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Investigating Ladybug as A Tool for Measuring Outdoor Thermal Comfort in Urban Neighborhoods

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Keywords
Outdoor Thermal Comfort (OTC); Universal Thermal Climate Index (UTCI); Urban Environments; Ladybug Tool.

Abstract
The increasing global temperature has increased awareness of enhancing Outdoor Thermal Comfort (OTC). OTC has become a primary indicator for the effectiveness of urban environments, which directly affects inhabitants' health, comfort, and quality of life. Consequently, many thermal comfort indices were developed to quantify outdoor thermal comfort; among them was the Universal Thermal Climate Index (UTCI), which is one of the broadly used thermal indexes in evaluating OTC. As another axis of this awareness, several computer-aided design (CAD) software have worked on developing their techniques to increase the accuracy of their outdoor simulations and climate measurements. The paper concerns exploring the potential of the Ladybug as a tool for measuring UTCI through an algorithmic script designed with the Ladybug (ver. 1.6.0) in the Grasshopper interface within Rhinoceros 3D software. The script was applied to two urban neighbourhoods in different climate zones of Egypt, Cairo (an inland city and the capital of Egypt) and New Damietta (a coastal city on the Mediterranean Sea), to investigate its capabilities in simulating and measuring the UTCI of different climate zones in the extreme hot week of the year as an examination period. Results showed that the maximum UTCI value in the coastal neighbourhood decreased from 32.93°C to 31.64°C, while its minimum value decreased from 28.79°C to 27.28 °C compared to the inland neighbourhood. The maximum and minimum UTCI values, hourly data, and the percentages of UTCI heat stress categories for six test locations in each neighborhood were also calculated and compared.

1. Introduction

Over the last few decades, urban environments have grown significantly; 54% of the world's population lives in urban areas, and this percentage is expected to rise to 66% by 2050 [1]. This vast urbanization growth has reduced the sustainability of urban environments as they have higher air and surface temperatures compared to rural cities, a phenomenon called urban heat island (UHI)

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[2,3]. A recent study showed that the average UHI intensity is between 4.1 °C and 5.0°C, with peaks of 11.0 °C in urban cities compared to rural cities. UHI is considered one of the main factors that led to the increasing global warming phenomenon, which has become more observed in recent years [1]. Global warming, or global mean surface temperature, is continuously increasing and will continue to increase along the lifespan of generations because of the increasing urbanization ratio. It was detected to be 1.09°C higher in 2011–2020 than in 1850–1900 [4] and was expected to increase by 0.3 to 4.8 °C by the year 2100., Fig. 1 [5].

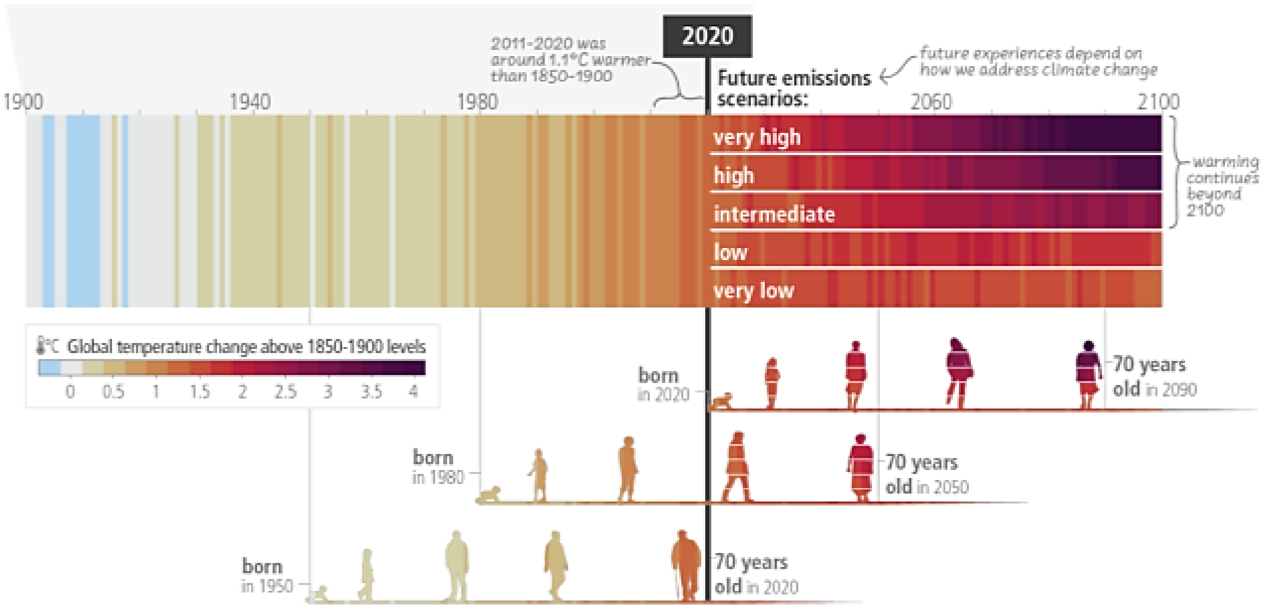


Fig. 1: The increases in the global surface temperature among generations [4].

The increases in global warming and urban heat island have become severe issues that need to be studied to decrease their negative consequences on the health and thermal comfort of citizens. Studies on outdoor thermal comfort (OTC) only began to increase around the early 2000s [6]. Its concept focuses on promoting the physical, environmental, and social conditions of outdoor spaces [7]. Optimizing OTC has become one of the main goals of urban planning designers, since providing comfortable outdoor space could positively encourage more inhabitants to spend a longer period outdoors and provide social, environmental, physical, and health benefits. [3].

On the one hand, several thermal comfort indices were developed to quantify OTC, such as the Universal Thermal Climate Index (UTCI), which is considered one of the most widely used indexes that has proven its efficiency in evaluating OTC [8]. On the other hand, many CAD software programs were continuously working on optimizing the accuracy of their technologies in simulating and measuring UTCI.

The research aimed to explore the capabilities of the Ladybug tool in calculating UTCI by using an algorithmic script designed with the Ladybug tool to measure the UTCI values of two neighbourhoods in two different climate zones, in an inland and a coastal city. To attain this aim, the research methodology was divided into three parts: **First,** a literature review clarifies the OTC concept, definition, and interrelated parameters. UTCI and its thermal stress categories, and the difference between temperature and UTCI in coastal and inland cities. Along with identifying Ladybug tool usage and capabilities. **Second,** illustrate the scripted algorithmic workflow, its steps, and the structure for measuring UTCI while applying it to the two neighbourhoods to validate the capabilities of Ladybug in measuring UTCI and distinguishing between different climate zones' values. **Third,** present the results and outputs of the two urban neighbourhoods, discuss, compare, and validate the measurements of the script with the results of relevant studies, and lastly, discuss the conclusion and future recommendations.

2. Literature review

2.1. Outdoor Thermal Comfort (OTC)

Thermal comfort can be defined as a state of mind that expresses satisfaction with the thermal condition of the surrounding environment. In outdoor spaces, it is a main indicator of the quality of the urban space; providing appropriate thermal comfort leads to prolonging the duration of outdoor activities, enhancing the life and vitality of the city, and reducing energy consumption in built environments. [7, 9]. However, outdoor thermal comfort is affected by multiple disciplines, as several factors affect the heat flow from the human body. Researchers have studied and classified these elements in several studies; Table 1 summarizes most of them.

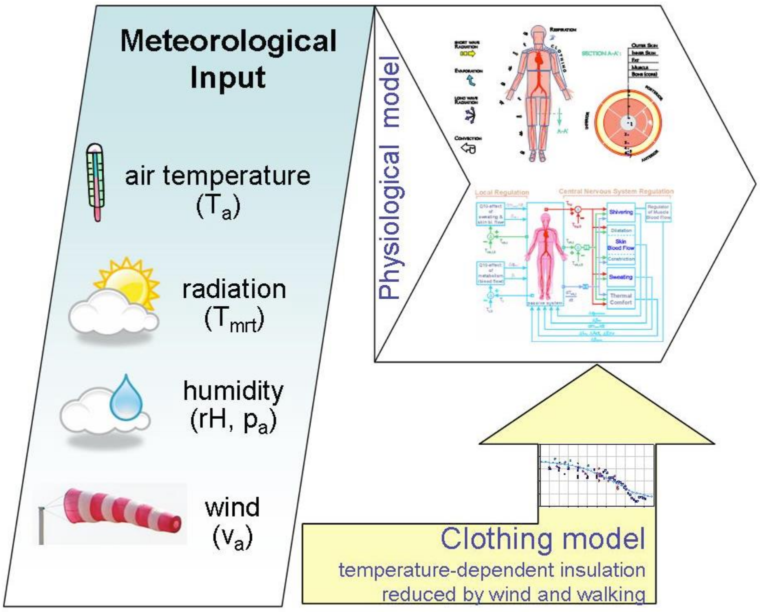
Table 1: Approaches that affect outdoor thermal comfort [2, 7, 8]

<table>
<tr><td rowspan="7">Approaches that affect outdoor thermal comfort</td><td rowspan="5">Environment-based approaches</td><td rowspan="3">Physical Characteristics</td><td>Morphology and geometry</td><td>- Buildings' form, height, and layout.
- Built-up density.
- Street canyon profile factors (building height to street width ratio, orientation, and pedestrian sidewalk).
- Open spaces ratio.</td></tr>
<tr><td>Landscape planning</td><td>- Green planning (vegetation cover).
- Blue planning (water Surfaces).</td></tr>
<tr><td>Material</td><td>- Buildings' material properties (albedo and reflectivity).
- Hardscape material properties.</td></tr>
<tr><td rowspan="2">Basic Parameter</td><td>Climate condition</td><td>- Land characteristics (topography, altitude, latitude, longitude, and surface coverage).</td></tr>
<tr><td>Meteorological parameters</td><td>- Atmosphere of the place (air temperature, wind velocity and flow rate, relative humidity, mean radiant temperature, and solar radiation.</td></tr>
<tr><td rowspan="2">Human-based approaches</td><td>Individual Parameters</td><td colspan="2">- Gender.
- Age category.
- Metabolic rate.
- Clothing insulation.</td></tr>
<tr><td>Sociological Parameters</td><td colspan="2">- Social aspects.
- Economic aspects.
- Cultural aspects.</td></tr>
</table>

Managing all these elements was the complexity that faced the designers in evaluating OTC. Accordingly, in the last few decades, many researchers have sought to standardize thermal comfort by developing thermal comfort indices; among these indices were Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI) [8]. However, in conditions of extremely high vapor pressure values, UTCI gives more accurate values, can describe the thermophysiological stress more appropriately, and is also better for warm and humid environments [10]. Since the research has used the extremely hot week of the year as an experimental period, UTCI was used to evaluate the outdoor thermal comfort of the two selected neighborhoods.

2.1.1. Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index was developed in 2009 through international cooperation between the International Society on Biometeorology (ISB) and the Cooperation in Science and Technical Development (COST-Action 730), as leading experts in the areas of human thermophysiology, physiological modelling, meteorology, and climatology. Their aim was to develop an international standard index that describes the effects of meteorological conditions (air temperature, radiation, air humidity, and wind speed) and thermo-physiological conditions (clothing and activity) on humans. UTCI is defined as the air temperature of the reference condition causing the same model response as actual conditions [10, 11, 12, 13]. It simply describes the thermal stress caused by the combined influence of air temperature, mean radiant temperature, relative humidity, and wind speed on an equivalent temperature scale and thermophysiological and behavioural clothing models [14, 15]. The UTCI values were categorized into ten categories of thermal stress, ranging from 'extreme cold stress' to 'extreme heat stress, based on criteria derived from the simulated physiological responses, Fig. 2 [16].



