THE EFFECT OF MICROCLIMATE SIMULATION ON URBAN SPACE

Abstract

With the rapid urbanization and rising affluence, the energy demand and climate change, as well as, health impacts of cities are correlational of increasing importance. Much of this intensive urban growth is wide spreading in parallel with the accelerated climate change detected problems and global warming effects which increasing so broadly as a hot current worldwide stream with facing more of intense and extreme heat waves due to the increase of atmospheric GHG emissions since the industrial revolution.

The problem statement is the following: Lack of using climate digital simulation in the conventional urban design process; High dense urban areas are directly influencing the urban heat island effect problems which needs mitigation strategies; Typologies of urban form have a climatic impact on climate orientation inside the districts and also affects the surroundings; Failure of regional climate models to take a consideration of the climatic parameters and human real feeling temperature as on urban microclimate scale and The missing of climate change adaptation strategies in a dynamic design of urban space.

The aim of the research will discuss the integrative usage of microclimate digital simulation models to validate the appropriate urban form of an open space in order to be adaptable with climate conditions and to detect the problems of space urban design. Practical urban micro climate scenarios can lead to create a better urban context during different seasons in different climate zones with the consideration of climate parameters through simulating and applying mitigation and adaptation strategies to achieve human thermal comfort in urban outdoor areas and to develop more compatible and healthier urban spaces with enhancing efficient thermal performance using microclimate digital models and find flexible solutions.

The research exploration method was initiated as a part of the author's work on a case study related to research project entitled “Sustainable Urban Planning via Establishment of Urban Climate Labs”. Training in Urban Climate Modeling and Measurement at the Institute of Meteorology - FU Berlin, Germany 2018.

Keywords: Urban Climate, Spatial Form, Climate Change, Microclimate Simulation, Urban Heat Island, PET

Introduction

The largest climatic challenge in cities is that to mitigate and adapt climate change and know how to achieve urban thermal efficiency in outdoor spaces even in hot, dry, humid or cold climate zones as all now have the same issue of global temperature rising. Urban environment determines urban climate and wellbeing, as well as, outdoor meteorological comfort and public health. Whereas tackling the issue of heat performance for the built environment in the districts of cities being on top of our focus.

Urban areas are both affected by weather and climate, it exerts an influence on regional, local and micro scale. The climate inside and around cities and other built up areas is altered in part due to modifications of man made to the surface of Earth during urbanization process. This change affects the absorption of solar radiation, surface temperature, evaporation rates, and storage of heat, also turbulence and wind. Climate change can drastically alter the conditions of the near-surface atmosphere.

Human activities in cities also produce emissions of GHG, water vapor and pollutants that directly impact the temperature, humidity, visibility and air quality in the atmosphere above cities. On slightly larger scales, urbanization can also lead to changes in precipitation above and downwind of the urbanized areas.

1. Climate Change

1.1. The Current State of the Climate

There have been previous periods of climate change on Earth, but the current changes are more rapid than any known events in Earth's history with its large-scale impacts on weather patterns. It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere have occurred due to a main cause of the emissions of greenhouse gases, mostly carbon dioxide. “Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences. Each of the last four decades has been successively warmer than any decade that preceded it since 1850”. [10] It’s expected to be warmer by 2100 (Fig. 2).

The increase in global surface temperature is principally due to further warming caused by GHG concentrations which accordingly affect climate system in our growing cities. Most of the warming occurred in the past 40 years, with the seven most recent years being the warmest. The years 2016 and 2020 are tied for the warmest year on record. [11] “Today’s rising climate emissions correspond broadly to rising energy use; this coupling will continue as long as energy supplies are largely fossil fuel based, and most projections suggest that, in 2050, two-thirds or more of global energy use will still be oil, coal and gas”. [18] Through the continued use of burning fossil fuel as energy source; the upraise emissions will be exacerbated.

1.2. Global Warming Potential (GWP)

Human influence has warmed the climate at a rate that is unprecedented as the global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades. [13] The changes in global surface temperature (annual average) shown as observed and simulated relative to 1850-2020 (Fig. 1). “The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of gas absorb over a given period of time, relative to the emissions of 1 ton of Carbon Dioxide”.

