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Energy efficiencies model for thermal comfort in urban applications

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ABSTRACT

Improving people's standard of living has increased their requirements for the environment. Increasing air temperature in urban areas due to urban heat islands (UHI) has been a global concern since industrialization. Apart from suitable facilities and landscapes, a comfortable outdoor thermal environment can improve the efficiency of urban space use. Ensuring outdoor comfort is an integral part of the design agenda where the UHI phenomenon plays a significant role. A study has been conducted on a residential building campus to analyze the effect of these heat island countermeasures (individual and combined) with the help of the simulation tool Grasshopper. A 3D reference model of a small residential campus is developed. The outdoor thermal comfort level is studied for this case, and Universal Thermal Climate Index (UTCI) is evaluated. Further, several UHI mitigation strategies such as wall and roof reflectivity, vegetation, plantation, pavement configuration, and shading are applied to find their effect on the micro-climate and outdoor thermal comfort. Based on the simulation outcomes, urban geometry is identified as the most influential design factor in decreasing the urban heat island effect and outdoor thermal comfort. The study's principal objective is to develop a simulation framework including all mitigation strategies and find the best case for UHI reduction.

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1. Introduction

Current century has witnessed a rapid growth of the urban environment, and the urban population is projected to be 60% of the entire world population in 2030 [1]. In recent years, the ambient temperature has increased due to global climate change, especially climate warming and ozone holes. Simultaneously, with the rapid population growth and urban expansion, urbanization has led to significant modifications in the urban climate. A large amount of greenhouse gases emitted from cities, as well as black asphalt pavement and roofs, have led to the development of the urban heat island (UHI) effect, specified as the temperature difference measured in urban areas and neighboring rural areas [2].

The UHI mainly consists of higher air temperatures observed in urban areas concerning air temperatures monitored in rural surroundings. The phenomenon has several negative consequences affecting (i) buildings' energy consumption [3], (ii) urban air quality [4], and (iii) citizens' health and life quality [5]. Furthermore, as global climate change continues, extreme weather events are becoming more common and intense, such as heatwaves, that act in synergy with the UHI to compromise human health even more [6]. Therefore, in recent decades, the scientific community has expended much effort to identify remedies to the UHI phenomena [7]. According to existing studies, the heat island effect may cause an average increase in the temperature of 2 to 6 °C [8,9]. Rising temperatures in the urban environment have resulted in an increasing number of studies focusing on improving urban thermal environments. Thermal comfort in outdoors is one aspect of citizens' life that is degraded by the UHI [10]. The improvement in people's standard of living has resulted in an increase in their requirements for the environment. Apart from suitable facilities and landscapes, a comfortable outdoor thermal environment can improve the efficiency of urban space use. Therefore, thermal comfort has gradually become essential in optimizing architectural design and urban planning.

It's remarkable to consider how thermally pleasant urban surroundings impact people's behavior, utilization of outdoor areas, and city quality of life in the context of urban planning [5]. Sustainable cities are always constructed considering their environmental impact [11]. Furthermore, the number of people who use outdoor areas determines the place's vitality, the local economy, and the city's long-term sustainability [7]. Additionally, the quality of urban environments is influenced by the outdoor microclimate or associated outdoor thermal comfort [12]. Space around the buildings is an essential component of urban design in the tropics, where increasing built density results in inadvertent microclimatic modifications. Ensuring outdoor thermal comfort is an integral part of the design agenda where the UHI phenomenon plays a significant role.

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2. Thermal Comfort Indices

Thermal comfort is defined as the 'condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation' [13]. The traditional thermal comfort theory is based on balancing human body heat production and loss [14]. Hence, designing effective standards and models can deepen the thermal environment understanding.

Outdoor thermal comfort is a mixture of effects from building reflectivity, emissivity, geometry, and morphology of buildings. From literature [15–17], it was observed that outdoor thermal comfort is a determinant of various parameters, which can be briefly classified under three types: 1) Climatical parameters, 2) Physical factors, and 3) Psychological constraints. The climatical parameter includes Air temperature, Wind velocity, Relative humidity (RH), and Mean Radiant Temperature (MRT). MRT is a crucial metric in evaluating how much radiation a person is exposed to in their environment. Although the climatical parameters are dynamic and uncontrollable, they can be influenced by efficiently designed physical parameters [18]. Physical characteristics that are part of the geometry of urban canyons significantly influence UHI by trapping heat [19]. The psychological parameter includes realizing thermal sensation beyond perception. However, physical aspects have been shown to significantly impact thermal comfort sensation; psychological constraints also play a role in determining thermal comfort [20].

Numerous thermal comfort models calculate outdoor human comfort [21], primarily based on the energy balance between people and their surroundings, like the COMFA* model [22], the Standard Effective Temperature [23], and the Index of Thermal Stress [24]. More than 165 indices have been developed [25] to reflect thermal comfort based on various criteria such as ambient temperature, subjective studies, heat transmission, and energy balance of a human body. This is why several models are developed to foresee the perception developed between the human and the adjacent environment from heat exchange [25,26]. Several indices exist to analyze outdoor thermal conditions based on outdoor thermal conditions. These mostly include UTCI (Universal Thermal Climate Index) [27,28], PET (Physiological Equivalent Temperature) [29], PMV (Predicted Mean Vote), SET (Standard Effective Temperature) [30], and WBGT (Wet-bulb globe temperature) [31].

2.1. Universal Thermal Climate Index (UTCI)

Universal Thermal Climate Index (UTCI) is one of the thermal comfort indices that calculates outside thermal conditions based on the equivalency of the physiological response anticipated by the human thermoregulation model and the state-of-the-art clothing model [32]. The UTCI intends to enlighten the people about how the weather feels, considering aspects such as wind, radiation, and humidity [33]. It is defined as the reference situation's air temperature (Ta) based on the Fiala heat balance model [25]. The deviation of UTCI from air temperature varies on the tangible values of air temperature, wind speed, mean radiant temperature, and relative humidity expressed as water vapor pressure. The UTCI is also described as an equivalent outdoor temperature that generates a similar physiological response of a reference individual as the real environment [33–35]. The impetuous power after the development of UTCI is the demand for the physiological reaction-based evaluation model, including harsh weather situations. It may be computed at all measuring positions for each hour of a regular year based on the appropriate environmental factors given in the weather file [36].

The reference conditions for defining UTCI consider a person walking at 4km/h with a metabolic rate of 2.0 met. Moreover, the reference wind speed is 0.3 m/s at the height of 1.1 m, and relative humidity is considered 50%. The UTCI value depends upon air velocity, mean radiant temperature, relative humidity, and air temperature. The UTCI model forecasts the thermal effect on the complete body and distinct body elements. It calculates a total of 188 human body points and 12 cylindrical body elements using active and passive systems [35,37,38]. The thermal stress levels used to measure outdoor thermal comfort [39–41] are shown in Table 1.

Table 1: UTCI thermal stress levels.

Outdoor Comfort Level	UTCI Range (°C)	Stress Category
Level -3 and below	above +46	extreme heat stress
	+38 to +46	very strong heat stress
	+32 to +38	strong heat stress
Level -2	+26 to +32	moderate heat stress
Level -1	+9 to +26	no thermal stress
Level 0	+9 to 0	slight cold stress
Level +1	0 to -13	moderate cold stress
Level +2	-13 to -27	strong cold stress
Level +3 and above	-27 to -40	very strong cold stress
	below -40	extreme cold stress

UTCI is an outcome of the world's foremost comfort specialists' attempt to make an international standard of outdoor temperature perception that satisfies the following conditions:

- Thermo-physiological significance across a wide variety of heat exchange conditions of current thermal conditions
- Appropriate for all climate types, seasons, and scales
- Useful in human biometeorology applications.