UTCI (°C)	Stress Category
UTCI > 46	Extreme heat stress
38 < UTCI < 46	Very strong heat stress
32 < UTCI < 38	Strong heat stress
26 < UTCI < 32	Moderate heat stress
9 < UTCI < 26	No thermal stress
0 < UTCI < 9	Slight cold stress
-13 < UTCI < 0	Moderate cold stress
-27 < UTCI < -13	Strong cold stress
-40 < UTCI < -27	Very strong cold stress
UTCI < -40	Extreme cold stress

Fig. 2: Concept of UTCI as a categorized equivalent temperature scale [11, 14, edited by author]**.**

2.1.2. Temperature and UTCI in Coastal and Inland Cities.

This part showed the differences in the temperature and UTCI values of the inland and coastal sites and the results of prior relevant research about this point, as the two selected neighbourhoods in this study are an inland city (Cairo) and a coastal city (New Damietta), and that to test the abilities of the ladybug tool in calculating the UTCI values of different climate zones.

Water has a higher heat capacity than soil and rock, which gives oceans and seas the ability to absorb large amounts of heat, store it, and release it over long periods of time, much slower than land, making coastal areas take a longer time to become hot in the daytime and remain warmer for a longer time at night than inland cities. Accordingly, coastal areas have more moderate temperatures than inland areas because of the heat capacity of the nearby ocean or sea, which acts as a temperature buffer [17, 18]. Coastal areas are also influenced by sea breezes, which bring in cooler air from the ocean during the day, moderating temperatures. While inland areas may experience different wind patterns depending on their local topography [19].

Several studies have analyzed the variation in temperature between coastal and inland cities. Their results showed that inland climate regions are subject to higher temperature ranges than coastal climate regions. Among them was a study performed on inland and coastal cities in South Korea for the past 60 years (from 1961 to 2020). It showed that the annual average maximum temperatures over 60 years were 18.3°C and 18°C in the inland and coastal areas, respectively, while the annual average minimum temperatures were 8.5°C and 10.4°C in the inland and coastal areas, respectively [19]. Another study was performed on Scone (an inland town) and Newcastle (a coastal city) in Australia to compare their temperatures over the past 40 years. The results showed that the mean maximum temperatures for Scone have increased with p-values of 0.058, while those for Newcastle have increased with p-values of 0.002. In addition, the mean minimum temperatures for Scone remained stable, while those for Newcastle increased with p-values of 0.015 [20].

The differences in UTCI values between coastal and inland cities have also been extensively investigated in many studies. Their findings demonstrated that the maximum and minimum UTCI values of coastal sites are lower than those of inland sites. From them was a study performed on an inland commercial street and a coastal park in China to study the difference between the thermal comfort of hot spots and cold spots. It was performed on a typical summer day and used UTCI to determine the thermal benchmarks. The results of the study showed that the neutral UTCI was 26.0°C in the commercial street and 24.1°C in the coastal park; the UTCI ranges were 23.3–28.7°C in the commercial street and 20.8–27.4°C in the coastal park, while the upper thermal range of the commercial street and the coastal park were 32.1°C and 30.2°C, respectively [9]. Another study was performed between three cities in the UAE, among them Al Ain (an inland city) and Dubai (a coastal city), to analyze their UTCI during the period 1980–2018. The results showed that the highest average UTCI values were in August; they reached 51.5 °C and 50.4°C in Al Ain and Dubai, respectively. While the lowest average UTCI values were in January, which reached 24.5°C and 18.2°C in Al Ain and Dubai, respectively [21]. Additional research has measured the differences in the mean yearly UTCI of eight cities in Poland; among them were Gdańsk (coastal city) and Kraków (inland city) in the period 1975–2014. Its results revealed that the mean yearly UTCI varied from 2.1 °C in Gdańsk to 6.8 °C in Kraków. [22].

2.2. Ladybug Tools Model

Over the past 40 years, a wide variety of computational software programs and models have constantly worked on maximizing the accuracy of their tools to simulate and measure the impact of climate on the effectiveness of urban environments [23]. Instances of these software and models are ENVI-met, RayMan, CityComfort+, CitySim Pro, and Ladybug Tools Model by Mackey [24].

Ladybug tools have the parametric abilities of the Grasshopper interface for Rhino3D. Grasshopper is a script-based modeling algorithm that creates geometries and their surrounding environment with a visual programming language interface, allowing designers to manipulate various design parameters and recreate different geometry configurations through geometrical iteration [15, 25]. This potential allows Ladybug tools to simulate numerous geometry configurations as well as measure, evaluate, and optimize their performance throughout the year, as opposed to other models, which can handle a limited number of urban canyon geometries to be able to optimize them. The Ladybug tools can also simulate the outdoor microclimate and simplify the long-wave radiation flow from the vegetation in noticeably less time compared to the other models, especially CFD-based models such as ENVI-met. These capabilities qualify the Ladybug tools to be one of the most efficient microclimate models when it comes to optimization studies and time and resource efficiency [24].

The Ladybug tools comprise Ladybug, Honeybee, Butterfly, and Dragonfly plugins. Each has its own capabilities that specialize in a particular field and analyze certain factors; they could also integrate to fulfill further analysis requirements [25]. For instance, the Honeybee tool performs daylight and radiation analysis using Radiance software and energy models using EnergyPlus or Open Studio software [26]. The Butterfly tool performs advanced computational fluid dynamics (CFD) using OpenFOAM software [27]. The Dragonfly tool analyses large-scale factors such as district-scale energy models for energy simulation with the URBANopt analytics platform and renewables optimization with the REopt energy planning platform [28].

The research focused on the first tool, the Ladybug tool, and its ability to simulate UTCI. The Ladybug tool is a comprehensive tool that can import EnergyPlus weather files (.epw) into Grasshopper, enabling dynamic cooperation between the visual programming interface of Grasshopper and validated environmental data sets and simulation engines. The Ladybug tool can perform sun path, wind roses and diagrams, shadow range, solar radiation, and outdoor thermal comfort analysis. It also creates psychrometric (thermal comfort graphics) and climate data in 2D and 3D charts. The relationships between Rhino, Grasshopper, and Ladybug are shown in Figure 3, along with the analysis done in the study using the Ladybug tool to simulate and measure UTCI [23, 25, 29], Fig. 3.

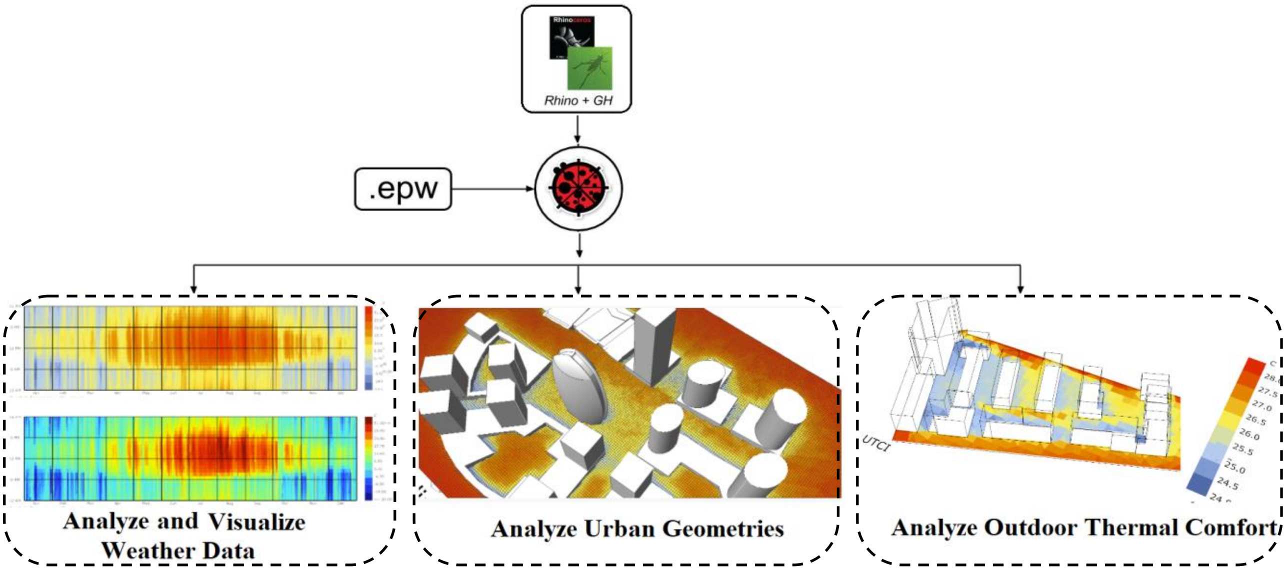


Fig. 3: The relationships between Rhinoceros, Grasshopper, and Ladybug to simulate an environmental model and calculate its climate data and UTCI [29, Author]**.**

3. Materials and Method

This section discusses the algorithmic script of the study, which was scripted to investigate ladybug capabilities in measuring UTCI in urban neighborhoods. It was divided into two stages. ***First,*** introduce the two selected neighbourhoods, their main characteristics, and models in Rhino software. ***Second,*** discuss the algorithmic script and its sequence; while applying it to the two neighbourhoods, measure the average UTCI of the two neighbourhoods through the extremely hot week of the year, locate the regions with high thermal stress, and measure the hourly UTCI values of six test locations in each neighbourhood.

3.1. The Selected Neighborhoods

The chosen neighborhoods are Sheraton Residences in Cairo and the 5th District in New Damietta, Fig. 4. The two residential neighbourhoods have close site areas, a linear street grid, close building functions (residential buildings, educational facilities (school/faculty), and a mosque), and similar construction materials (brick-concrete building structures). However, they were chosen to have different geographical locations and different climate zones in Egypt (Cairo is an inland city and the capital of Egypt, while New Damietta is a coastal city on the Mediterranean Sea) to explore the capabilities of the ladybug tool in measuring different sites’ climate data and UTCI.

Fig. 4: The Google Earth images of Sheraton Residences Neighborhood in Cairo and the 5th District Neighborhood in New Damietta, respectively [Author]**.**

Table 2 clarifies the coordination, area, and main characteristics of the two neighbourhoods (the Sheraton Residences and the 5th District neighborhoods).

Table 2: The two main characteristics of the two neighborhoods [Author]

	Sheraton Residences Neighborhood, Cairo	**The 5th District Neighborhood, New Damietta**
Coordination	30.1055° N, 31.3854° E	31.4313° N, 31.6853° E
Area (m^2)	165,281 m^2	165,502 m^2
Buildings Functions	Residential buildings, educational facilities (school) and mosque	Residential buildings, educational facilities (faculty) and mosque
No. of Floors	from 4 to 10 floors high	from 5 to 6 floors high
Buildings (%)	35.5%	25.6%
Open Spaces (%)	64.5%	74.4%
Streets, Pavements, and parking areas (%)	60.2% Which is 93.3 % of the open spaces	63.2% Which is. 85% of the open spaces
Green Spaces (%)	4.3% Which is 6.7% of the open spaces	11.2% Which is 15% of the open spaces

To assure the accuracy of the measurement, both neighborhoods were modelled using Rhino 3D software with their real size and measurements, Fig. 5.

