysing the urban climate and its influence on human life in urbanised areas. The direct impact of climate change on public health is linked to changes in mortality rates resulting from exposure to extreme ambient temperatures [9]. Each year, various regions around the world report cases of deaths associated with extreme weather conditions, including both heatwaves and cold temperatures. The elderly population is the most vulnerable group in these situations [10]. Without adequate societal adaptations to changing climatic conditions, it is projected that by 2050, heat-related deaths may increase by approximately 257% [11]. Air temperature and atmospheric carbon dioxide (CO2) levels are significantly higher in urban areas compared to rural ones, making urban dwellers more susceptible [12]. This urban-rural difference is due to changes in air pressure arising from variations in air density and mass, which are linked to excessive heat in urban areas generated by factors such as solar radiation, heat retention by urban surfaces, and heat produced in industrial and technological processes. In conditions of weak atmospheric circulation, especially during periods of low wind and calm weather, the phenomenon known as the urban heat island (UHI) is formed [13], [14]. The warming of urban areas can be attributed to the noticeable excess heat generated by rapidly heating urban surfaces, including buildings, asphalt, bare soil, and low vegetation. During the summer, symptoms related to daily warming can manifest in the morning hours and result in temperatures about 10°C higher than those in nearby forests [15]. Modern cities are characterised by dense urban development, extensive land paving, and limited greenery, and the more urbanised an area is, the more pronounced the urban heat island effect becomes [16].

Thermal comfort is a key aspect of residents' quality of life. Increasing thermal discomfort is associated with a growing burden that affects the cardiovascular and respiratory systems. It's worth noting that tolerance to extreme temperatures is determined by several individual characteristics, including age, physical fitness, gender, acclimatisation level, body morphology, and the amount of body fat. Among these factors, age and physical fitness level are key predictors showing strong correlations [17], [18]. Advanced age and low physical fitness are linked to limited cardiovascular reserves, resulting in reduced tolerance to thermal changes [19]. A person exposed to higher temperatures becomes less productive, affecting the quality of work performed [20]. Extreme temperatures can also lead to health issues, such as heat-related illnesses or heat strokes, especially in individuals over 60 years of age and those with obesity, cardiovascular diseases, diabetes, and respiratory diseases [21].

For this reason, researchers and urban planners focus on identifying areas with the most significant thermal changes and developing remedies to improve thermal comfort in the city. Various indicators are used to assess thermal comfort, such as the Heat Index (HI), Physiological Equivalent Temperature (PET), and others. However, the UTCI index better represents specific climates, weather conditions, and locations. UTCI demonstrates significant sensitivity to fluctuations in surrounding factors, including temperature, sunlight, wind speed, and air humidity. Compared to other indicators, the UTCI index is more capable of accurately reflecting dynamic changes in thermal conditions. The UTCI scale has the ability to record even small differences in the intensity of meteorological factors [22]. The UTCI index is defined as the ambient temperature (expressed in degrees Celsius) that, under reference conditions, elicits the same physiological response in a reference person as the real environment [23].

The UTCI index, as a bioclimatic indicator, has the capacity to capture both thermal fluctuations in the bioclimate of Europe and correlate these changes with their impact on human health [24]. The UTCI index is utilised in biometeorological forecasts, with the Institute of Meteorology and Water Management in Warsaw issuing biometeorological predictions based on the UTCI index [25]. Similar research to that presented in this article was conducted by a group of researchers from Lublin during a heatwave in August 2015. The study focused on the temperature perception according to the UTCI index for several days [26]. Many articles have highlighted the crucial role of wind in temperature perception [27], [28]. In urbanised areas, the discomfort zones exhibit significant variability over time. Ongoing efforts are being made to standardise wind comfort criteria [29]. Various alternative criteria are proposed for use in urban planning to compare different design solutions [30]. The UTCI index is employed in various other studies, including assessing the susceptibility of construction workers to heat stress [31]. Results were compared between detailed and simplified UTCI. The article utilised meteorological data obtained from urban areas and a meteorological station located outside the built-up area. According to the conclusions drawn from these studies, utilising publicly available environmental data collected by meteorological stations allows for a simplified assessment of thermal comfort or discomfort. For the New Łódź Centre, using ENVI-met software, it was found that Nature-Based Solutions strategies contribute to improving air temperature, perceived humidity temperature, and the thermal comfort index PET [32]. The impact of new construction on wind speed and direction was observed, affecting the temperature perception, which would be different with a different building orientation. The simulations with weather data obtained from field measurements at the research site exhibit the highest degree of conformity with the actual conditions, but simulations with data from a weather station are also performed [33]. Compared to the results from data obtained from the weather station, there was a difference on the order of 1.84°C [33].