3. Urban Heat Island (UHI) mitigation strategies

There has been a lot of research on the aspects that determine outdoor thermal comfort and assessment methodologies to reduce the urban heat island. Unlike indoor environments, urban microclimates are dynamic; and the altering daylight, wind, and shading from trees make the environment unpredictable [42]. Aside from the climatic components of thermal comfort, several physical and social variables impact people's perceptions of urban space while they are outside [5]. There are several strategies to alleviate the UHI effect, which positively influences climate. These mitigation strategies include Roof strategies (cool roof, high reflectance roof, vegetated green roof), non-roof strategies (shading structures, reflective pavement, vegetation, plantation, and water forms), and covered parking approaches [43]. In one of the studies [44], psychological mechanisms were studied in assessing outdoor places and weather, as well as the major impacts of weather parameters and personal characteristics such as environmental attitudes and age on the perception and assessment of urban locations. The ideal industrial building designs to increase outdoor thermal comfort employing UTCI, as well as inside thermal comfort and cooling energy usage required to maintain comfort during the summer season, were examined in Estonian research [45].

3.1. Roof strategies

Reflectance of solar radiation can be changed regularly by modifying the color of the roof surface or utilizing highly reflecting materials [46]. Increased reflectivity of the outside surface lowers the quantity of energy absorbed by the roof and allows less heat to enter the structure. As a result, roofs with high solar reflectivity, high infrared radiation emissivity, and great thermal insulation absorb less energy and are easier to cool than regular roofs. Amongst the materials, white coatings are the most often used; studies have proven that the high solar radiation reflectance of white paints can even cool metal roofs with low emissivity and high thermal conductivity [47]. Cool roofs can lower building cooling loads while also enhancing the urban thermal environment and occupants' thermal comfort.

3.2. Non-roof strategies

Many elements, including urban green spaces, affect outdoor thermal comfort in metropolitan environments, which may be exploited to alleviate UHI. Since urban green places such as shrines and parks are cooler than surrounding metropolitan areas, climatic conditions in urban areas may be improved and environmental stress caused by heat islands can be alleviated [48]. It may significantly improve the outdoor thermal environment while mitigating the UHI effect by lowering summer air temperatures [49]. Another strategy that can maintain outdoor spaces cool is green space [50]. It provides cooling to the urban microclimate with the help of evaporation and transpiration [51]; creates shading [52]; and reflects the sun radiation because of the higher albedo values. Additionally, plants develop a positive effect on strong winds during the winter season [53]. Several studies [54–57] observed the connection between thermal comfort and the variety of outdoor vegetation.

Outdoor thermal comfort can also be reduced by adjusting the material's albedo [58]. The term albedo means the amount of radiation reflected by a flat surface [59]. The light-colored materials reflect more sunlight than dark colors and, therefore, have a high albedo value. Hight albedo can mitigate the UHI effect; however, always increasing the albedo is not useful for thermal comfort improvements [60]. Materials used in urban fabric play a very crucial position in urban thermal balance as they absorb incoming solar radiation and increase the surrounding temperature [61].

Urban vegetation is an important technique for managing microclimate in urban architecture. When properly angled in colder areas, it acts as a wind buffer [62] and in warmer climates, it lowers the air temperature through evapo-transpiration, shading, and wind direction [63]. Trees have been proven to be more efficient than grass in improving microclimate because of the high transpiration rate and impact of shading [64]. The result of tree crown covers has been simulated [65] while considering the effects of tree crown covers (small and big) and tree planting densities on pedestrians. It has been discovered that as plantation densities grow, so does visual comfort, whereas lowering tree density enhances illuminance with large crowns.

3.3. Covered parking strategies

Parking areas may take up to half of a city's land area, providing an excellent chance to address urban climate issues [43]. The transformation from asphalt-covered parking spaces to grass-sheltered parking spaces is beneficial in reducing UHI impact [66]. The parking space might be covered with at least one of the following methods: (a) have SRI coated roof; (b) a vegetated roof [67]; (c) covered with energy generation systems such as thermal collectors, photovoltaics, and wind turbines [68].

4. Development of simulation framework

Based on the current literature, the major research issues that arise are 1) What are the critical parameters defining outdoor thermal comfort; and 2) What strategies can be adopted to improve thermal comfort. Several studies are present in the area where researchers develop the framework for simulation to calculate the mean radiant temperature and UTCI with the help of different simulation tools [69–72]. However, it has been seen from the literature review that UTCI analysis has been done only for individual parameters. Few studies in the domain consider the combined effect of UHI mitigating strategies and simulate all parameters together.

The main intention of this study is to identify important parameters with the help of simulation that can enhance thermal comfort conditions in outdoor areas. The present study explains a parametric analysis for the thermal simulation of a residential area, executed in the Grasshopper tool and depending on its plugins Honeybee and Ladybug. It explains one of the outdoor thermal comfort indices, i.e., UTCI and with the help of a simulation tool, gives the best options to increase the outdoor thermal comfort in urban areas. Further, the study can help improve outdoor thermal comfort through a developed simulation framework with various UHI mitigation strategies in existing areas or by developing new guidelines for planning and designing outdoor spaces.

4.1. Urban area identification

Within the Noida region, the residential campus of an area of approximately 1,50,000 sqm was selected for the simulation and modeling. The residential campus is more than 20 years old having mostly low-rise buildings. For each building, the average width and length are about 18 m and 50 m, respectively and the number of floors is up to 5 floors. All streets are double directions for vehicles with widths ranging from 10 m to 15 m. The major reason for choosing a residential region was because of its huge population, and by implementing proper measures, it is possible to improve outdoor comfort conditions. Only a small block of the residential campus has been considered for the complete analysis as the building layout is uniform for all the buildings, so considering the small uniform building block saves the computation time. Figure 1(a) shows the 3D view of the residential area, and Figure1 (b) shows the area considered for outdoor thermal comfort simulation.

Figure 1. View of the considered area for simulation.

Figure 2. A google earth view of the residential campus.

4.2. Methodology

The main objective of this study is to uncover a variety of urban geometries by filtering out design alternatives with lower UTCI values to increase outdoor thermal comfort rather than providing a limited number of optimal solutions. Figure 3 shows the framework, which is divided into three phases as follows:

- Pre-processing: The pre-processing phase contains setting up the simulation parameters and weather data. This step also includes 3-D modeling of the residential building with the help of the Rhinoceros tool. The setting up of weather data has wind velocity, relative humidity (RH), and Mean Radiant Temperature (MRT). This phase allows the model to consider the surface temperature of every single section of the ground, which shall directly impact the MRT's assessment inside the urban area.
- Simulation and Analysis: This step includes the building simulation with the ladybug tools' help. This tool is identified for this study due to numerous reasons. It consumes less time to perform calculations compare to ENVI-met, and evaluates a variety of thermal indices. UTCI is the focus of this study, and the ability to do the parametric simulations to visualize the outcomes within the Grasshopper setting [73]. The ladybug-tools microclimate model combines Grasshopper plugins LadyBug and HoneyBee, which helps assess the outdoor thermal comfort with a graphical interpretation. The model is based on connecting Grasshopper to previously validated software engines such as EnergyPlus to calculate the thermal comfort factors independently [74].
- Outdoor thermal comfort valuation: This step visualizes the simulation results. The outputs of hourly air temperature and relative humidity, hourly surface temperature, and hourly wind speed were utilized for evaluating outdoor thermal comfort metrics using the microclimate map component. The UTCI was chosen

as the key metric for assessing outdoor thermal comfort, and the post-processing of outdoor thermal comfort has been done.