3.2 The Algorithmic Script

The Grasshopper interface within Rhino software was used to start using the Ladybug tool. The Ladybug tool was developed in many versions within the last few years to increase the accuracy of the simulated environment and its measurements. The algorithmic script of the research was scripted with the latest version of the Ladybug tool, version 1.6.0, released on January 17, 2023 [30]. The entire algorithmic script with its three phases is shown in Fig. 6. ***First,*** import the climate data for the two cities and specify the required examination period. ***Second,*** import the two neighborhoods and calculate their MRT and UTCI, then detect the areas with high heat stress. ***Third,*** specify the six test locations in each neighbourhood to detect their hourly UTCI, daily max and min UTCI values, percent of thermal stress categories, and occurrence hours, to further detect the extent of the ladybug in specifying outdoor thermal comfort in specific regions.

The script is made up of several components that require input parameters (whether prerequired or optional) to calculate output results. Each component's output data is fed into other components of the Grasshopper constraint script until they achieve the required UTCI measurements, which were directly modelled and displayed in Rhinoceros 3D.

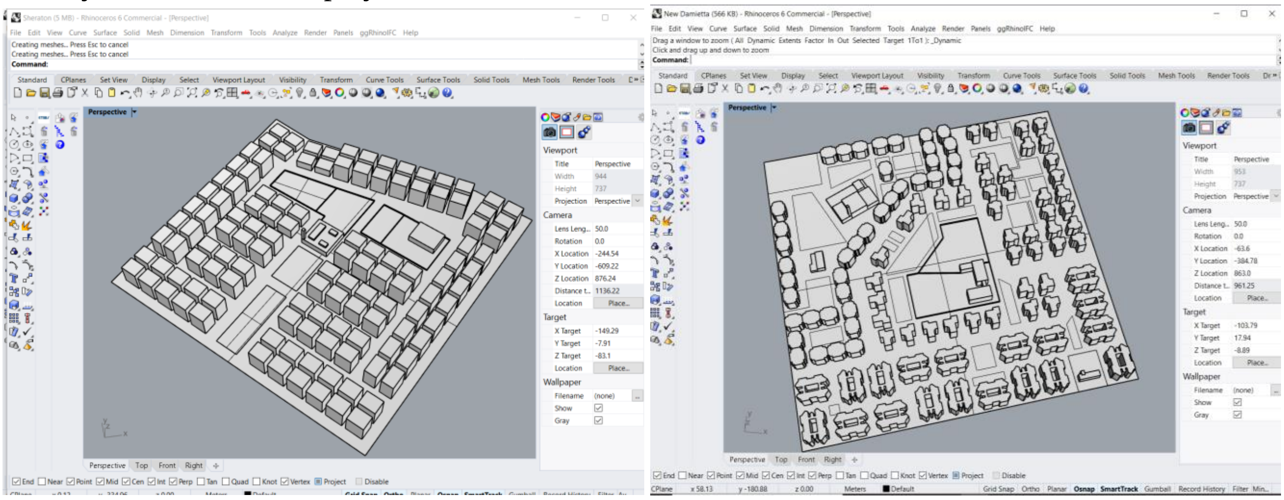


Fig. 5: The Models in Rhino 3D Software [Author]**.**
Right: The Sheraton Residences neighborhood in Cairo
Left: The 5th District neighborhood in New Damietta

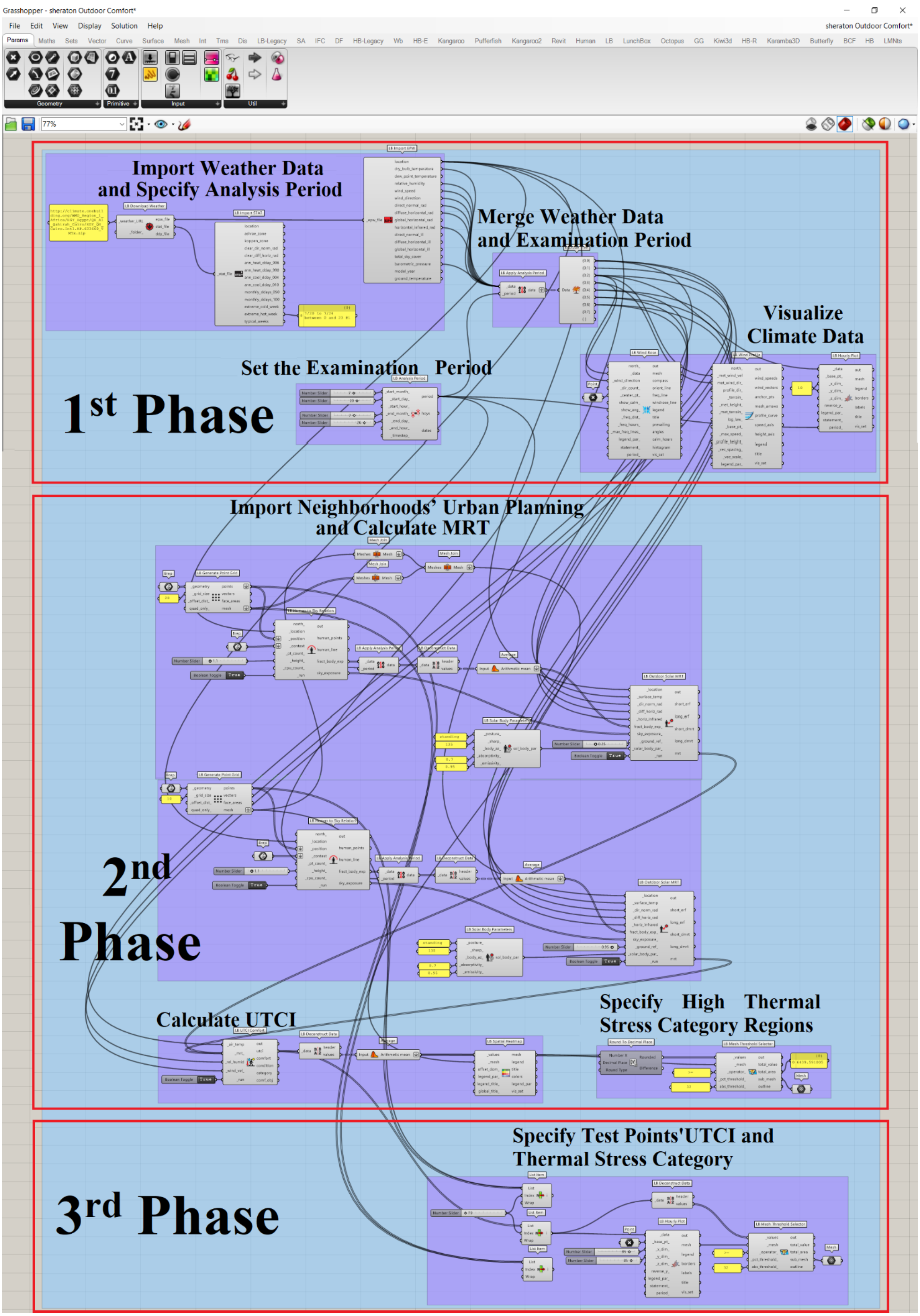


Fig. 6: The full algorithmic script in the Grasshopper interface [Author].

3.2.1. The 1st Phase: Cairo and New Damietta Climate Data Measurement

1. *Import weather data and define the analysis period.*

First, the "LB Download Weather" component was used to convert the two locations' URLs into (.epw) and (.stat) weather files [31]. Then, the (.epw) file was used as input for the “LB Import EPW” component, which in turn calculated the dry bulb temperature, relative humidity, wind speed, wind direction, direct normal radiation, diffuse horizontal radiation, and horizontal infrared radiation for each location. These weather data are effective parameters and prerequisites for measuring and calculating MRT and UTCI. While the (.stat) file was used to specify the analysis period duration (the extremely hot week in the year) for each location by inserting it in the “LB Import STAT” component, which stated that the required duration was from 20/7 to 26/7 in Cairo and from 1/8 to 7/8 in New Damietta.

2. *Set the analysis period.*

The “LB Analysis Period” component was used to script the required week; it was set from July 20 to July 26 for the Sheraton Residences neighborhood in Cairo and from August 1 to August 7 for the 5th District neighborhood in New Damietta, Fig.2.

3. *Merge the weather data with the analysis period.*

Both the “LB Import EPW” and “LB Analysis Period” components were connected into the “LB Apply Analysis Period” component to merge their data and get the climate data for the required analysis period, which was then connected to the “Explode Tree” component to differentiate the required data.

4. *Visualize the climate data for the required analysis period.*

To clarify the differences between the climate values and measurements of the two locations, the dry bulb temperature, relative humidity, and direct normal radiation were used as input for the “LB Hourly Plot” component to create and visualize their hourly plot, Fig. 7. Also, the wind speed and wind direction data were used as input for the “LB Wind Rose” and the “LB Wind Profile” components to generate the wind rose and calculate the prevailing wind direction and speed in each location, Fig. 8.

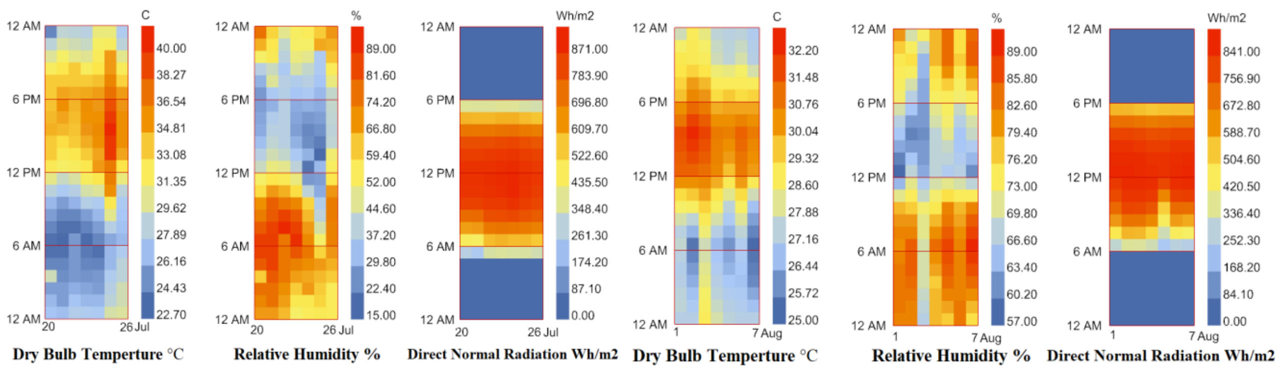


Fig. 7: Hourly plots for the dry bulb temperature, relative humidity, and direct radiation, in Cairo (from 20/7 to 26/7) and New Damietta (from 1/8 to 7/8), respectively [Author]**.**