In the context of Poland, research on urban climate is becoming increasingly important due to climate change and growing urbanisation. Studies on thermal comfort have been conducted in Lublin, using the PET index for sensitive age groups, and assessing the potential reduction of air temperature through vegetation [34]. Research also focuses on the urban heat island effect and how to mitigate it using green infrastructure [35], [36].

This study stands out for its use of an advanced computer simulation tool, the ENVI-met program, allowing for precise modelling of the microclimate on a specific housing estate and real-world evaluation of temperature perception and physiological impacts according to the UTCI index. The findings may serve as a guide for implementing green infrastructure in specific areas to reduce perceived temperatures within the housing estate's space.

1.1. Characteristics of the study area

Lublin is in eastern Poland and is home to 334,681 residents, making it the ninth most populous city in Poland [37], [38]. As one of the largest urban centres in eastern Poland, it is experiencing dynamic development of its urban infrastructure [39]. One of the areas undergoing significant changes is the district of Weglin, situated in the southern part of the city. The development of multi-family housing plays a crucial role in this district. Over the past few years, there has been a noticeable increase in the number of newly constructed residential buildings in this area, contributing to growth in the local population. This district has seen the highest population growth in comparison to the entire city [40].

The study area is located between Cyrkonowa Street and Koralowa Street (φ = 51°13'24.5"N, λ = 22°29'12.5"E) (Fig. 1). The newly established residential area lacks significant greenery. The predominant landscape is centred around multi-family buildings, paved road surfaces, and pavements. The absence of recreational green spaces or parks affects the quality of life for residents and can lead to issues related to comfort and health.

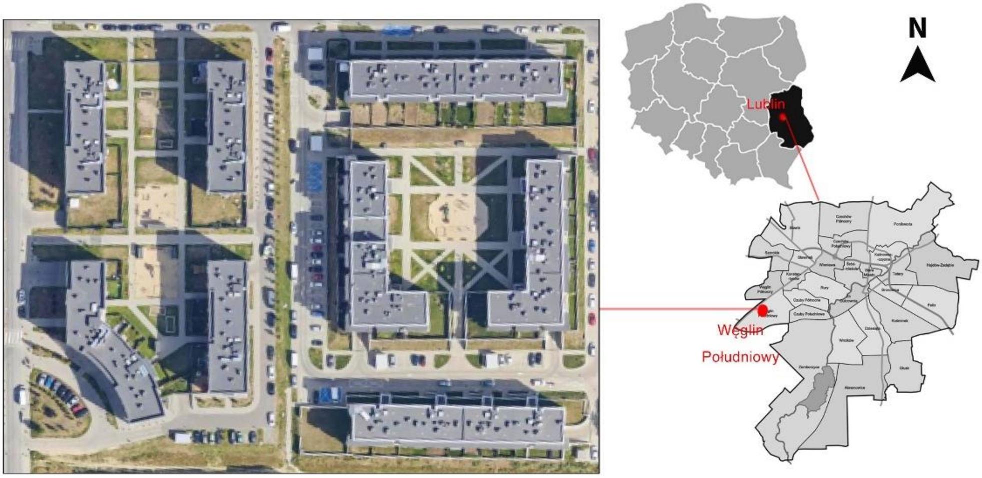


Fig. 1. Study area, Poland, Lublin, Weglin district, Cyrkonowa and Kwarcowa Street, Lublin. *Source*: [41]

The climate of the Lubelskie Upland is characterised by a pronounced thermal continental climate. This is reflected in relatively high summer temperatures and significant differences in precipitation between seasons. It results in a high percentage of sunny days during the summer and throughout the year, early frosts, a long spring, frequent cold weather, and substantial variations in precipitation between summer and winter. The average annual air temperature in Lublin during the 1981-2015 period was 8.8°C, with an upward trend of approximately 0.5°C per decade. The number of days with maximum temperatures exceeding 30.0°C also shows an upward trend, increasing by an average of 3 days in each decade. The highest recorded maximum air temperature of 35.8°C was observed on 8 August 2013, at the UMCS weather station in Lublin. Conversely, the lowest daily temperature of -29.2°C was recorded on 8 January 1987. The greatest snow cover thickness reached 48 cm and occurred in February 2010. These data illustrate the diverse climate characteristics of Lublin and its seasonal variability [42].