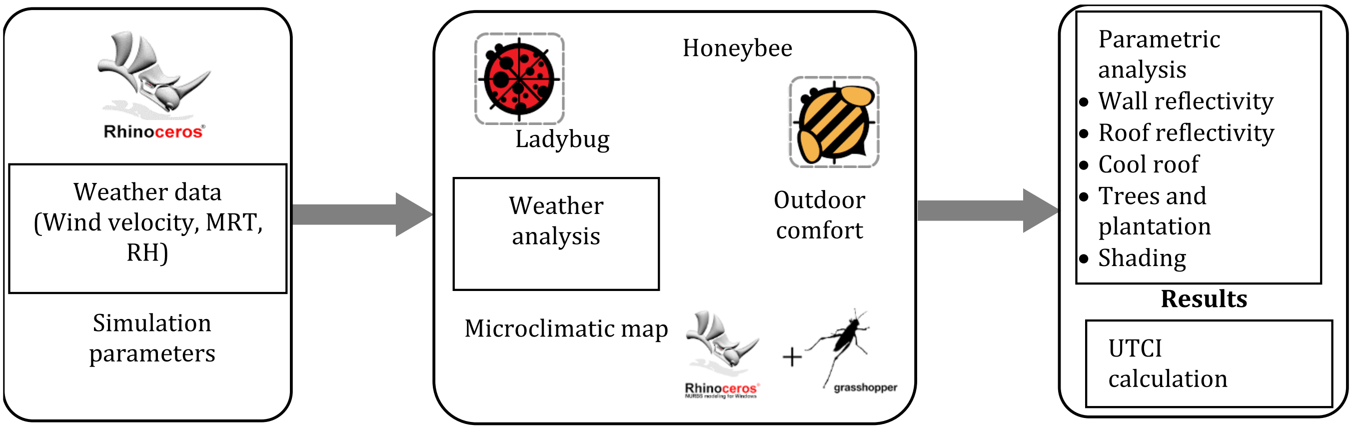

Figure 3. Analytical framework for optimizing the UTCI analysis.

4.3. Modelling workflow

Various softwares are available to examine the climatic conditions depending upon the scale between city and urban. Envi-MET is one of the most used tools to analyze outdoor thermal comfort. Still, it is restricted to building morphology and does not support complicated geometry to be modeled [69,70,75]. In this study, the Grasshopper tool has been used with Rhinoceros, while LadyBug and HoneyBee are grasshopper plugins used for determining the parametric and outdoor thermal comfort analysis.

This section talks about the algorithmic sequence used by grasshopper plugins to calculate outdoor thermal comfort. A 3-Dimensional residential campus model has been modeled in the Rhinoceros tool from which the building typology, building heights, terrain, and other integrated inputs have been defined. Figure 4 shows the 3-D model of the residential campus.

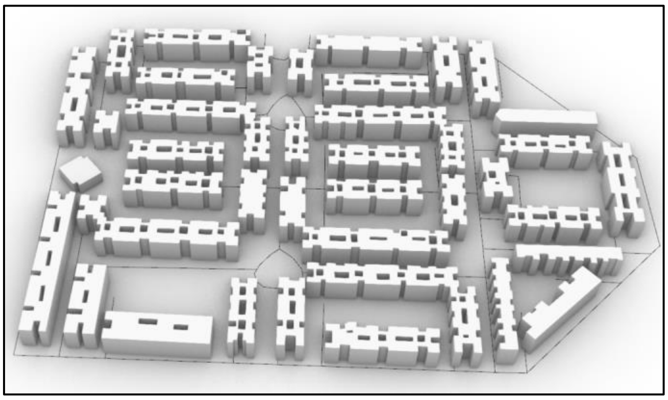

Figure 4. 3-D model of the residential campus generated in Rhino.

It appears challenging to calculate the mean radiant temperature [76] in complicated urban areas because of the combination of short-wave and long-wave. The ladybug and honeybee plugins supported a component named 'Solar temperature adjustor' [69]. This component, shown in Figure 5(a), is used for exploring and calculating the radiated and reflected long-wave and short-wave solar radiations and their effects on the pedestrian's thermal comfort. After analyzing the 'Solar Adjusted Temperature,' a mesh is created covering the whole grid at the height of human height, i.e.,1.5 m. This mesh can measure and identify the mean radiant temperature, wind speed, and relative humidity and may be used to create input data for UTCI calculations.

The "Outdoor Comfort Calculator" component has been used to calculate the UTCI and to combine numerous parameters such as MRT, RH, wind speed, and wind direction. The outdoor thermal calculator component is shown in Figure 5(b). It is used to establish the correlation between thermal stress and UTCI values, varying from excessive heat stress to severe cold stress indices.

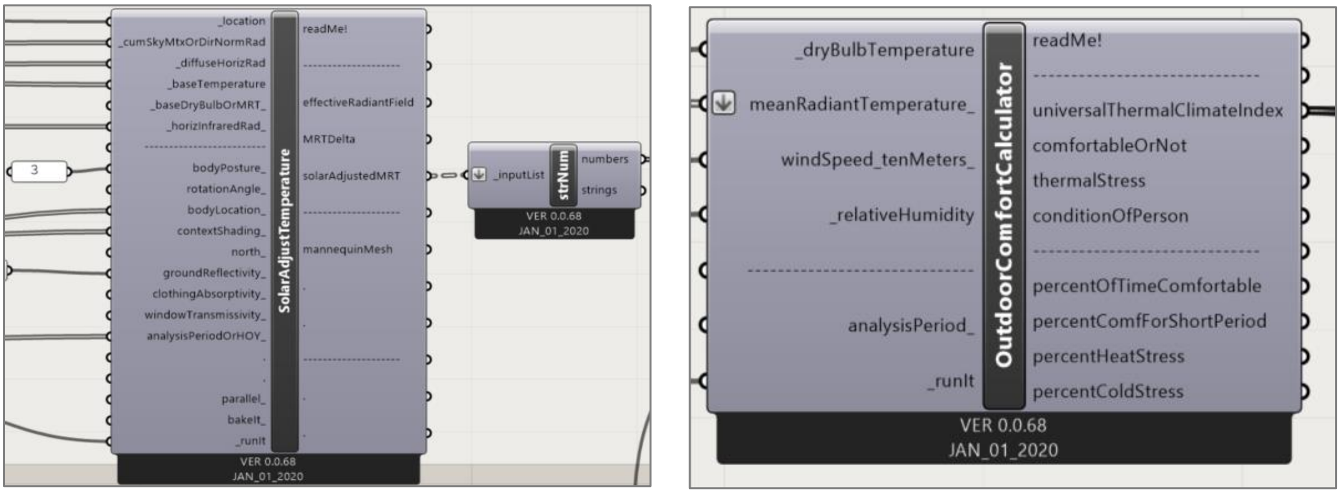

Figure 5. Grasshopper components used in the modeling (a) Solar adjusted mean radiant temperature; (b) Outdoor thermal comfort calculator.

5. Modelling and simulation

5.1. Weather analysis

This study was conducted in Noida City (28°32′ N;77°23′ E), India's northern state of Uttar Pradesh, India. As per the climate classification [77], it is defined as a composite climate area. In Noida, the monsoon season is hot, harsh, partly cloudy and the dry season is warm and mostly clear. January is the coolest and June is the warmest month of the year in the region. The weather data has been selected for its nearest available city, i.e., New Delhi. A typical summer weak has been chosen for the outdoor thermal comfort analysis. The International Weather for Energy Calculations (IWEC) weather file for New Delhi was taken from the official webpage of the ISHRAE (Indian Society for Heating, Refrigeration and Air-conditioning Engineers) and used as input for the simulation. The dry bulb temperature plot for the whole year is shown in Figure 6 from and it can be seen from the temperature data that the dry bulb temperature typically varies from 8°C to 38°C (96% of the time), and only 4% of the time, it goes beyond these values.

As per the weather file of New Delhi, the typical summer week is from May 13, 0100 hrs to May 19, 2400 hrs. Figure 7 shows the variation in dry bulb temperature and relative humidity (Secondary axis) for a typical summer week. Figure 8 shows the wind speed and direction variation (Secondary axis) for the same time duration.

The min, max, and average range for dry bulb temperature (Minimum: 28.9 °C, Average: 35.8 °C, Maximum: 43.6 °C), relative humidity (Minimum: 14.0 %, Average: 36.4 %, Maximum: 58.8 %), and wind speed (Minimum: 0.07 m/s, Average: 3.5 m/s, Maximum: 7.6 m/s) calculated from the typical summer week.

The UTCI for the climate of New Delhi has been plotted below in Figure 9. The percentage of time in which conditions are within the acceptable limits is found to be 44% which means 56% of the time UTCI is out of the thermal comfort range (either colder side or hotter side).