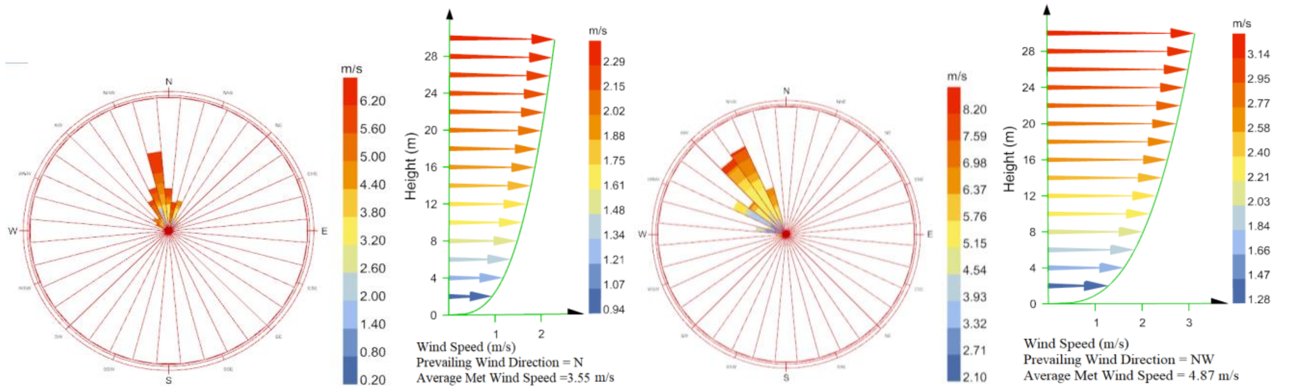


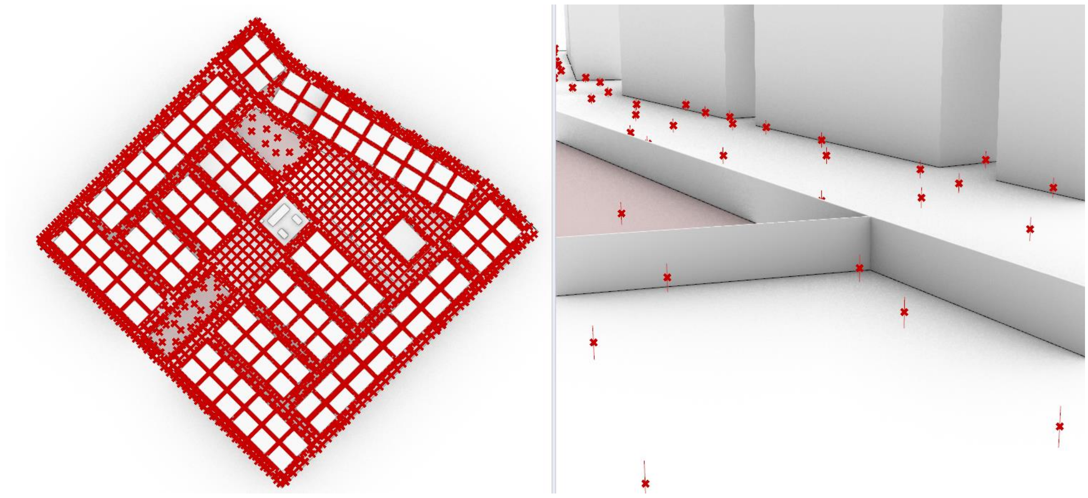
Fig. 8: The Wind rose and wind speed
in Cairo (from 20/7 to 26/7) and New Damietta (from 1/8 to 7/8), respectively [Author]**.**

3.2.2. The 2nd Phase: UTCI Calculation

1. *Import the urban planning of the neighborhoods.*

In this stage, the urban planning of each neighborhood was imported into the grasshopper interface to accurately calculate fraction body exposure and sky exposure, which were two required inputs to accurately measure MRT and consequently UTCI. Fraction body exposure is a number between 0 and 1 that indicates the fraction of the body exposed to direct sunlight; it includes the shading from surroundings, not the body's self-shading. While sky exposure is a number between 0 and 1, it represents the percentage of the sky vault that a person can see. [32].

Both requirements were estimated by the “LB Human to Sky Relation” component by giving it the location of the neighborhood, the position of residents in the outdoor environment, the context surfaces that can block the direct sun, and the height at which it needed to be calculated. The location was gotten from the “LB Import EPW” component. For getting the position of residents, the “LB Generate Point Grid” component was used to define the location of streets and green areas separately. For the context, the buildings were inputted as context geometry that can block the residents from being subjected to direct sun and the view of the sky. Lastly, the height was set to be 1.1 m high (the height of the gravity center of the human body [10]). By running the “LB Human to Sky Relation” component, a grid was generated; each point in it represents the location of a pedestrian in the outdoor environment, Fig. 9.



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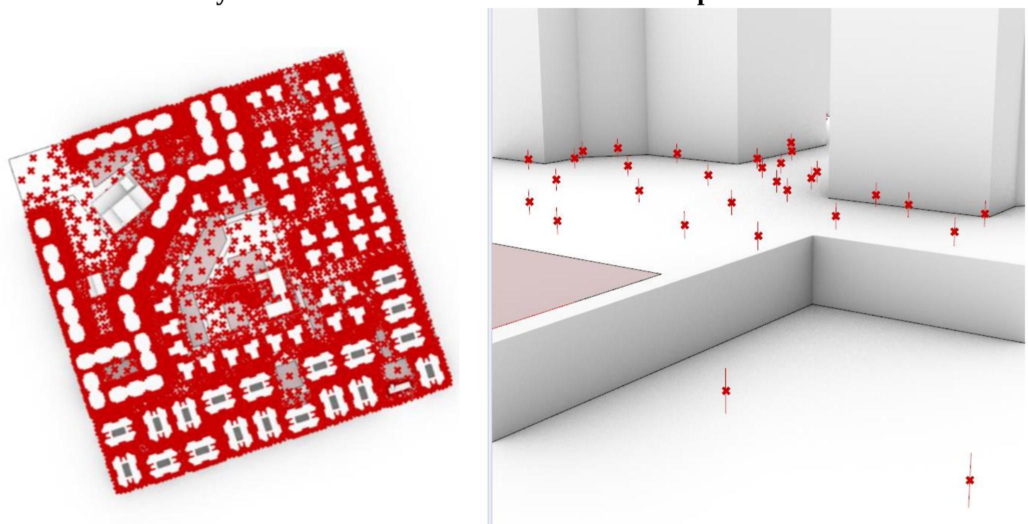


Layout Prespecrive

Fig. 9: The generated grid from the "LB Human to Sky Relation" component [Author]**.**
Up: Sheraton Residences Neighborhood in Cairo.
Down: The 5th District Neighborhood in New Damietta.

2. *Calculate Mean Radiant Temperature (MRT).*

Mean radiant temperature is one of the main parameters in calculating thermophysiological comfort indexes (UTCI). It is the uniform temperature of an imaginary environment in which the radiant heat transfer from the human body is equal to that in the actual environment. It is the main parameter that oversees human energy balance, especially on hot sunny days. [33].

MRT was calculated by using the "LB Outdoor Solar MRT" component, which requests many inputs. The first five inputs (location, surface temperature, direct normal radiation, diffuse horizontal radiation, and horizontal infrared radiation) were gotten from the "Explode Tree" component that merged climate data and the analysis period. The next two requested inputs, fraction body exposure and sky exposure, came from the "LB Human to Sky Relation" component. The next requested input was ground reflectivity. The reflectivity of a surface (albedo) is a number from 0 to 1. A value represents the percentage of solar energy reflected by a surface; 0 indicates total absorption of solar energy, and 1 indicates total reflectance. Surfaces that have low albedo, such as asphalt and concrete, have a higher temperature during the day, while surfaces that have high albedo, such as grass, show a lower temperature [34]. The two neighbourhoods have asphalt for the streets and grassy open spaces. Asphalt pavements have an albedo of 0.05, as they reflect 5% and absorb 95% of the solar radiation [35]. while grass has albedo values of 0.15 to 0.25

[36]. However, ground reflectivity in the Ladybug was set to have a default value of 0.25 for outdoor grass or dry bare soil and coded to let the user increase the value for concrete material and decrease it for water, Fig.10. Accordingly, it was set to be 0.25 for the outdoor grass and 0.95 for the asphalt pavements.

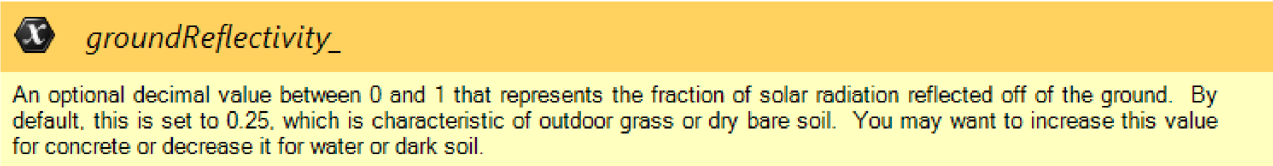


Fig. 10: Print screen for the instruction of ground reflectivity in the grasshopper interface [Grasshopper interface].

The last input in the “LB Outdoor Solar MRT” component was solar body parameters, which are the characteristics of the human geometry that will be assumed in the MRT calculation. The “LB Solar Body Parameters” component was used to set these characteristics; it needed five inputs. The first was "posture", which was scripted as standing; it can also be changed to seating or supine. The second was "sharp", which is a number between 0 and 180 representing the solar horizontal angle relative to the front of a person, 0 if the sun is shining directly into the person’s face, and 180 if the sun is shining at the person’s back. The default is 135, which assumes that person faces their side or back to the sun to avoid glare; the default was kept as set. The third was “body az”, which is a number between 0 and 360, representing the direction that the human is facing in degrees (0 for north, 90 for east, 180 for south, 270 for west). The default is none, which assumes that the sharp input dictates the degree the human is facing from the sun; therefore, the default was set. The fourth was "absorptivity", which is a number between 0 and 1, representing the average shortwave absorptivity of the body, including clothing and skin color, whether white, brown, or black. The default was 0.7, which is brown skin and medium clothing, so the default was kept. The last input was "emissivity", which is a number between 0 and 1, representing the average longwave emissivity of the body. The default is 0.95, which is almost always the case except in the rare situation of wearing metallic clothing, thus the default was set as an input. Each of these inputs can be changed according to the usage and characteristics of the site and its users. The output of these parameters was plugged into the “LB Outdoor Solar MRT” component as the last require. Then the “LB Outdoor Solar MRT” component was run to calculate the MRT, Fig.11.

Notice that MRT was calculated twice to ensure the accuracy of the results, one for the position of residents in the streets and the other in green areas, as they have different locations and ground reflectivity.

3. Calculate and visualize the Universal Thermal Climate Index (UTCI).

The universal thermal climate index was calculated by the “LB UTCI Comfort” component, which required four inputs: air temperature, MRT, relative humidity, and wind velocity. The air temperature, relative humidity, and wind velocity were obtained from the “Explode Tree” component, which combined climate data and the chosen analysis time. While the MRT was gotten from the two “LB Outdoor Solar MRT” components. Lastly, the “LB UTCI Comfort” component was run to start calculating UTCI.

To visualize the calculated UTCI values, first the “LB Deconstruct Data” component was used to separate the header and the values of the results, then the average values were taken and used as an input for the “LB Spatial Heatmap” component, which visualized the calculated values that indicate the average UTCI values of the extremely hot week of the year in Sheraton Residences and the 5th District neighborhood, Fig. 12.