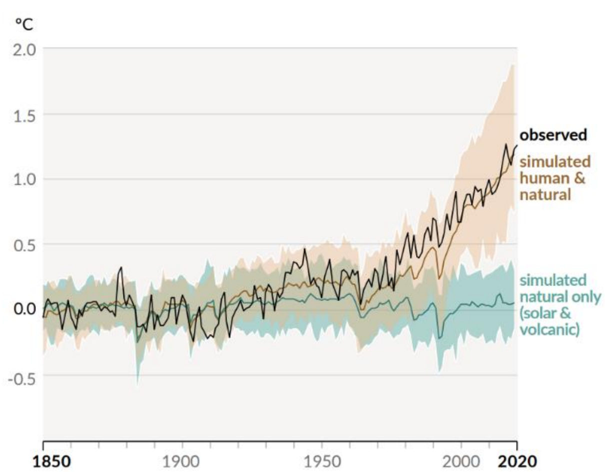


Fig. 1. Global surface temperature relative to 1850-2020
Source, IPCC, 2021 [10]

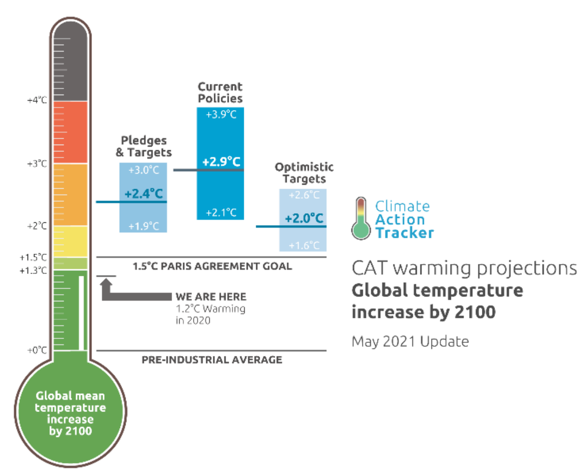
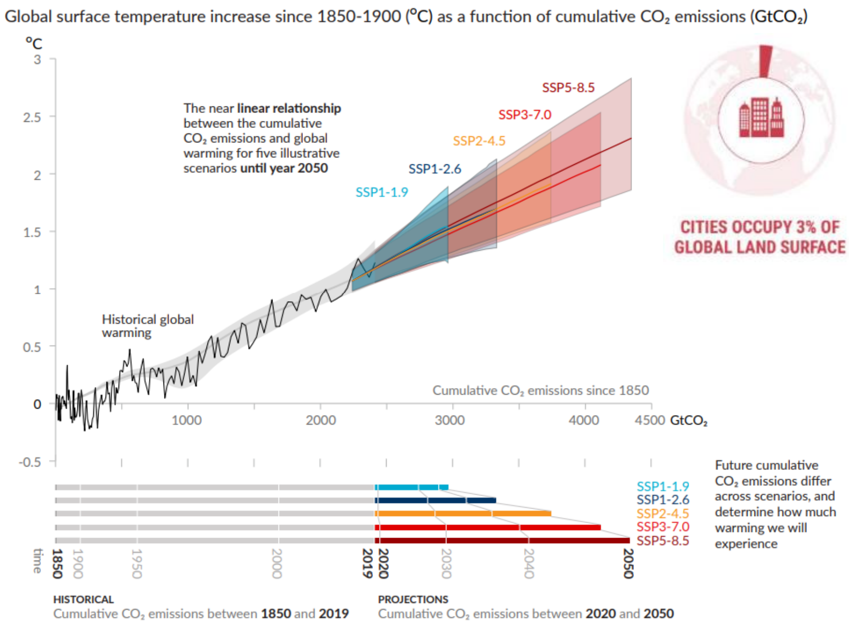


Fig. 2. Global mean temperature relative to 2100
Source, Climate Action Tracker [3]

1.3. Greenhouse Gases (GHG) Emissions

The largest source of greenhouse gas emissions from human activities is from burning fossil fuels for electricity, heat, industry and transportation (Fig. 4). Every tone of CO_2 emissions adds to global warming, with linear relationship between the cumulative CO_2 emissions and global warming for five illustrative scenarios until year 2050 (Fig. 3). Future cumulative CO_2 emissions differ across scenarios, and determine how much warming we will experience as human activities affect all the major climate system components, with some responding over decades and other irreversible over centuries. [10]



The world's cities occupy just 3 per cent of the Earth's land, but account for 75 per cent of energy consumption and about 60-80 per cent of GHG & Carbon emissions.