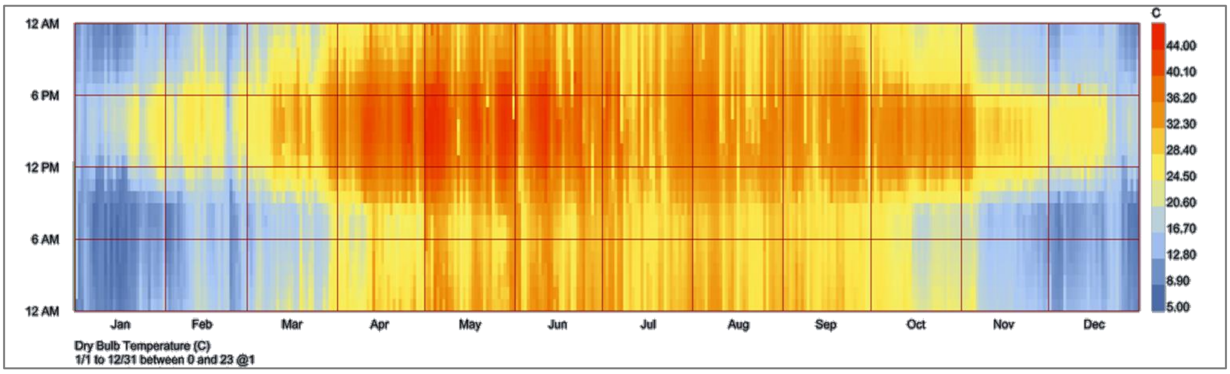

Figure 6. Dry bulb temperature plot of a whole year for the climate of New Delhi.

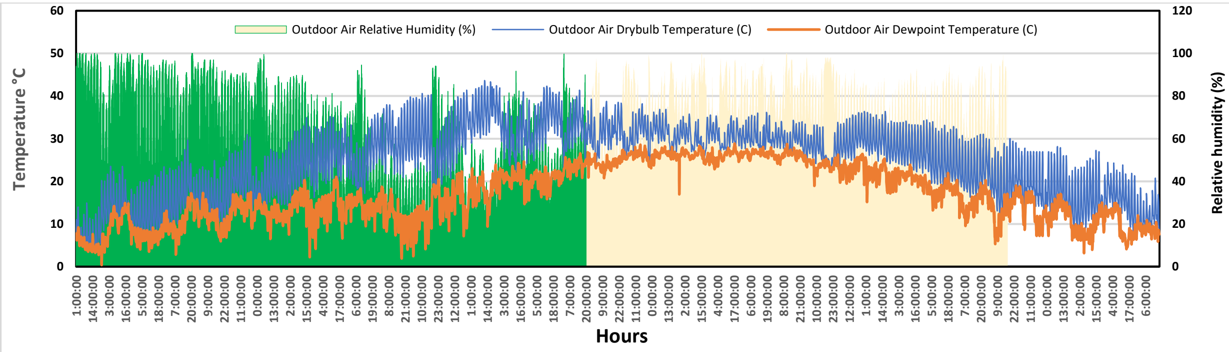

Figure 7. Dry bulb temperature, dew point temperature, and RH plot of New Delhi for typical summer days.

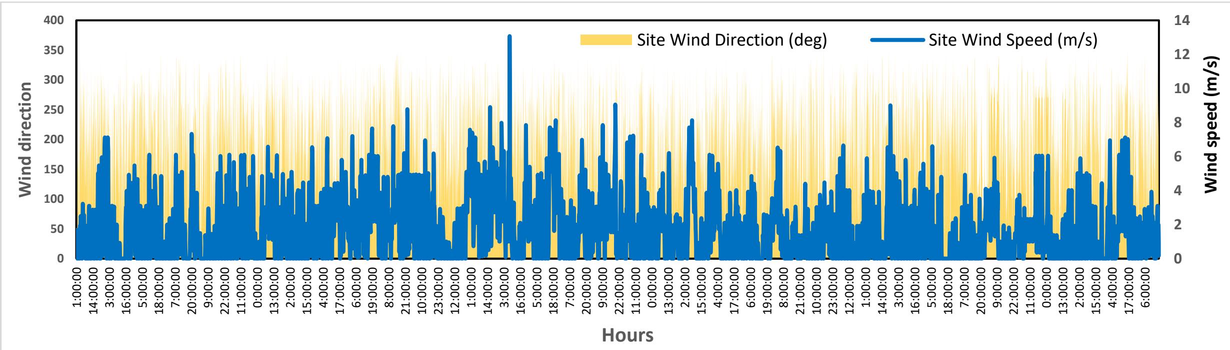

Figure 8. Wind speed and direction analysis of New Delhi for a typical summer day.

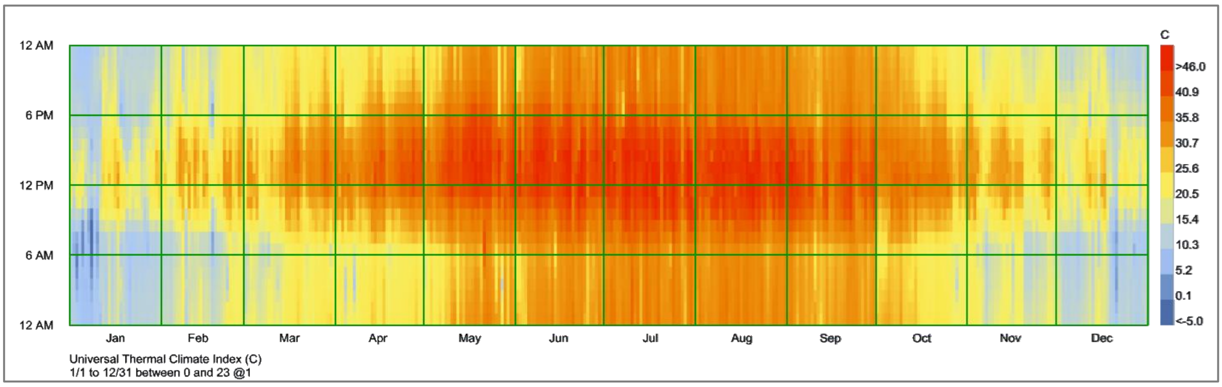

Figure 9. UTCI for New Delhi climate.

5.2. Modelling inputs for reference case

The modeling steps for calculating the UTCI are- 1) Importing climate data from weather file; 2) importing urban geometry from Rhino; 3) Generating mesh to create test points; 4) Using solar adjusted temperature to find out the MRT; 5) Selecting analysis period, i.e., typical summer days; 6) Calculating UTCI hour by hour and averaged for the selected time. Figure 10 shows the Grasshopper script created for the UTCI calculation in this study.

All the buildings have been considered mid-rise apartments with the same height per the actual drawings. A reference case has been simulated first with the actual values of each parameter considered in the simulation. The parameters needed for running the Grasshopper script are listed in Table 2.