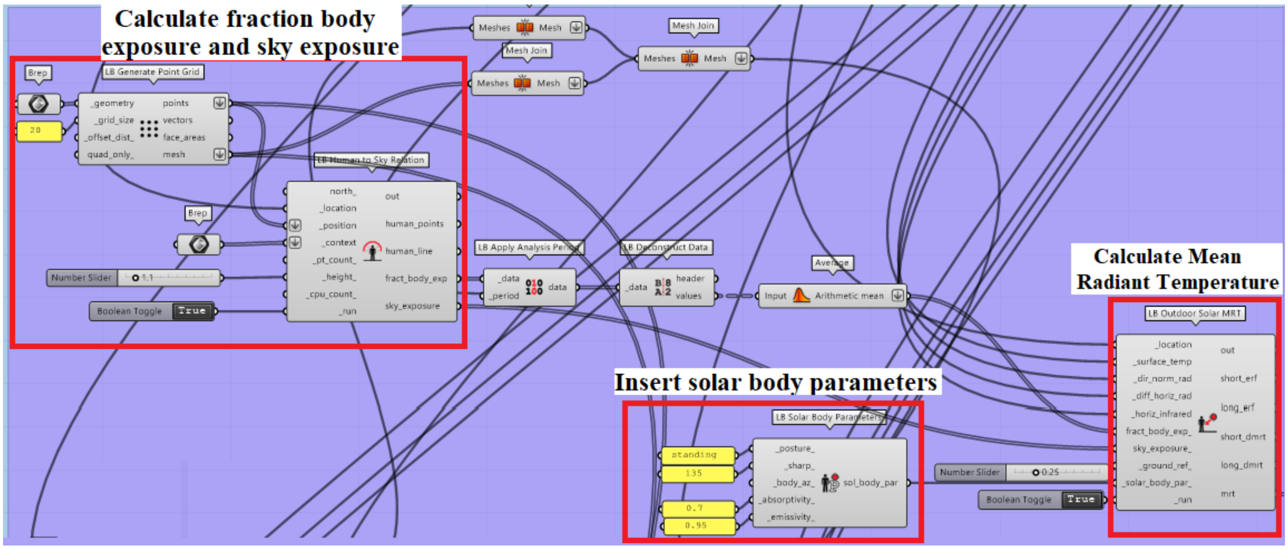


Fig. 11: The calculations of the MRT [Author]**.**

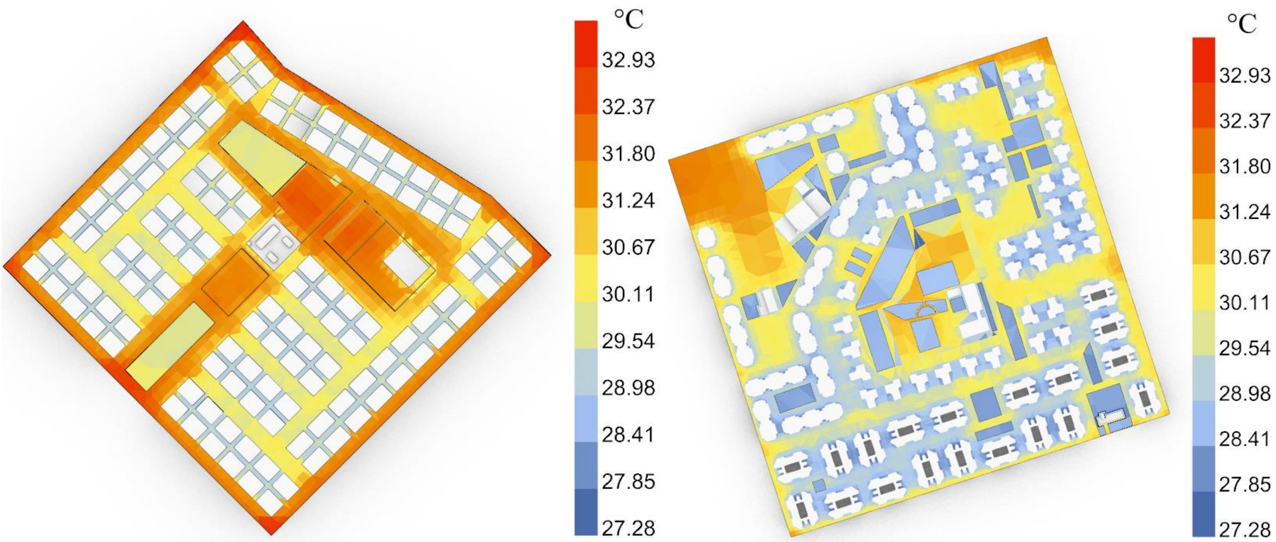


Fig. 12: The average UTCI values of the extremely hot week of the year [Author]**.**
Left: Sheraton residences neighborhood in Cairo (from July 20 to July 26)
Right: The 5th district neighborhood in New Damietta (from August 1 to August 7)

4. *Define regions with high thermal stress.*

The "LB Mesh Threshold Selector" component was used to detect the regions that were in the high thermal stress category. The component uses a conditional criterion and a certain value; the criterion can be adjusted to be greater than, less than, or equal to that certain value. According to the adjusted constraints, the component selects sub-regions from the original mesh that pass the required criteria. It facilitated quantifying the required area from the UTCI analysis by adjusting the criterion to select the regions with average UTCI values greater than or equal to 32°C. The results showed that the high thermal stress regions have a total area of 6439.59 m^2 (3.54% of the total neighborhood area), Fig. 13. This step was applied to the Sheraton Residences neighbourhood in Cairo only, as the average UTCI of the 5th District neighbourhood in New Damietta did not exceed 32°C, so it has no high thermal stress.

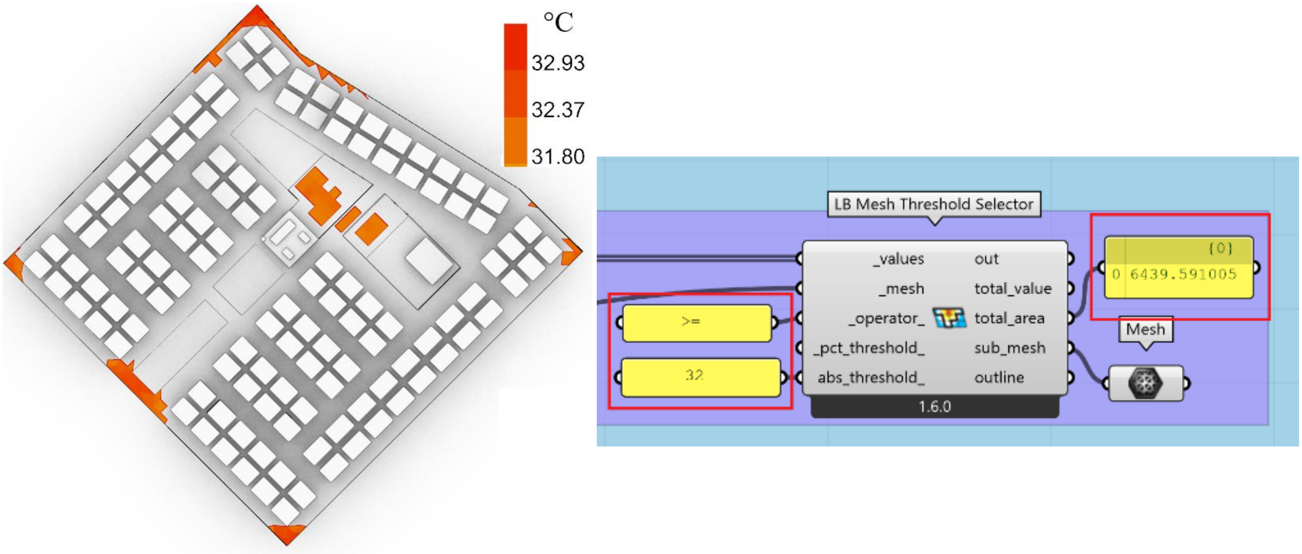


Fig. 13: The generated sub-mesh by "LB Mesh Threshold Selector" component [Author]**.**

However, these results are the average data for day and night during the entire week; they include nighttime, which decreases the average levels. Therefore, to further test the extent of the ladybug in specifying the measurements of UTCI in specific regions and duration, six test locations in each neighborhood were used to measure their hourly UTCI throughout the week and their high thermal stress hours.

3.2.3. The 3rd Phase: Define the hourly UTCI values of specific test points

Six test points in each neighborhood were selected to specify their hourly UTCI values through the entire week. The points were chosen to be as similar as possible in their function, location, and surrounding shading geometries in the two neighborhoods.

To locate the points in the outdoor space mesh and start detecting their hourly values, three "List Item" components were used. The first list was plugged into the calculated UTCI values of the "LB UTCI Comfort" component; the second was linked to the emerged points and mesh from the "LB Generate Point Grid" components (that represents the mesh and points of the streets); and the third was connected to the emerged points and mesh from the "LB Generate Point Grid" components (that represents the mesh and points of the green areas). Afterwards, each chosen point was attached to the "LB hourly Plot" component to visualize its hourly UTCI values. The output was then connected to the "LB Mesh Threshold Selector" component to specify the thermal stress category of each hour and the percentage of each category throughout the week, which were marked as the following:

- High heat stress values were marked with a red color.
- Moderate heat stress values were marked with a green color.
- No thermal stress values were marked with a blue color.

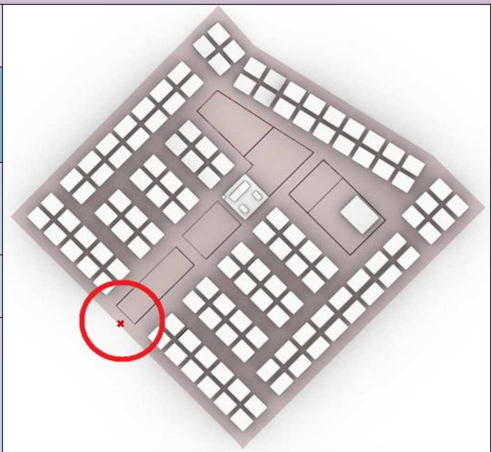
Table 3 presents the hourly UTCI values of the six selected points during the entire week, their UTCI range, percentage of each thermal stress category, and occurrence hours.

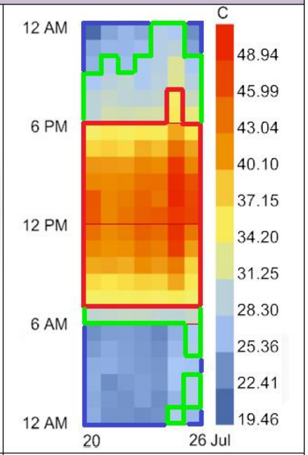
Table 3: The hourly UTCI of the six test points during the extreme hot week [Author]**.**

The Hourly UTCI of the Extreme Hot Week in the year

Test point 1: At Neighborhood's Boundaries (Sheraton Residences)

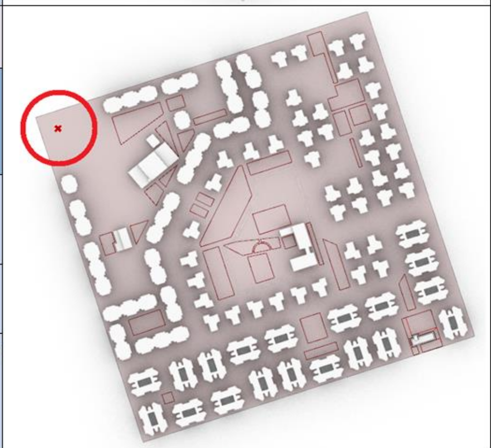
Stress Category	**High heat stress**	**Moderate heat stress**	**No thermal stress**
UTCI Range	From 32 to 48.94 °C	From 26 to 32 °C	From 19.46 to 26 °C
Per-cent	47%	23.8%	29.2%
Hours (Majority)	From 7 am to 6 pm	From 6 to 7am, from 6 to 10 pm,	From 10 pm to 6 am