2. Methodology

The research conducted is quantitative, based on a case study and computer simulation. ENVI-met software was used for the research. It allows for the modelling of both real and theoretical urban layouts in 3D, along with associated vegetation, building materials, and other elements related to urban planning and design. It enables the analysis of relationships between airflow among buildings and greenery, heat exchange processes of various surfaces, and vegetation parameters. It is a unique tool that integrates various environmental elements such as wind and sunlight as microclimatic processes related to building physics and urban morphology. This software is currently one of the leading tools in urban climate research. The incorporation of actual data obtained from the nearest meteorological station or available national data allows for the replication of real weather conditions in a given area. The essential data required for conducting simulations include maximum temperature, minimum temperature, humidity, wind direction, and wind speed [43]. ENVI-met conducts calculations of short- and long-wave radiation, taking into account shading, reflections, and re-radiation from building and vegetation systems. In this context, the model actively considers processes such as transpiration, evaporation, and sensible heat flux from plants, while also performing precise computations of water and heat exchange in the soil system, considering water absorption by plants. The model incorporates the significant role of the photosynthesis process for each plant, influencing the overall dynamics of the simulation. Concerning temperature, ENVI-met, when properly configured, computes the surface temperature of facades based on the type of material used. It is worth emphasising that the model also handles particles, neutral gases, and reactive gases as part of the NO-NO2-Ozone reaction cycle. Furthermore, ENVI-met has the functionality to calculate bioclimatic indicators such as average radiation temperature, PMV/PPD, PET, and UTCI, which is a crucial element in the analysis of microclimatic conditions [43].

In the wind field domain, ENVI-met employs a comprehensive 3D Computational Fluid Dynamics (CFD) model that solves the non-hydrostatic Navier-Stokes equations, Reynolds-averaged for each grid in space and for each time step. The latest version used for this study is ENVI-met V5.5, which features improved vertical wind profiles. The influence of vegetation is simulated as wind resistance in the wind field. The model meticulously represents building physics, allowing wind flow calculations around each facade and roof segment. Additionally, ENVI-met enables the simulation of wind distributions within complex or semi-open structures. There is also the capability to perform real-time wind flow calculations, treating the flow field as a prognostic variable, allowing updates at each stage.

ENVI-met employs a two-equation k-epsilon turbulence model to predict air turbulence (TKE) [44]. This model utilises a first-order E-psilon closure model for turbulence computations, with two prognostic equations related to turbulent energy generation (E) and dissipation (epsilon). Importantly, air exchange coefficients (K) are determined using the Prandtl-Kolmogorov relationship [43]. The temperature and humidity of the air are determined by various elements introducing sensible heat and water vapour within the analysed modelled space. Advection and diffusion in the air are simulated based on the calculated three-dimensional wind field. Both the land surface and plant leaves act as sources or absorbers of both temperature and humidity within the atmospheric model. Concerning buildings, walls and roofs primarily function as surfaces exchanging heat with the atmosphere. However, when greenery is implemented, they can also act as sources of moisture [29]. Building facades and roofs play a significant role as primary areas exposed to sunlight in the urban environment context. ENVI-met employs the Indexed View Sphere (IVS) method, allowing precise modelling of radiation streams considering multiple reflections and an accurate assessment of thermal radiation [43]. The choice of Lublin as the research area was dictated by the fact that this district has experienced the highest population growth in relation to the entire city. The selected area has a repetitive, regular layout with a limited amount of greenery. The dimensions of the chosen area were 150 metres by 200 metres for analysis, covering the largest number of buildings. Additionally, this area size was chosen to facilitate efficient computational processes by computer hardware. On-site building analysis revealed that the buildings in this area are made of brick, with external thermal insulation in the form of styrofoam and white plaster finishing in some areas with wood-like inserts. The buildings have 4 floors with a height of 14 metres and 6 floors with a total height of 20 metres. All buildings have flat roofs covered with roofing felt. The parking areas are paved with cobblestones, and the roads are made of asphalt. In the vicinity of the roundabout, the presence of small shrubs was observed, while the remaining part of the area is covered with grass. Additionally, underground parking facilities are located beneath the building blocks. These parameters are crucial for accurate modelling of the real area in the ENVI-met software. The entire area was independently modelled in the ENVI-met software using map data from the geoportal and on-site building analysis [41].