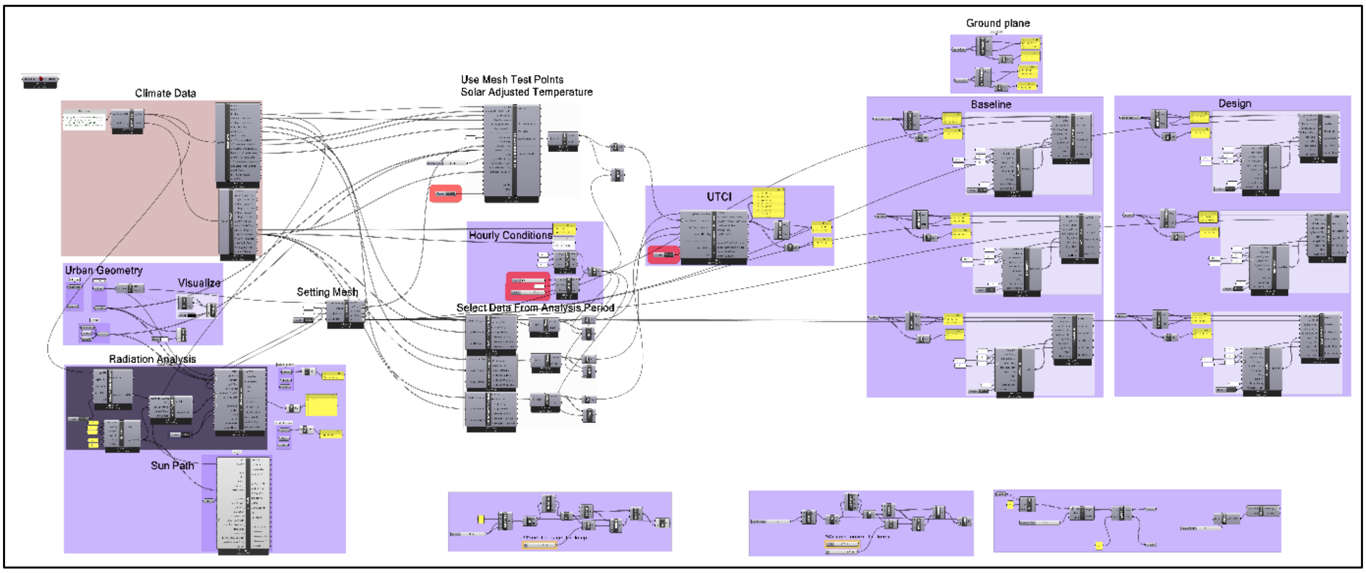

Figure 10. A snapshot of the Grasshopper interface for calculating UTCI.

Table 2: Inputs required for running the Grasshopper script.

	Building type	Mid-rise apartment Old construction
Building typology	Average building height	20 m
	Wall reflectivity	0.2
	Roof reflectivity	0.2
	Pavement reflectivity	0.2
	Site coverage ratio	46%
	Tree coverage ratio	0.05
Modelling in-puts	Grid size	2
	Distance from base surface	1.5 m
	Time period	Typical summer week

5.3. Results for reference case

This section explains the outcomes of the simulation for the reference case for the time from May 13 to May 19. As discussed earlier, two different metrics are used to evaluate outdoor thermal comfort, i.e., MRT and UTCI. The MRT is determined as the accumulation of the three components; long-wave radiation from the surfaces; long-wave radiation absorbed by the human body, and absorbed solar short-wave radiation. After MRT assessment, calculation of various comfort metrics such as Predicted Mean Vote (PMV), UTCI can be estimated.

Figure 11 shows the UTCI value for the complete residential campus and a part of the residential campus for the representative case. It is shown from the graph that using the reference case parameters, the UTCI lies in the range of 31.8 °C to 37.8 °C with a mean average value of 33.6 °C. The UTCI level for the reference case falls under 'Strong heat stress,' meaning the outdoor temperature is not comfortable for a typical summer weak.

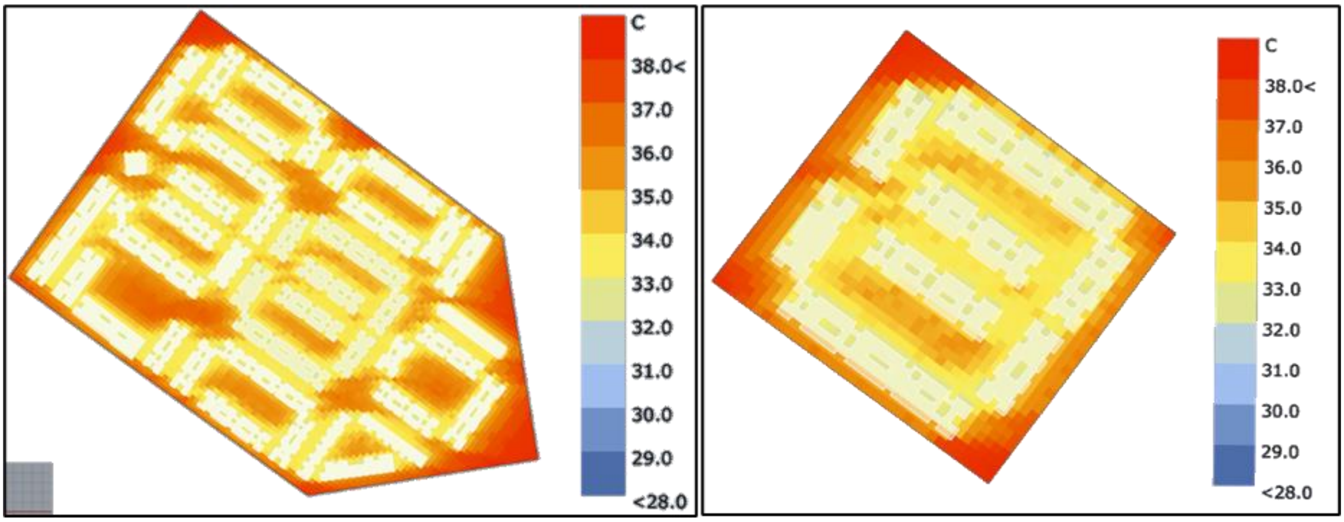

Figure 11. Representation of UTCI for (a) Complete residential campus; (b) A block of the residential campus.

Also, it has been concluded that because of the uniformity of the building's location and size, the UTCI is evenly distributed in the whole area, so only one block of the campus has been chosen for the parametric study to reduce the computation time.

6. Parametric analysis

The study's main objective is to identify the combined strategies to reduce UHI mitigation. The combined approach has been used for the parametric simulation. This approach models a combination of all possible measures (parameters) to account for the cascading benefit of each component. These measures are applied over the Reference Case. The simulation outcomes for each combination will be recorded as UTCI values, and the final recommendation will be based on a reduction in the UHI with respect to the reference building.

Figure 12 provides an overview of the combined approach. It is noteworthy that the Combined approach is a 'Brute Force' approach and to keep the number of simulations manageable, the resolution of parametric variations will have to be assessed.

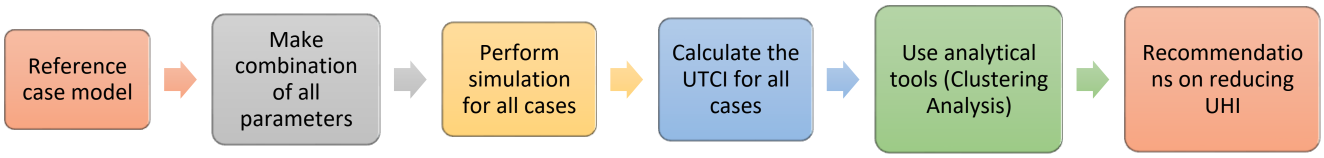

Figure 12. Steps for the combined approach.

6.1. Sensitivity analysis

Sensitivity analysis is used to distinguish the major input parameters of the UTCI metric in distinct conditions [78]. Primarily, it is used to develop the rank-order significance of input variables in multivariate analysis. It is valuable to understand how the variables affect the solutions and quantify the total impact when concurrently altering all parameters. In this study, UTCI has been chosen as a suitable metric as it is precise and accurate for all possible variables. The sensitivity analysis has been performed on three parameters with all possible variables such as wall reflectivity, Roof reflectivity, and pavement reflectivity. These three parameters will affect the outdoor thermal comfort simulation significantly. The graph between UTCI at 1.5 m height for different reflectivity values has been defined in Figure 13.

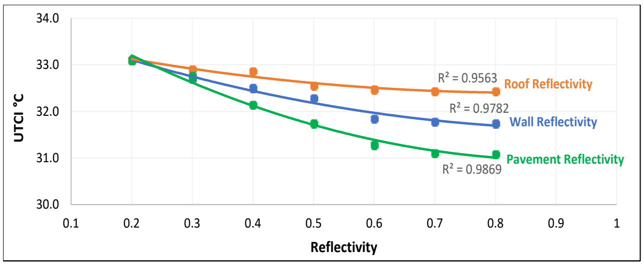

Figure 13. Sensitivity analysis for roof, wall, and pavement reflectivity.