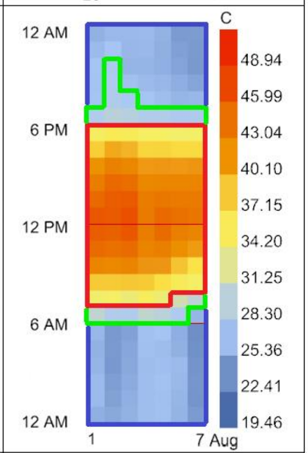




Test point 1: At Neighborhood's Boundaries (The 5th District)

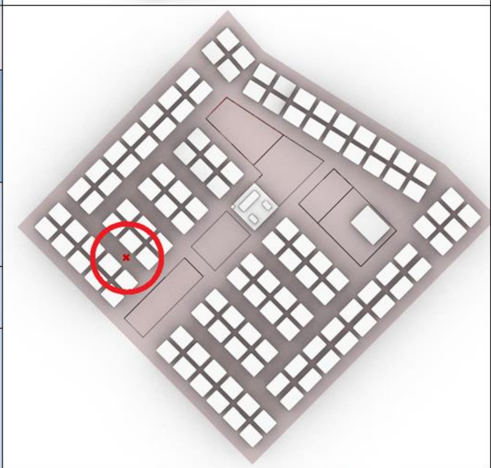
Stress Category	**High heat stress**	**Moderate heat stress**	**No thermal stress**
UTCI Range	From 32 to 45.18 °C	From 26 to 32 °C	From 22.38 to 26 °C
Per-cent	44.7%	11.3%	44%
Hours (Majority)	From 7 am to 6 pm	From 6 to 7 am, from 6 to 7 pm	From 7 pm to 6 am

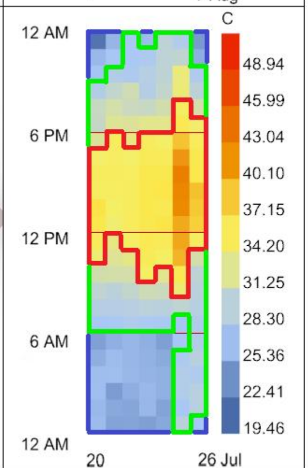




Test point 2: Between Residential Buildings (Sheraton Residences)

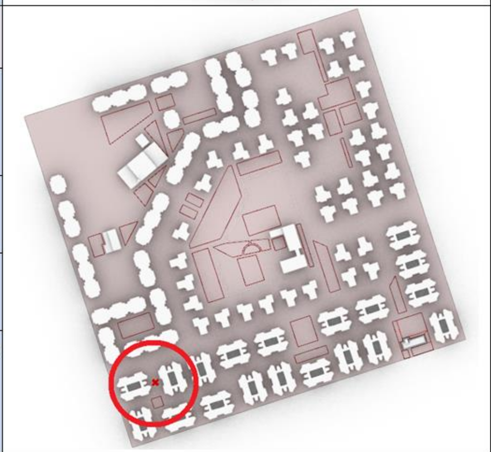
Stress Category	**High heat stress**	**Moderate heat stress**	**No thermal stress**
UTCI Range	From 32 to 41.88 °C	From 26 to 32 °C	From 20.21 to 26 °C
Per-cent	33.3%	42.3%	24.4%
Hours (Majority)	From 10 am to 6 pm	From 6 to 10 am, from 6 to 11 pm	From 11 pm to 6 am

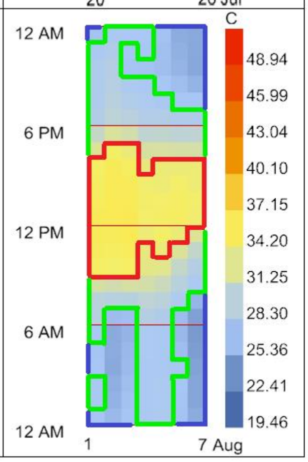




Test point 2: Between Residential Buildings (The 5th District)

Stress Category	**High heat stress**	**Moderate heat stress**	**No thermal stress**
UTCI Range	From 32 to 34.72 °C	From 26 to 32 °C	From 23.17 to 26 °C
Per-cent	25%	45.8%	29.2%
Hours (Majority)	From 10 am to 4 pm	From 7 to 10 am, from 4 to 9 pm	From 9 pm to 7 am

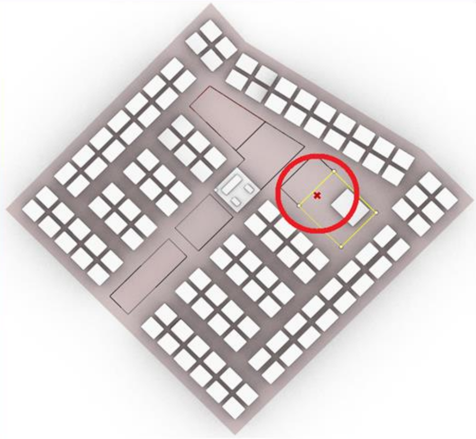


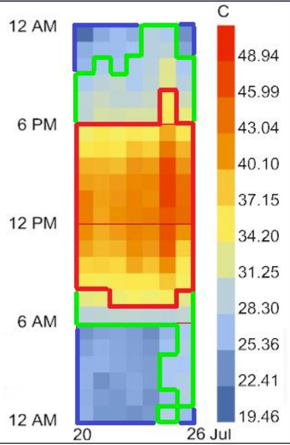


The Hourly UTCI of the Extreme Hot Week in the year

Test point 3: At School Courtyard (Sheraton Residences)

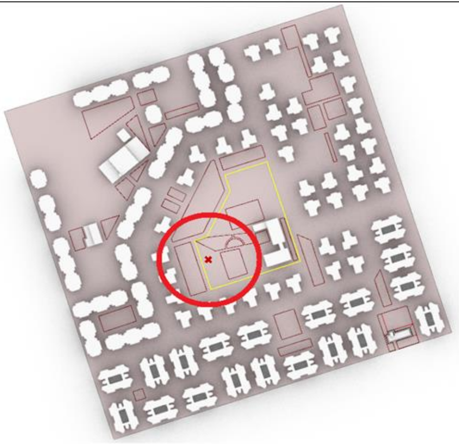
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 46.81 °C	From 26 to 32 °C	From 19.67 to 26 °C
Per-cent	45.8%	26.8%	27.4%
Hours (Majority)	From 7 am to 6 pm	From 6 to 7am, from 6 to 10 pm,	From 10 pm to 6 am

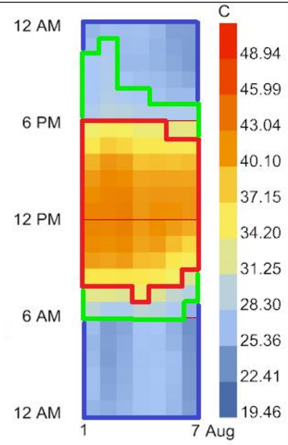




Test point 3: At Faculty Courtyard (The 5th District)

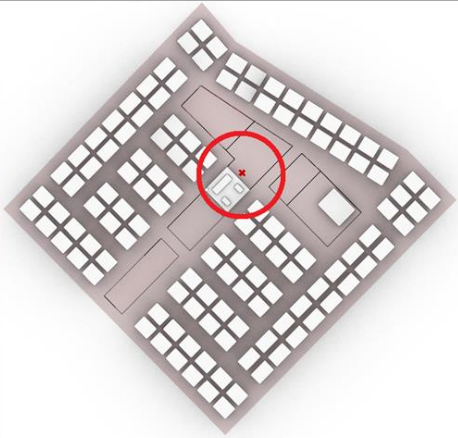
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 42.13 °C	From 26 to 32 °C	From 22.61 to 26 °C
Per-cent	40.5%	18.5%	41%
Hours (Majority)	From 8 am to 6 pm	From 6 to 8 am, from 6 to 8 pm	From 7 pm to 6 am

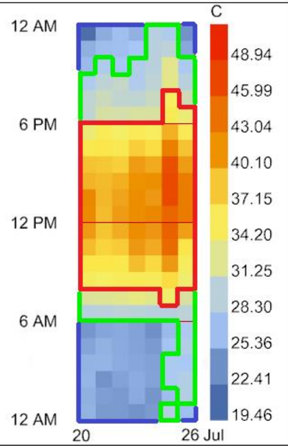




Test point 4: At the Mosque Courtyard (Sheraton Residences)

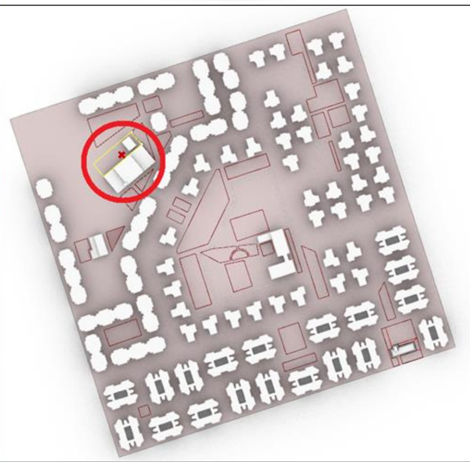
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 45.62 °C	From 26 to 32 °C	From 19.77 to 26 °C
Per-cent	44%	28.6%	27.4%
Hours (Majority)	From 8 am to 6 pm	From 6 to 8 am, from 6 to 10 pm	From 10 pm to 6 am

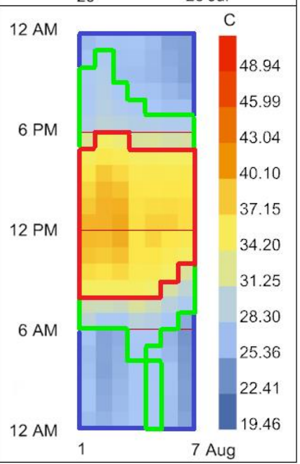




Test point 4: At the Mosque Courtyard (The 5th District)

Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 38.56 °C	From 26 to 32 °C	From 22.89 to 26 °C
Per-cent	37%	26.7%	36.3%
Hours (Majority)	From 8 am to 5 pm	From 6 to 8 am, from 5 to 8 pm	From 8 pm to 6 am

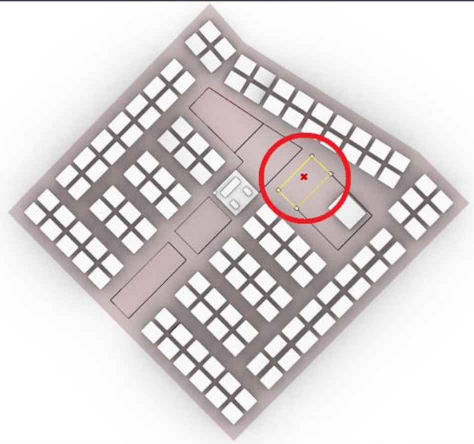


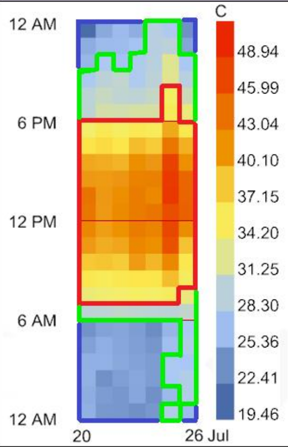


The Hourly UTCI of the Extreme Hot Week in the year

Test point 5: At Parking area (Sheraton Residences)