To conduct climate simulations, it is necessary to input weather data into the software. Historical data from the Lublin-Radawiec station provided by the Institute of Meteorology and Water Management (IMGW) for Lublin were used as the starting data [45]. These are public data based on which research is conducted throughout Poland [26], [33]. Analysing the weather data from 2022, 22 July was selected as the hottest day. Based on historical data, an approximate maximum temperature of 32°C, minimum temperature of 14°C, minimum humidity of 30%, maximum humidity of 60%, and wind speed of 1.4 m/s were adopted. It should be noted that in the analysed area, the temperature may be slightly higher than the one introduced from the meteorological station since the station's location is outside the city. The introduced meteorological data are intended to approximate the temperature perception prevailing in the studied area.

To assess human perception of temperature using the UTCI index, the BIO-met component of the ENVI-met software was utilised. After generating simulations, a 35-year-old woman dressed for summer was selected, and a temperature perception simulation was generated for her. This could potentially be a limitation of the study, but generating a simulation for a man was omitted because the difference in perceived temperature between men and women is negligible and not significant for this study. The simulations presented in this article are the result of generating the final simulations in the Leonardo ENVI-met tab.

The research was conducted for the entire day (excluding the night) from 7:00 am to 9:00 pm, as these are the peak hours of human activity in the area.

To determine whether an individual may experience thermal stress on a hot day in a particular area, the obtained results were assigned corresponding levels of heat stress. This process was based on information developed by scientists responsible for creating the UTCI index. An analysis of thermal comfort and physiological reactions of the human body was conducted.

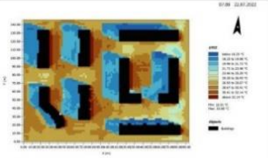
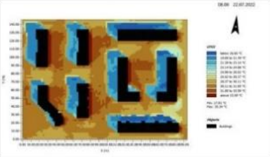
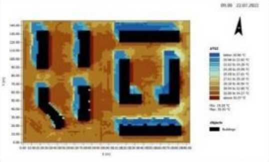
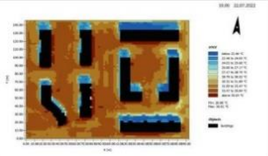
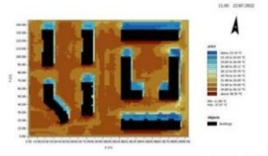
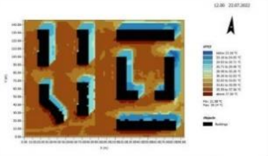
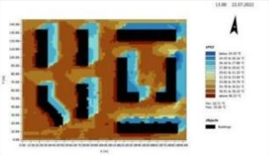
Table 1. The range of UTCI index and their corresponding levels of heat stress, along with recommended protective measures based on thermal conditions. *Source:* [46]

UTCI (°C)	Heat Stress Category	Recommended Action
> +46	Intolerable Heat Stress	Periodic body cooling is essential, fluid intake >0.5 l/h required. Avoid heavy physical exertion.
+38 - +46	Very Strong Heat Stress	Periodic use of air-conditioned rooms or shaded areas necessary, fluid intake >0.5 l/h required. Limit physical exertion.
+32 - +38	Strong Heat Stress	Fluid intake of 0.25 l/h required, prefer use of shaded areas and periodic reduction of physical exertion.
+26 - +32	Moderate Heat Stress	Fluid intake of 0.25 l/h required.
+9 - + 26	No Thermal Stress	Physiological thermoregulation is sufficient to maintain thermal comfort.
0 - +9	Mild Cold Stress	Use of gloves and head cover recommended.
-13 - 0	Moderate Cold Stress	Increase physical activity and protect limbs and face from cooling.
-27 - -13	Strong Cold Stress	Increase physical activity and protect limbs and face from cooling. Use of warmer clothing is preferred.
-40 - -27	Very Strong Cold Stress	Increase physical activity and protect limbs and face from cooling. Essential to increase clothing thermal insulation and limit time spent in open areas.
< -40	Extreme Cold Stress	Limit time spent outdoors to the absolute minimum. Essential to increase clothing thermal insulation and wind protection.