The following inferences were drawn from the sensitivity analysis:

- Increasing the wall reflectivity after 0.6 has only minor effects on outdoor thermal comfort, whereas low wall reflectivity has a significant impact. Thus, it has been concluded that the variable greater than 0.6 wall reflectivity can be ignored for parametric simulation.
- There was a minor impact on UTCI values in the case of roof reflectivity. It does affect the UHI mitigation, but the outdoor thermal comfort values remain almost the same because of the working plane height to calculate it, i.e., at the human height of 1.5 m.
- The pavement configuration is the most valuable parameter; thus, it plays a major role in outdoor thermal comfort. All values for pavement reflectivity have been included in the parametric run.

6.2. Parametric analysis

The parameters have been taken from the literature review earlier in this study. The parameters include wall and roof reflectivity, vegetation, plantation, pavement configuration, and shading. Table 3 shows the number of parameters taken along with their respective values. It also explains the modeling strategy for each parametric run.

Several parameters are considered for parametric runs, which comes out to be 1,920 different simulations considering the combined approach. The high number of cases was also one of the reasons to select the small area of the whole residential campus to save computation time. The wall, roof, and pavement reflectivity directly changed into the model with their respective values selected for parametric analysis. For Tree plantation, the tree has been created with specific foliage density and size of the crown of the tree, and it has been distributed to those places where the UTCI was maximum and based on the feasibility. Same for vegetation, some grass pavers have been created to make a Park subject to space availability. The density of vegetation has varied based on the defined parameters.

The snapshot of tree modeling and vegetation modeling script in the Grasshopper has been shown in Figure 13.

Table 3: Parameters considered after sensitivity analysis.

No.	Parameters	No. of variables	Parameter's value	Modelling strategy
1	Wall reflectivity	4	0.2 - Concrete (Reference case) 0.3 - Brick 0.4 - Concrete, light grey 0.5 - White paint on concrete	Wall and roof properties have been calculated in Grasshopper with the help of energy simulation using EnergyPlus and OpenStudio
2	Roof reflectivity	3	0.2 - Concrete (Reference case) 0.4 - Concrete, light grey 0.6 - White paint on tiles	
3	Vegetation	4	None (Reference case) 20% of the available area 30% of the available area 40% of the available area	The grass has been added to the model as per the available area, such as the park can be created between the buildings with ample spaces.
4	Plantation	5	None (Reference case) Small crown + 70% foliage density Small crown + 90% foliage density Big crown + 70% foliage density Big crown + 90% foliage density	Trees are modelled in the Grasshopper with specific foliage density, then distributed based on space availability.
5	Pavement configuration	4	0.2 – Asphalt (Reference case) 0.3 - Grass 0.4 – Cemented blocks 0.5 - Cemented blocks, light grey	Pavement reflectivity is varied. Different type of pavers has been modelled except on the road. The Grasshopper takes advantage of multiple test points for other types of pavements.
6	Shading	2	None (Reference case) Shading is provided in the parking areas and pedestrian areas	Radiation analysis is done to find out the requirement of shading. Shading is provided at the spaces on both sides of the road where there is parking.

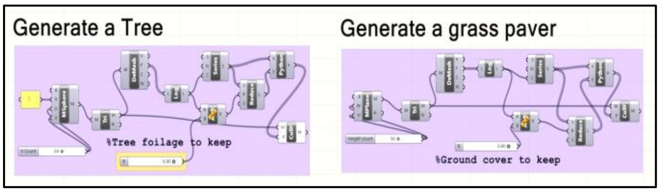

Figure 14. A snapshot of Grasshopper script to generate tree and grass paver.

A radiation analysis also has been done to evaluate the effect of shading. It helps to find the places where direct sunrays incident on surfaces and blocking them from reaching the ground helps to reduce the UTCI, thus reducing the UHI. Figure 14 shows the snapshot of the grasshopper script of radiation analysis.

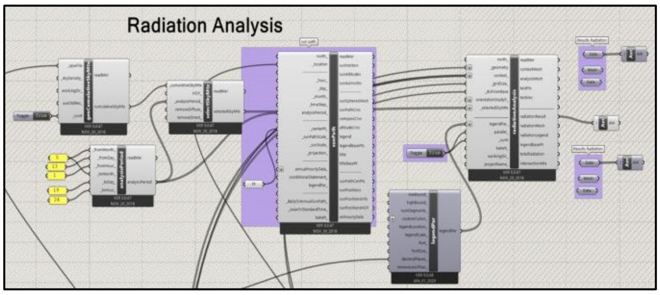

Figure 15. A snapshot of radiation analysis script in Grasshopper.

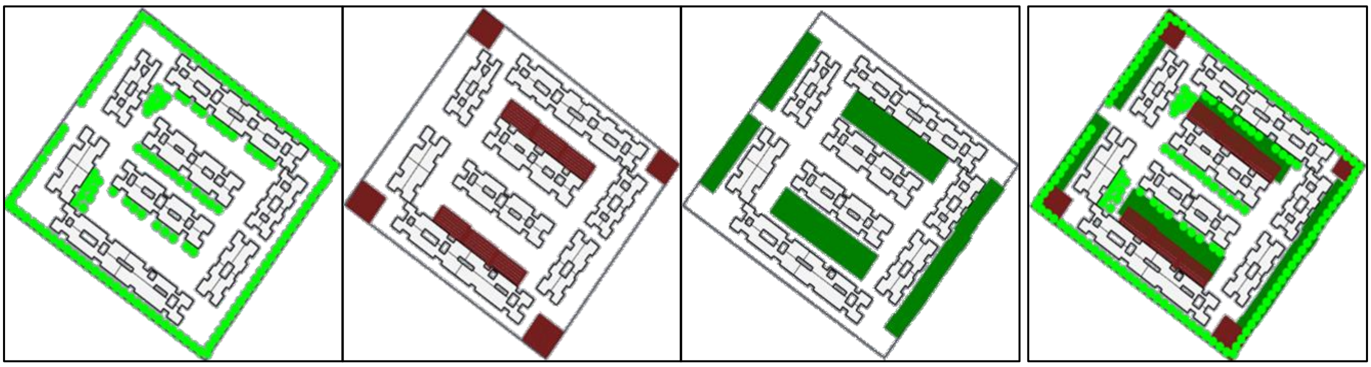

Figure 16. Representation of parameters (a) Trees; (b) Shading; (c) Vegetations; and (d) all three combined.

The radiation analysis has been done to find the requirement of shading in the urban areas of the residential campus. The sun path has been simulated, and the sun's position has been estimated on a typical summer day. It has been found that during the typical summer days in Delhi, the sun stays overhead most of the time, so the angle of shading to cut the direct sun rays should be overhead only. The analysis evaluates the shading spaces from which the long-wave radiation of the sun can be reflected without reaching the ground, thus reducing the UTCI. Figure 16 shows the sun path and radiation analysis for the peak day in summer.