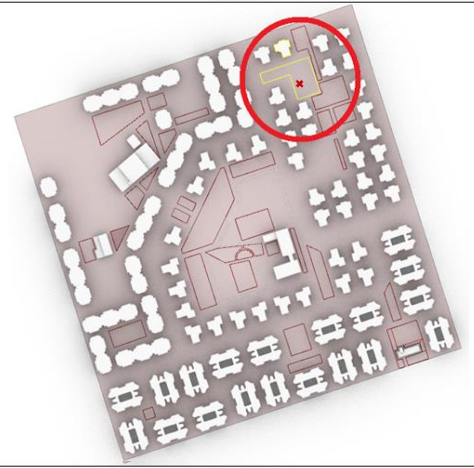
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 47.17 °C	From 26 to 32 °C	From 19.64 to 26 °C
Per-cent	46.4%	26.2%	27.4%
Hours (Majority)	From 7 am to 6 pm	From 6 to 7am, from 6 to 10 pm,	From 10 pm to 6 am

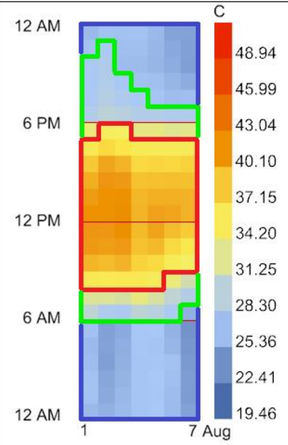




Test point 5: At Parking area (The 5th District)

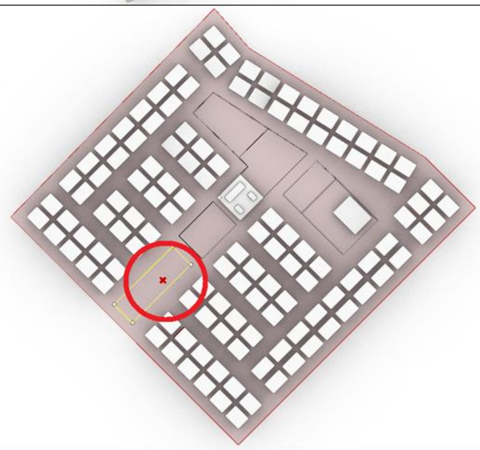
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 40.58 °C	From 26 to 32 °C	From 22.74 to 26 °C
Per-cent	37.5%	22%	40.5%
Hours (Majority)	From 8 am to 5 pm	From 6 to 8 am, from 5 to 8 pm	From 8 pm to 6 am

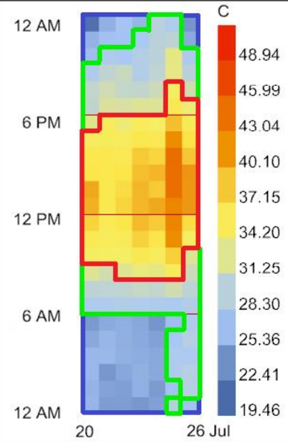




Test point 6: At Green area (Sheraton Residences)

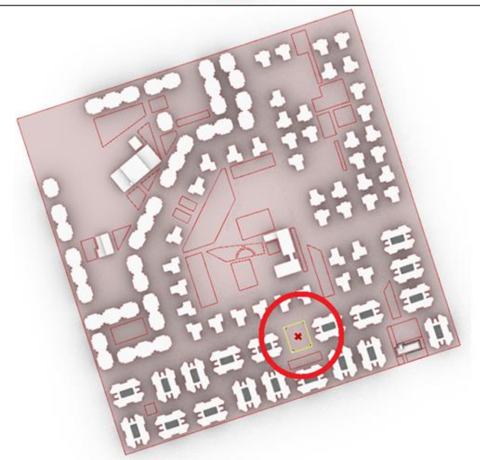
Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 43.79 °C	From 26 to 32 °C	From 20.03 to 26 °C
Per-cent	40.5%	33.9%	25.6%
Hours (Majority)	From 8 am to 6 pm	From 6 to 8 am, from 6 to 10 pm	From 10 pm to 6 am

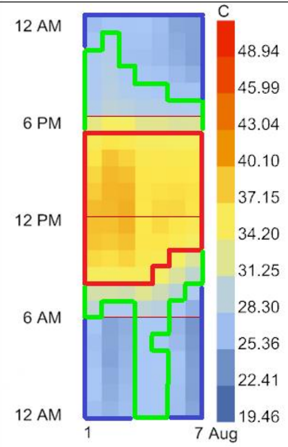




Test point 6: At Green area (The 5th District)

Stress Category	High heat stress	Moderate heat stress	No thermal stress
UTCI Range	From 32 to 37.55 °C	From 26 to 32 °C	From 22.94 to 26 °C
Per-cent	34.5%	29.8%	35.7%
Hours (Majority)	From 8 am to 5 pm	From 7 to 8 am, from 5 to 8 pm	From 8 pm to 7 am





4. Results

The following part presents the results of the study and its algorithmic workflow.

4.1. Results of the First and Second Phases.

The first two phases dealt with the climate data and UTCI measurements of the two neighborhoods; their results showed noticeable variations between the measurements of the Sheraton Residences neighborhood in Cairo (an inland city) and the 5th District neighborhood in New Damietta (a coastal city).

The results of the first phase revealed that the dry bulb temperature in New Damietta has decreased by 8°C in its maximum value and increased by 2.3°C in its minimum value compared to Cairo. The relative humidity has remained the same in its maximum value for the two cities; however, it increased by 42% in the minimum value of New Damietta as a coastal city. While the direct normal radiation in New Damietta has decreased by 30 Wh/m^2 in its maximum value compared to Cairo, both minimum values remain the same. The results of the second phase showed that the maximum average UTCI value of the 5^{th} District neighborhood has decreased by 1.29°C in its maximum value and 1.51°C in its minimum value compared to the Sheraton Residences neighborhood. Accordingly, the thermal heat stress in the Sheraton Residences neighborhood lied in the moderate to high thermal stress category (from 28.79°C to 32.93°C), while the 5^{th} District neighborhood was in the moderate thermal stress category (from 27.28°C to 31.64°C), and its levels did not reach the high thermal stress zone. Table 4 summarizes the results of the first two phases.

Table 4: The climate data and average UTCI in the extreme hot week [Author]**.**

	Sheraton Residences Neighborhood, Cairo - From 20/7 to 26/7				**The 5^{th} District Neighborhood, New Damietta - From 1/8 to 7/8**			
Dry bulb temperature (°C)	**Max.**	**40**	**Min.**	**22.7**	**Max.**	**32**	**Min.**	**25**
Relative humidity (%)	**Max.**	**89**	**Min.**	**15**	**Max.**	**89**	**Min.**	**57**
Direct normal radiation (Wh/m^2)	**Max.**	**871**	**Min.**	**0**	**Max.**	**841**	**Min.**	**0**
Prevailing wind direction	**North**				**Northwest**			
Average wind speed (m/s)	**3.55**				**4.87**			
Average UTCI (°C)	**Max.**	32.93	**Min.**	28.79	**Max.**	31.64	**Min.**	27.28
Thermal stress Category	Moderate to high thermal stress				Moderate thermal stress			
High thermal stress regions (%)	3.54% of neighborhood area				No high thermal stress			

4.2. Results of the Third Phase.

The third phase dealt with the hourly UTCI values of six test locations in each neighborhood. Its results showed that the maximum values of the 5^{th} district neighborhood decreased by 3.76°C, 7.16°C, 4.68°C, 7.06°C, 6.59°C, and 6.24°C, while their minimum values increased by 2.92°C, 2.96°C, 2.94°C, 3.12°C, 3.1°C, and 2.91°C compared to the Sheraton Residences neighborhood in the test points 1, 2, 3, 4, 5, and 6, respectively. This result could be explained by the fact that, in comparison to inland cities, coastal cities take a longer time to get hot during the daytime and stay warmer for longer at night. The following chart shows this variation, Fig. 14.

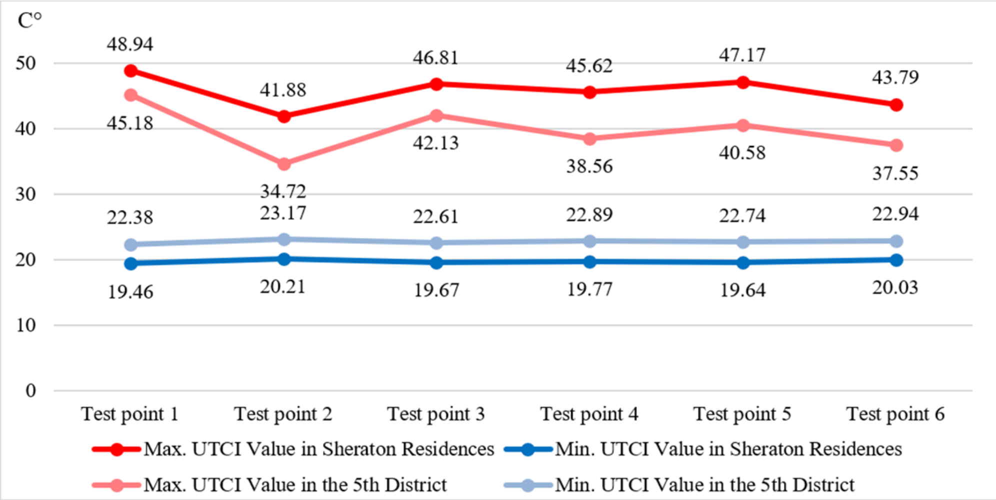


Fig. 14. The maximum and minimum hourly UTCI value [Author]**.**

Accordingly, there were noticeable variations in the ratio of their thermal stress categories throughout the week. The high thermal stress category decreased in the 5th district neighborhood by 2.3%, 8.3%, 5.3%, 7%, 8.9%, and 6% compared to the Sheraton Residences neighborhood in test points 1, 2, 3, 4, 5, and 6, respectively. The moderate thermal stress category decreased by 12.5%, 8.3%, 1.9%, 4.2%, and 14.1% in the 5th district neighborhood compared to the Sheraton Residences neighborhood in test points 1, 3, 4, 5, and 6, respectively, while increased by 3.5% in test point 2. The ratios of the no thermal stress category were higher in the 5th district neighborhood than in the Sheraton Residences neighborhood by 14.8%, 4.9%, 13.6%, 8.9%, 13.1%, and 10.1% in test points 1, 2, 3, 4, 5, and 6, respectively. Briefly, the percentage of high and moderate thermal stress categories has decreased, and the percentage of no thermal stress category was noticeably increased in the 5th district neighborhood in New Damietta, as a coastal city, compared to the Sheraton Residences neighborhood in Cairo, as an inland city. The following chart shows these ratios, Fig.15.