3. Results

The research results reveal a significant variation in human thermal perception according to the UTCI in the studied residential area, depending on the time of day (Fig. 2). Throughout the day, in areas sheltered by buildings, a noticeable temperature decrease is observed. The lowest shaded perceived temperature occurs at 9:00 pm, measuring 16.16°C, while at 7:00 am, it is slightly higher, at 16.51°C. The highest perceived temperature in the shade reached 26.08°C at 4:00 pm. In sun-exposed areas, from the early morning hours, perceived temperatures exceeded 33°C and peaked at 3:00 pm, reaching 41.39°C. Sunlit temperatures decreased as the day progressed, dropping to 22.95°C by 9:00 pm.

Simulation of the UTCI for a 35-year-old woman, dressed lightly, on July 22nd.

Hour	View of the temperature distribution simulation	Temp. min. [°C]	Temp. max [°C]
7:00 a.m		16.51	33.88
8:00 a.m		17.91	35.34
9:00 a.m		19.29	35.93
10:00 a.m		20.88	36.61
11:00 a.m		21.55	37.97
12:00 a.m		21.38	39.14
1:00 p.m.		22.71	39.96

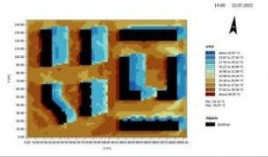
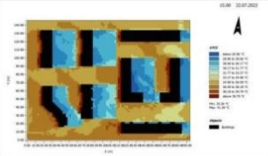
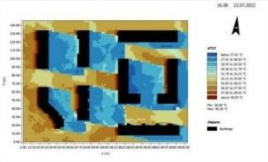
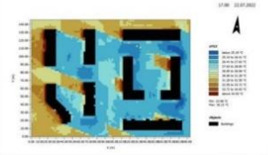
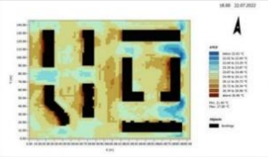
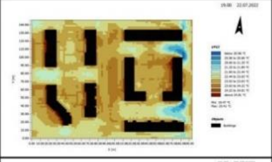
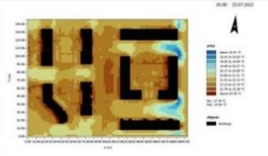
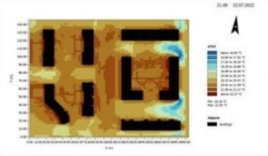
Hour	View of the temperature distribution simulation	Temp. min. [°C]	Temp. max [°C]
2:00 p.m.		24.19	40.97
3:00 p.m.		25.36	41.39
4:00 p.m.		26.08	40.36
5:00 p.m.		23.98	36.15
6:00 p.m.		21.40	27.58
7:00 p.m.		19.47	25.41
8:00 p.m.		17.79	24.00
9:00 p.m.		16.16	22.95

Fig. 2. The human perception of perceived temperature according to the UTCI index for a 35-year-old woman dressed lightly on 22nd July, from 7 a.m. to 9 p.m. *Source:* Author

A significant range of shadows cast by buildings is noticeable during the hours between 2:00 and 5:00 pm. This has a considerable impact on the perceived temperature for people moving within this area. A potential resident returning from work around 4:00 pm would experience less thermal stress when navigating the pavements and streets since they are in the shade. Greater thermal discomfort may be felt from 8:00 am to 1:00 pm because the shadows do not have as wide a range as in the afternoon, and the main traffic routes remain in full sunlight. The highest occurring temperatures are observed on the building facades exposed to direct sunlight. This is particularly evident in the simulation at 3:00 pm on each of the western facades (Fig. 3). Undoubtedly, the materials from which the building is constructed play a significant role in this, as they tend to heat up the most during the day.