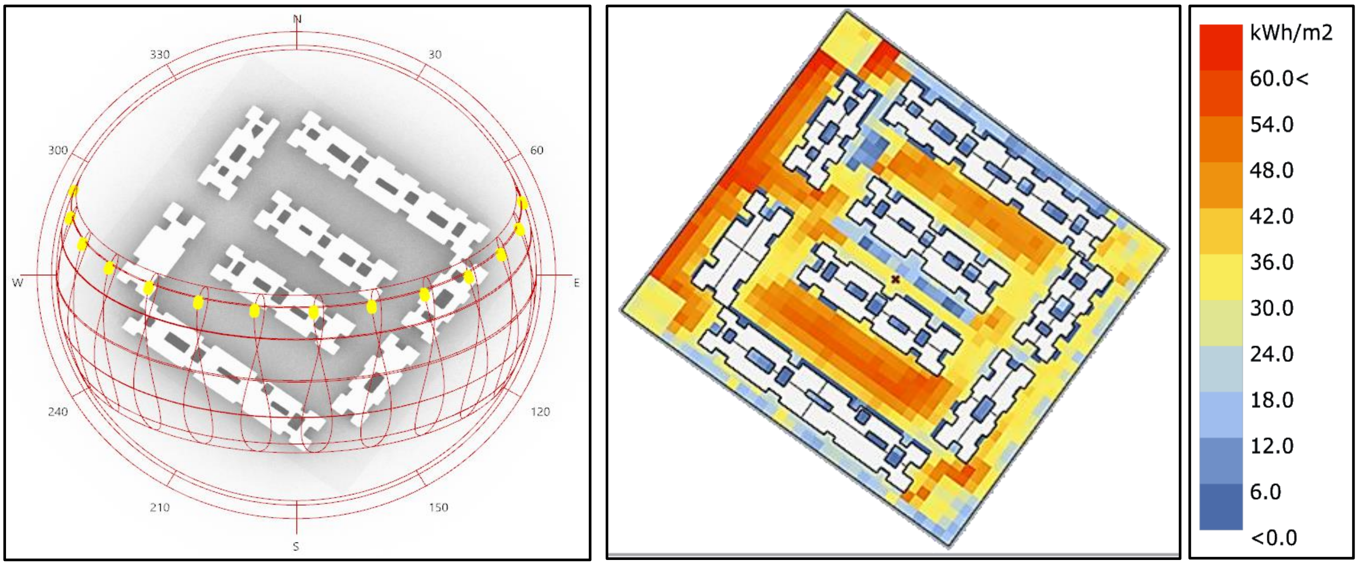

Figure 17. (a) Sun path and (b) Radiation analysis to find out the shading location.

The combined approach has been followed with different variables to calculate UTCI. Each parameter result has been plotted in the parallel plot. A Parallel plot permits a comparison of the feature of various individual values on a group of numeric variables. Each vertical column represents a variable and has its own scale. The values are then defined as a set of lines connecting each axis. The parallel plot shows the combined effect of each parameter on the UTCI values, and the best case to reduce the UTCI reduction can be selected knowing all the parameters used to bring the final value. Figure 17 shows the parallel coordinate chart for 1,920 variables.

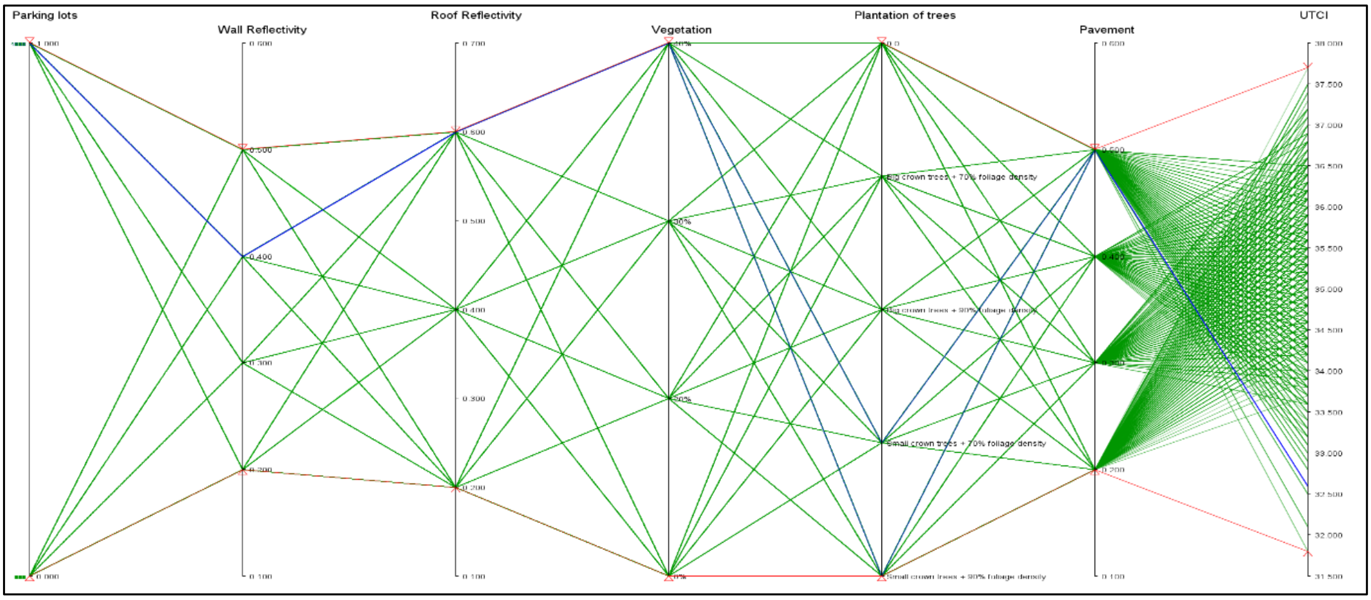

Figure 18. Parallel plot of UTCI as an output for parametric analysis.

It can be seen from the parallel plot that the UTCI range varies from 32.2°C to 37.7°C, i.e., approximately 5.5 °C reductions in UTCI values by applying different types of UHI reduction strategies. The best cases with different variables have been identified from the analysis and summarized below in Table 4.

Table 4: Best cases to reduce UTCI by approximately 5.5 °C.

Case no.	Wall reflectivity	Roof reflectivity	Vegetation	plantation of trees	Pavement reflectivity	Parking lots	UTCI
1	0.5	0.6	40%	Big crown trees + 90% foliage density	0.4	Yes	32.2
2	0.5	0.6	30%	Small crown trees + 90% foliage density	0.5	Yes	32.5
3	0.4	0.6	40%	Big crown trees + 70% foliage density	0.4	Yes	32.6
4	0.3	0.6	40%	Small crown trees + 70% foliage density	0.5	Yes	32.7
5	0.5	0.4	40%	Big crown trees + 70% foliage density	0.4	Yes	32.8
6	0.5	0.4	30%	Big crown trees + 90% foliage density	0.5	Yes	32.8
7	0.4	0.4	40%	Big crown trees + 90% foliage density	0.4	Yes	32.9
8	0.5	0.4	40%	Small crown trees + 70% foliage density	0.5	Yes	32.9
9	0.4	0.4	30%	Big crown trees + 90% foliage density	0.5	Yes	33.0
10	0.5	0.4	30%	Small crown trees + 70% foliage density	0.5	Yes	33.1
11	0.4	0.4	40%	Small crown trees + 70% foliage density	0.5	Yes	33.1
12	0.3	0.4	40%	Big crown trees + 90% foliage density	0.5	Yes	33.2
13	0.5	0.6	40%	Small crown trees + 70% foliage density	0.3	Yes	33.2

There are 13 best cases found where the UTCI gets reduced from approximately 4.5°C to 5.5°C. Below inferences can be drawn for each parameter from the parametric analysis:

- UTCI level decreases significantly while varying the pavement configuration and keeping it as high as possible along with other parameters. Thus, pavement reflectivity plays a major role in decreasing the UTCI levels. However, there can be some limitations to increasing the reflectivity to some extent due to physical constraints.
- Roof reflectivity hardly impacts the UTCI levels by 0.2 to 0.3°C only. As these are midrise buildings, roof reflectivity does not impact very much on the UTC levels. However, it may reduce the UHI effect, which was not a part of the study.
- Tree plantation varying foliage density of leaves affect the UTCI level. Trees with a small crown with high foliage density significantly reduce UTCI compared to big crown trees with low foliage density. Thus, shrubs and plants can be sown to reduce UTCI effectively.
- Shading provides a good reduction in the UTCI levels, but for the New Delhi climate, the sun angle is mostly overhead in the summer period, so the shading also should be done horizontally to the pavement to minimize the radiation. The representation of some cases simulated is given below to understand the change in UTCI by changing the parameters. Figure 18 shows four different cases with different parametric values, and it can be easily visualized that the UTCI value is changing by changing the values of parameters individually.