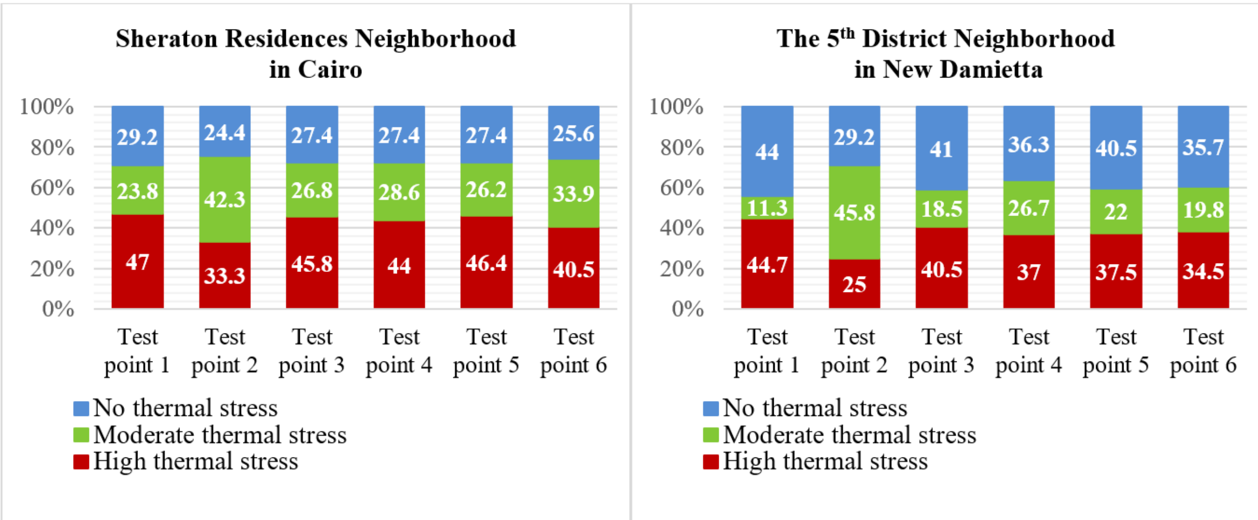


Fig.15. The percentage of thermal stress categories [Author]**.**

5. Discussion

This study sets out with the aim of exploring the potential of the ladybug as a tool for measuring outdoor thermal comfort and its extent in simulating and measuring UTCI. The research used an algorithmic script designed by the latest version of the Ladybug tool, version 1.6.0, to perform analysis on two neighbourhoods in two different climate zones (an inland and a coastal city) to investigate its capability of distinguishing between their measurements. The results showed that the maximum average UTCI of the 5th District neighbourhood in New Damietta (a coastal city) showed a decrease of 1.29°C in its maximum value and 1.51°C in its minimum value in the Sheraton Residences neighbourhood in Cairo (an inland city). Accordingly, the Sheraton Residences neighbourhood lies in the moderate to high thermal stress category, while the 5th District neighbourhood is in the moderate thermal stress category. Another interesting finding was the capability of the ladybug tool to specify the hourly UTCI values and the percentage of thermal stress categories at any required location. The research selected six test points in each neighbourhood to study and compare their maximum and minimum hourly UTCI values and the ratio of their thermal stress categories throughout the week. The results revealed that the percentages of the high and moderate thermal stress categories were lower, while the percentage of the no thermal stress category was higher in the 5th district neighbourhood over the week compared to the Sheraton Residences neighbourhood.

As mentioned in the literature review, several research have studied the differences in UTCI values between coastal and inland cities. To validate the script measurements, Table 5 compares the results of the current study with the findings of two prior studies. The selected related studies have used different software, tools, and meteorological equipment to study and measure the differences in the UTCI values between coastal and inland sites.

Table 5: Comparison between the results of the study and relevant research [Author]**.**

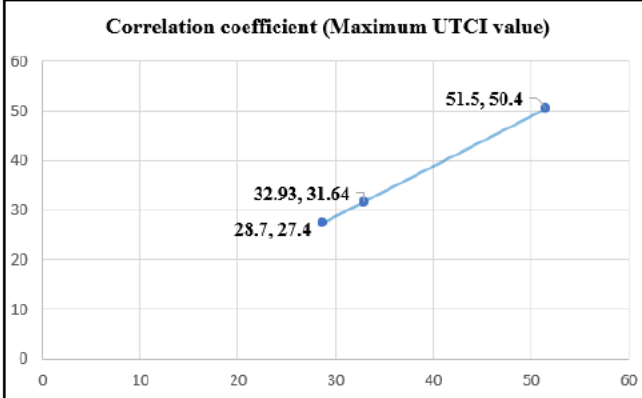
Location	**Egypt** [Author]		**China** [9]		**UAE** [21]	
Site	**Inland**	**Coastal**	**Inland**	**Coastal**	**Inland**	**Coastal**
	Cairo	New Damietta	Street	Park	Al Ain	Dubai
Duration	Extreme hot week		A typical summer day		Period 1980 -2018	
Tool	The Ladybug tool		Meteorological instruments/ RayMan software		Calculated by UTCI Calculator www.utci.org	
Max. average UTCI value (°C)	32.93	31.64	28.7	27.4	51.5	50.4
Min. average UTCI value (°C)	28.79	27.28	23.3	20.8	24.5	18.2
Research results	▪ The max. UTCI value of the coastal site was lower by 1.29 °C. ▪ The min. UTCI value of the coastal site was lower by 1.51°C.		▪ The max. UTCI value of the coastal site was lower by 1.3°C. ▪ The min. UTCI value of the coastal site was lower by 2.5°C.		▪ The max. UTCI value of the coastal site was lower by 1.1°C. ▪ The min. UTCI value of the coastal site was lower by 6.3°C.	

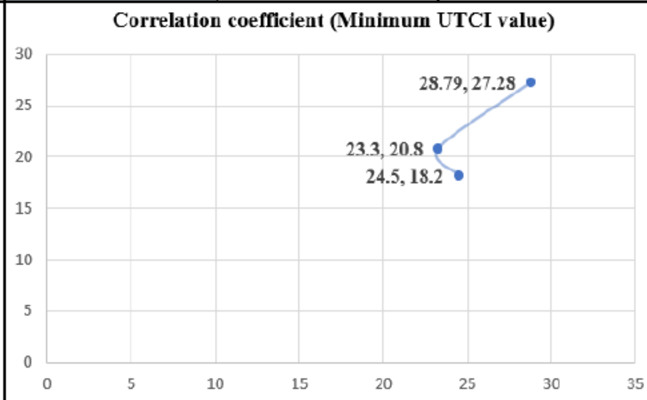
The comparison has covered and monitored the variation in the UTCI values between coastal and inland sites over a short period of time (day or week) as well as their increasing values over a long period of time (decades). It clarified that coastal sites have lower UTCI values in their maximum and minimum measurements compared to inland sites, which is consistent with the outcome of the algorithmic script of the study.

However, to validate the research measurements compared to the results of the two discussed studies, the correlation coefficient between them was calculated in Table 6. The correlation coefficient is a number ranging from -1 to +1 that represents the strength and direction of a relationship between variables. A correlation coefficient of 1 describes a strong positive association, -1 describes a negative association, and 0 indicates that there is no association between the two variables. Note that in cases of strong positive association, the coefficient comes closer to an absolute value of 1, and the relationship graph approaches a straight line or a continuously increasing curve [37].

Table 6: The correlation coefficient between the measurements of the research and two relevant studies [Author]**.**

The correlation coefficient between the measurements of the research and two relevant studies					
Maximum UTCI value (°C)			**Minimum UTCI values (°C)**		
	Inland	**Coastal**		**Inland**	**Coastal**
Egypt [Author]	32.93	31.64	**Egypt** [Author]	28.79	27.28
China [9]	28.7	27.4	**China** [9]	23.3	20.8
UAE [21]	51.5	50.4	**UAE** [21]	24.5	18.2





Correlation value = 0.999999278	**Correlation value = 0.881802464**
A strong, positive correlation	**A strong, positive correlation**

The values of the correlation coefficient have clarified the strong positive correlation between the measurements of the research and two relevant studies, validating the capabilities of the ladybug as a tool for measuring and simulating UTCI and the accuracy of the scripted algorithm.

6. Conclusion

The main goal of the study was to explore the capabilities of the Ladybug tool in measuring UTCI as one of the broadly used thermal indexes for evaluating outdoor thermal comfort. The results have shown that the Ladybug tool could efficiently distinguish between the temperature and UTCI measurements of the different climate zones, locate areas that need future optimization, specify the hourly UTCI data, and define the percentage of thermal stress categories in any required location. These capabilities qualify the Ladybug tool to be one of the most efficient tools for simulating and measuring outdoor thermal comfort. The study has gone some way towards enhancing our knowledge and understanding of the Ladybug tool and its capabilities and extent in measuring outdoor thermal comfort. Its results could assist architects and urban planners in simulating, measuring, and visualizing outdoor thermal comfort analysis, quantifying thermal measurements, and detecting regions that need further optimization, whether in the urban planning stage or in an already-built environment. The current study has only examined the abilities of the Ladybug tool in measuring the UTCI; further studies with more focus on optimizing the regions with high thermal stress using the Ladybug tool are therefore suggested. It would be interesting to assess the effects of using the Ladybug tool in finding solutions in this optimization process.

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دراسة Ladybug كأداة لقياس الراحة الحرارية الخارجية للمجتمعات العمرانية

الملخص

إن الأرتفاع المتزايد في درجات الحرارة العالمية أدي إلي زيادة الوعي بأهمية تنمية الراحة الحرارية الخارجية للمجتمعات العمرانية. حيث أصبحت الراحة الحرارية الخارجية تعد مؤشراً رئيسيًا لكفاءة البيئة العمرانية ، والذي يؤثر بشكل مباشر على صحة وراحة وجودة حياة السكان. ونتيجة لذلك ظهرت العديد من مؤشرات قياس الراحة الحرارية الخارجية والتي تعمل على قياس الراحة الحرارية الخارجية بشكل دقيق ومنها مؤشر المناخ الحراري العالمي UTCI والذي يعتبر من أهم المؤشرات الحرارية المستخدمة على نطاق واسع في العقد الأخير. وعلي محوراً أخر لهذا الوعي قامت العديد من برامج التصميم بمساعدة الكمبيوتر (CAD) بالعمل المستمر على تطوير تقنياتها لزيادة دقة عمليات المحاكاة والقياسات المناخية الخارجية.

يهدف البحث الي أستكشاف إمكانات وقدرات أداة Ladybug في قياس UTCI من خلال نص خوارزمي مصمم بأستخدام أداة Ladybug (الإصدار ١,٦,٠) في واجهة Grasshopper بواسطة برنامج Rhino 3D، تم تطبيقه على مجاورتين في مناطق مناخية مختلفة في مصر وهما مدينة القاهرة (عاصمة مصر) ومدينة دمياط الجديدة (مدينة ساحلية على البحر الأبيض المتوسط)، لقياس ومقارنة قيم UTCI الخاصة بهم في أشد الأسابيع حرارة خلال العام كفتره اختبارية. أظهرت النتائج أن الحد الأقصى لمتوسط قيمة UTCI خلال أسبوع الأختبار قد أنخفض من ٣٢,٩٣ درجة مئوية في مدينة القاهرة إلى ٣١,٦٤ درجة مئوية في مدينة دمياط الجديدة، بينما أنخفض حده الأدنى من ٢٨,٧٩ درجة مئوية في مدينة القاهرة إلى ٢٧,٢٨ درجة مئوية في مدينة دمياط الجديدة، وبهذا أظهرت دمياط الجديدة كمدينة ساحلية إنخفاضًا بمقدار ١,٢٩ درجة مئوية في القيمة الحد الأقصى و١,٥١ درجة مئوية في القيمة الحد الأدنى عن مدينة القاهرة. كما تم أيضًا قياس ومقارنة الحد الأقصى والحد الأدنى لقيم UTCI وبيانات كل ساعة خلال أسبوع الأختبار لستة نقاط أختبار في المجاورتين وحساب النسب المئوية لفئات الإجهاد الحراري UTCI لكلاً منهم.