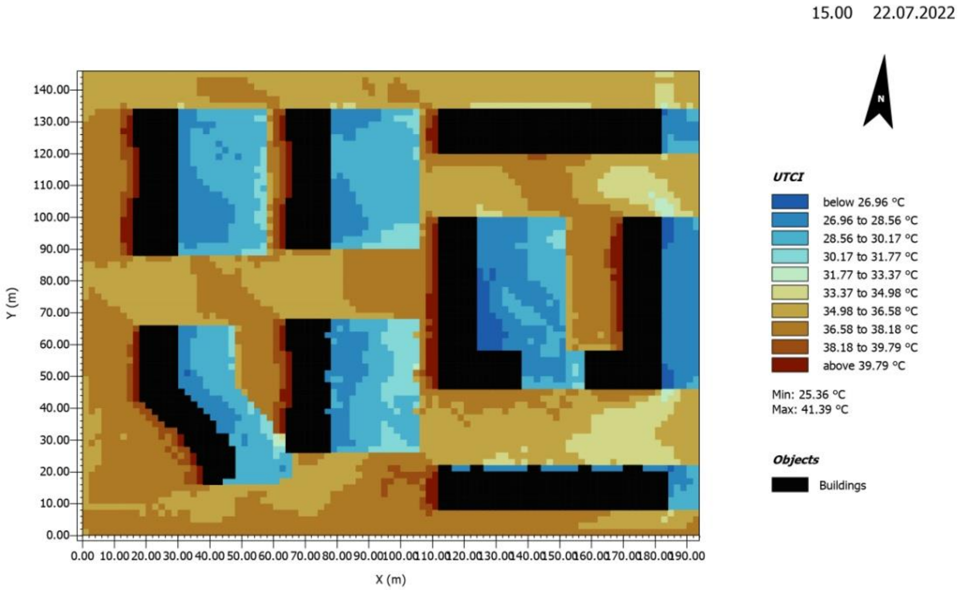


Fig. 3. The temperature distribution at the warmest moment with the highest temperatures visible near building facades on the western side at 3 p.m. *Source:* Author

To assess thermal stress in the studied area for each hour and the obtained perceptible temperature, thermal stress categories were assigned according to the UTCI index (Table 2). The results show that throughout the day, an individual in the shade does not experience thermal stress, except around 4:00 pm, when moderate heat stress may be felt. At the same hour in full sunlight, an individual will experience very strong heat stress, making it not recommended to spend time outdoors in any part of the studied residential area around that time. In full sunlight during the 15 hours studied, an individual experiences heat stress for as long as 12 hours. Starting from the early hours, i.e., from 7:00 am, a resident of the housing estate walking to work through unshaded areas will experience strong heat stress.

To investigate thermal stress in the studied area for specific hours and the obtained perceived temperatures, thermal stress categories were assigned according to the UTCI (Table 2). The results show that from 12:00 am to 4:00 pm, the range of thermal stress in sunny areas reaches a very strong heat stress level. Only around 5:00 pm, as the temperature drops, does the thermal stress level decrease, reaching no thermal stress at 7:00 pm.

Table 2. A comparison of hours and thermal stress according to the UTCI index in the surveyed area. *Source:* Author

Hour	UTCI in shadow	UTCI in the sunshine
7:00 a.m	No Thermal Stress	Strong Heat Stress
8:00 a.m	No Thermal Stress	Strong Heat Stress
9:00 a.m	No Thermal Stress	Strong Heat Stress
10:00 a.m	No Thermal Stress	Strong Heat Stress
11:00 a.m	No Thermal Stress	Strong Heat Stress
12:00 a.m	No Thermal Stress	Very Strong Heat Stress
1:00 p.m.	No Thermal Stress	Very Strong Heat Stress
2:00 p.m.	No Thermal Stress	Very Strong Heat Stress
3:00 p.m.	No Thermal Stress	Very Strong Heat Stress
4:00 p.m.	Moderate Heat Stress	Very Strong Heat Stress
5:00 p.m.	No Thermal Stress	Strong Heat Stress
6:00 p.m.	No Thermal Stress	Moderate Heat Stress
7:00 p.m.	No Thermal Stress	No Thermal Stress
8:00 p.m.	No Thermal Stress	No Thermal Stress
9:00 p.m.	No Thermal Stress	No Thermal Stress

As previously mentioned, the graphical representation of the simulations reveals that while the maximum thermal stress occurs in the afternoon hours, the shadows cast by the buildings on the transport areas mitigate the perception of this stress. This is because only a small number of people may be present in these spaces. Residents are most exposed to strong heat stress in the morning hours as they are exposed to direct sunlight when walking.