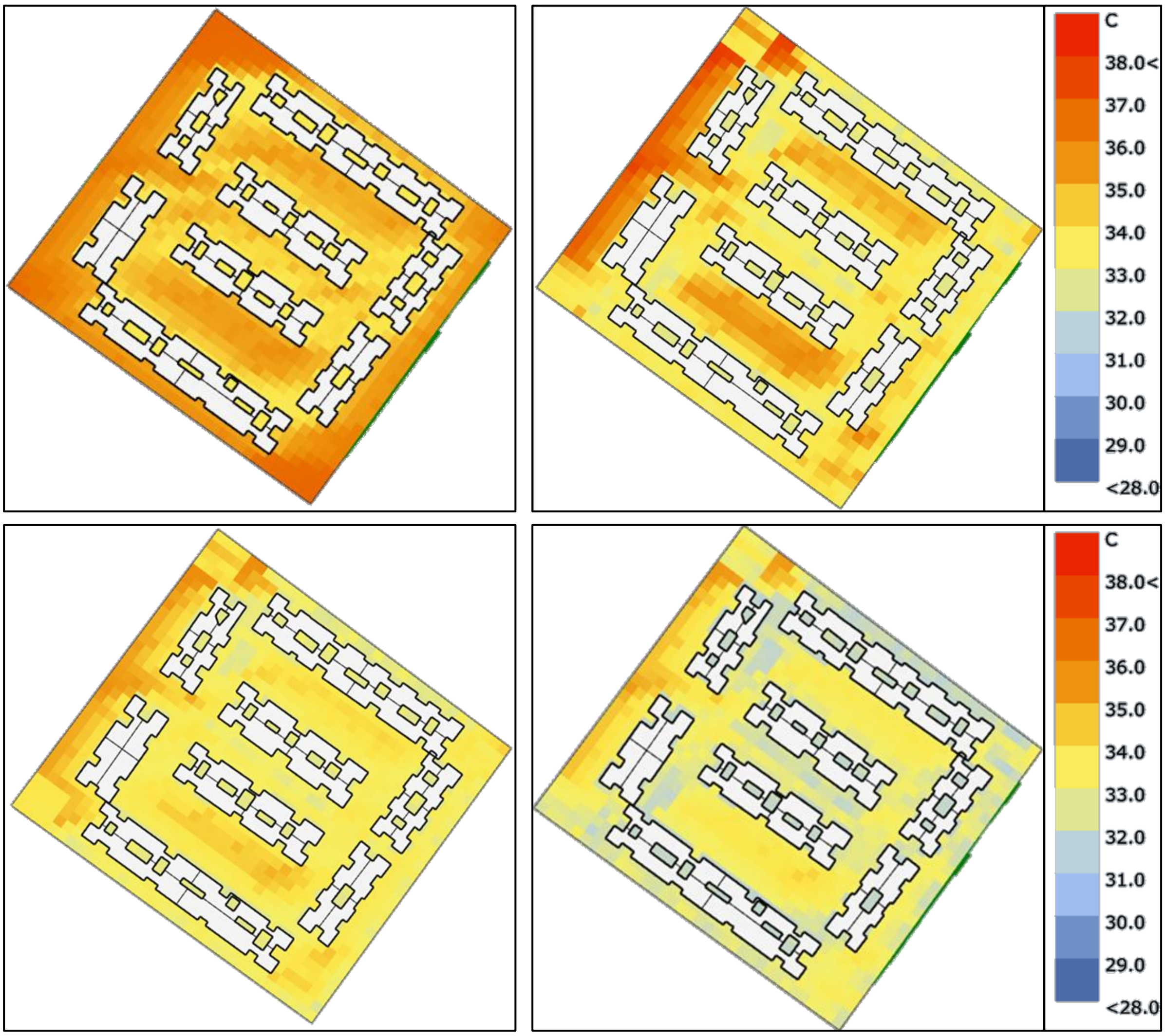

Figure 19. Representation of UTCI for (a) considering wall and roof reflectivity; (b) considering shading and trees plantation; (c) considering pavement configuration, shading, trees, and vegetation (d) considering all parameters in effect for the best case.

7. Limitations and future scope

A thorough approach requires using some necessary assumptions and algorithms to minimize the computational time and cost, thus introducing potential inaccuracies worthy of debate and additional improvement. This is especially true when evaluating the external thermal field, whereas defining the internal thermal conditions depend on highly verified simulation engines like EnergyPlus and OpenStudio. There are few assumptions taken while simulating the model due to incompatibility of the tool or other reasons. There is a possibility to work on these assumptions to make results more robust and reliable. A summary of these limitations is discussed in this section.

The outcomes of the analysis provide several ideas about possible weaknesses in the model. One example is the interpretation of the ground surface. Grasshopper needs to handle it as a surface of a thermal region to estimate its temperature; as a result, an imaginary thermal region was created in the model. However, there is no literature on this thermal ground zone definition.

Another limitation of the study defines that the plugin Ladybug and Honeybee is not a viable approach for quantifying the impacts of the evapotranspiration mechanism across vegetation spaces; in other words, it is only used to assess the shade effects on either structures or passageways between barriers. The water bodies' incorporation can also be done if the evapotranspiration mechanism is integrated with the Grasshopper plugins.

However, the workflow's usefulness is limited by the need to offset the computational expense of adding thorough bottom-up techniques, such as doing CFD, and the consistency of the model's performance. The authors decided not to incorporate wind analysis to conduct a significantly higher number of geometry variations because the methodology has been demonstrated to be reasonably reliable when applying wind speeds from the weather file. Other methods available in Grasshopper comprise wind analysis using Butterfly [79] or Eddy3D [80], which generate wind factors and the ratio between simulated and the inlet wind speed produced from various directions. On the other hand, these methods are less accurate than including turbulent heat exchanges into the model, a feature of the OpenFOAM program that has not yet been incorporated (presently work in progress) in any plugins.

The future scope can integrate the daylight performance metrics such as Spatial Daylight Autonomy (SDA) with this framework. Moreover, as previously stated, the influence of urban green infrastructure on energy and outdoor comfort was not taken into account in this study. As a result, more studies may be done to address this issue and examine its larger implications.

Finally, the process is a useful tool for estimating MRT dispersion in urban areas and the efficacy of relevant mitigation efforts using appropriate metrics like the UTCI and evaluating the energy implications of building operations in urban regions. The authors are presently investigating ways to improve the workflow, including confirming the methods used in some components.

8. Conclusion

Thermal outdoor discomfort is becoming a major concern for pedestrians' areas present in urban canyons or open spaces that are enclosed by built structures. In the context of climate change, urban layout, dimensions, and building envelope features impact efficient energy use and outdoor thermal comfort. Hence, this analysis suggested a simulation modeling context based on the Grasshopper plugin to model the building characteristics and parameters affecting outdoor thermal comfort. The study aims to find the most used indices for outdoor thermal comfort, i.e., the Universal Thermal Climate Index (UTCI). It is a widely acknowledged, simple to calculate the human thermal index, and the outcomes can be plotted as human bioclimatic maps. They would be a valuable tool for evaluating the outdoor thermal effects of urban landscape planning and design.

A 3-dimensional simulation model of a residential area in a composite climate has been developed. This model predicts the microclimate with different parameters. Based on the simulation results, the UTCI was revised to evaluate the outdoor thermal comfort. The Ladybug-tools microclimate model has demonstrated its potential to calculate the mean radiant temperature and the resultant outdoor thermal comfort. It was shown that the UTCI could be reduced by almost 5°C by combining UHI mitigation strategies such as changing the reflectivity, tree plantation, vegetation, pavement configuration, and providing shading. Furthermore, the established simulation methodology can assist urban designers in more efficiently designing and optimizing buildings and outdoor spaces to enhance energy efficiency and minimize thermal discomfort in outdoor areas.

The simulation framework supports less simulation time having greater flexibility, with the caution of less accuracy due to ignoring energy models. However, it is not very important in the early stages of design. These outcomes, despite advances in urban microclimate research, establishing a connection between urban design elements/strategies and human comfort, as assessed by UTCI, is still a work in progress.

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