According to the levels of perceived temperature developed by scientists using the UTCI index [6], when the perceived temperature exceeds 33°C, a physiological response occurs in humans. In the case of this area, this response persists throughout the day in sunny locations, leading to an average sweat rate exceeding 200 g/hour and an increase in rectal perceived temperature after 2 hours of exposure. Around 12:00 am, when the temperature exceeds 38°C, the increase in rectal temperature occurs after 30 minutes of exposure. While staying in the sunniest area where the perceived temperature exceeds 40°C, a reduction in the temperature gradient between the interior and the surface of the body to <1°C occurs within 30 minutes. In the afternoon, when the perceived temperature reaches 26°C, people will perceive warmth after 2 hours and "very hot" after 2 hours.

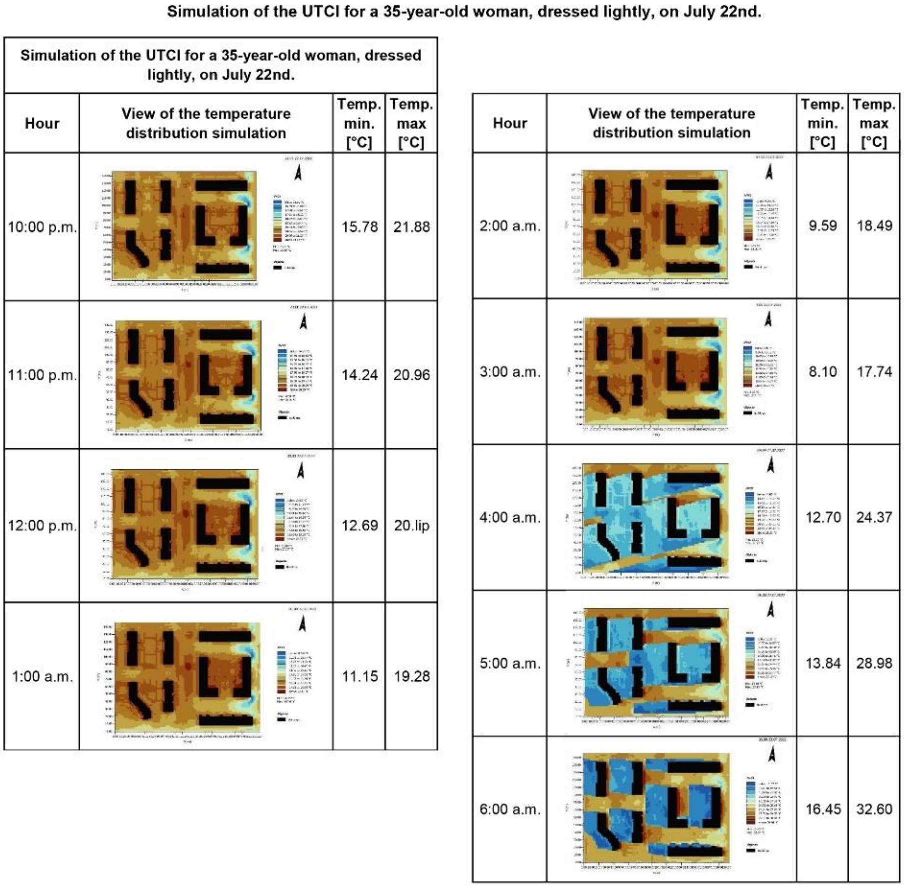
A preventive measure to reduce thermal stress in this area, especially during the morning hours when people are most exposed to sun exposure while moving around the residential area, is the proper placement of green infrastructure, such as trees, to naturally create shade on pavements and roads. Worth considering are various solutions in the form of ivy-covered structures in parking areas, so that cars are not directly exposed to sunlight. All south-facing parking lots are exposed to this, and consequently, the people who use them. In many publications, including those cited in this article, the beneficial effects of plantings on reducing perceived temperatures have been proven.

Thanks to such simulations, it is clear where planners and urban designers should implement measures to lower perceived temperatures and positively impact the living conditions in the studied residential area. Such actions are particularly important in the era of climate change, where the average perceived temperature is rising, which will adversely affect people's health and quality of life.

4. Discussion

The research findings are limited to daytime hours. Restricting the simulation period from 7:00 am to 9:00 pm, excluding nighttime conditions, may potentially overlook crucial information regarding temperature changes and thermal comfort during nighttime hours. The results could be equally significant for urban planning and design. In the illustration below (Fig. 4), the nocturnal temperature distribution is evident. A key observation is that between 10:00 pm and 3:00 am, sealed surfaces such as roads and pavements distinctly stand out. This effect is attributed to surfaces that absorb heat during the day releasing it at night. Between 10:00 pm and 6:00 pm, the lowest temperature is 8.10°C at 3:00 am, while the highest temperature occurs at 6:00 am, reaching 32.60°C.

Sensitivity tests conducted in Germany using ENVI-met software indicate that the wind direction effect can lead to local differences in air temperature, averaging up to 4K. These results illustrate that even on summer days with low wind speeds, accurate wind direction data play a crucial role in precise air temperature simulations. As the authors emphasise, this discovery may have significant implications for urban planning and the design of green infrastructure in cities [47].



Simulation of the UTCI for a 35-year-old woman, dressed lightly, on July 22nd.

Simulation of the UTCI for a 35-year-old woman, dressed lightly, on July 22nd.

Hour	View of the temperature distribution simulation	Temp. min. [°C]	Temp. max [°C]
10:00 p.m.		15.78	21.88
11:00 p.m.		14.24	20.96
12:00 p.m.		12.69	20.lip
1:00 a.m.		11.15	19.28

Hour	View of the temperature distribution simulation	Temp. min. [°C]	Temp. max [°C]
2:00 a.m.		9.59	18.49
3:00 a.m.		8.10	17.74
4:00 a.m.		12.70	24.37
5:00 a.m.		13.84	28.98
6:00 a.m.		16.45	32.60

Fig. 4. Distribution of apparent temperature according to UTCI index from 10:00 pm to 6:00 am. *Source:* Author

5. Conclusions

The results of this study, obtained under specific meteorological conditions on the hottest day of the year, reveal that residents in the local neighbourhood experience significant thermal stress, especially during the morning hours. During this period of the day, while active on roads and pavements, they are exposed to intense sunlight, resulting in noticeable thermal stress. The highest temperature in the shade reached 26.08°C and occurred at 4:00 pm. This means that even in the shade, residents would feel moderate thermal stress. Meanwhile, in areas exposed to direct sunlight, the highest perceived temperature is 41.39°C, occurring at 3:00 pm. It is worth noting that being in the studied area at 4:00 pm can still lead to the experience of thermal stress, both in sunny and shaded areas. At that time, individuals would experience very strong thermal stress. During nighttime hours, there is a noticeable higher temperature emitted by the surfaces of the pavements, which absorbed heat throughout the day. It's worth noting that being in the studied area at 4:00 pm can still lead to the experience of thermal stress, both in sunny and shaded areas. In this context, simulations generated using the UTCI index provide valuable insights into potential areas for implementing green infrastructure. Based on the literature review, it can be concluded that these types of simulations help to identify optimal locations for planting vegetation to effectively reduce perceived temperatures, create shade, and enhance thermal comfort in the studied area. However, this requires much more extensive comparative analyses.

It is important to emphasise that wind significantly influences the perceived temperature. On the hottest day of the year, the wind direction may vary, potentially altering the perceived temperature. Therefore, it is crucial to highlight that the above conclusions pertain to a specific scenario with given parameters for the hottest day of the year. If the wind direction changes, the perceived temperature will also be affected. The presented results are for a specific location with a characteristic climate and therefore cannot be extrapolated to any location worldwide. However, they can serve as valuable guidance for local authorities and developers constructing neighbourhoods within the city area. Nevertheless, it is crucial to underscore that the design of neighbourhoods necessitates comprehensive analyses, which the authors will undertake in subsequent research endeavours.

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