Rapid urbanization is exerting pressure on the living environment, and public health.

Fig.4. Cities as leverage points Source,www.un.org/sustainabledevelopment/cities/ [16]

Fig. 3. CO_2 emissions and global surface temperature across illustrative 5 scenarios by 2050. Source, IPCC, 2021 [10]

1.4. Urban Heat Island (UHI)

An urban heat island is an urban or metropolitan area that is significantly warmer than its surrounding rural areas due to modification of land surfaces and human activities. The term "Urban Heat Island Effect" refers to the phenomenon resulting in the temperature difference especially at night (Fig. 5). "Hot-climate cities are increasingly problematic due to congestion, pollution and deteriorating microclimates, not least growing urban heat island (UHI) effects". [1] (Fig. 6).

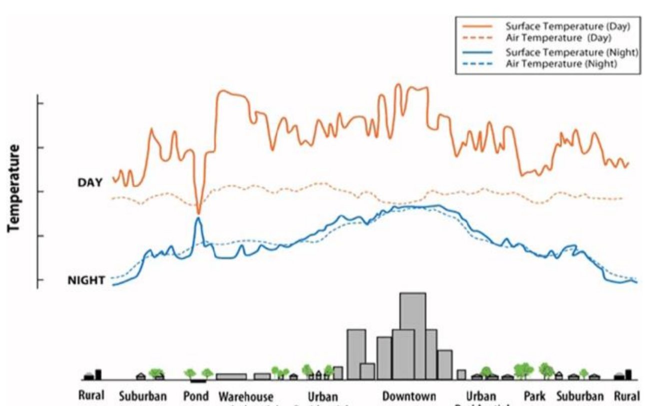


Fig. 5. Typical Urban Heat Island Profile Source, U.S. EPA (Environmental Protection Agency), September 2016 [19]

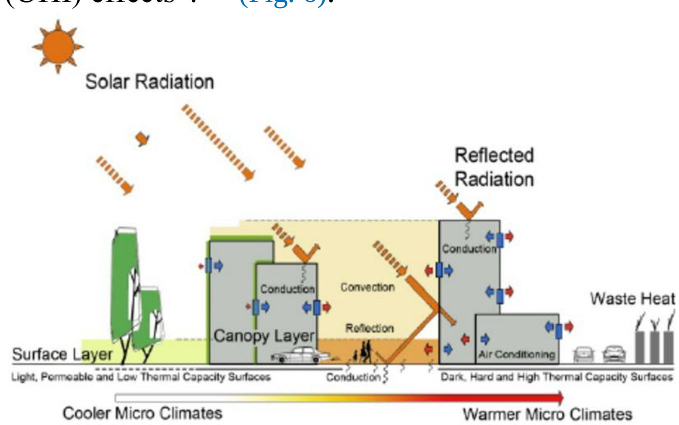


Fig. 6. Urban structure, landscape, land-cover and metabolism contribute UHI effect in cities. Source, www.researchgate.net [4]

2. Climate Action

2.1. Prioritizing Climate Solutions

Climate change is one of the defining challenges of our time. Sustainable Development Goal 13 is about climate action and is one of 17 Sustainable Development Goals established by the United Nations in 2015 to take urgent action to combat climate change emergency and its impacts.

The Paris Agreement, adopted in 2015, aims to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels. The agreement also aims to strengthen the ability of countries to deal with the impacts of climate change, through appropriate financial flows, a new technology framework and an enhanced capacity building framework. [16] When the gavel came down on Paris Agreement, governments formally acknowledged that their national climate targets collectively would not meet the goal of limiting warming to 1.5˚C. So they undertook to do the first update of their 2030 targets which are part of a country's "nationally determined contribution" (NDC) by 2020, backed by the IPCC Special Report on 1.5˚C, which was completed in October 2018. [3] This Agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects for saving lives and livelihoods which requires an urgent action. Climate Action Tracker (CAT) is an independent scientific analysis produced by two research organizations tracking climate action since 2009. It track progress towards the globally agreed aim of holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C (Fig. 7).

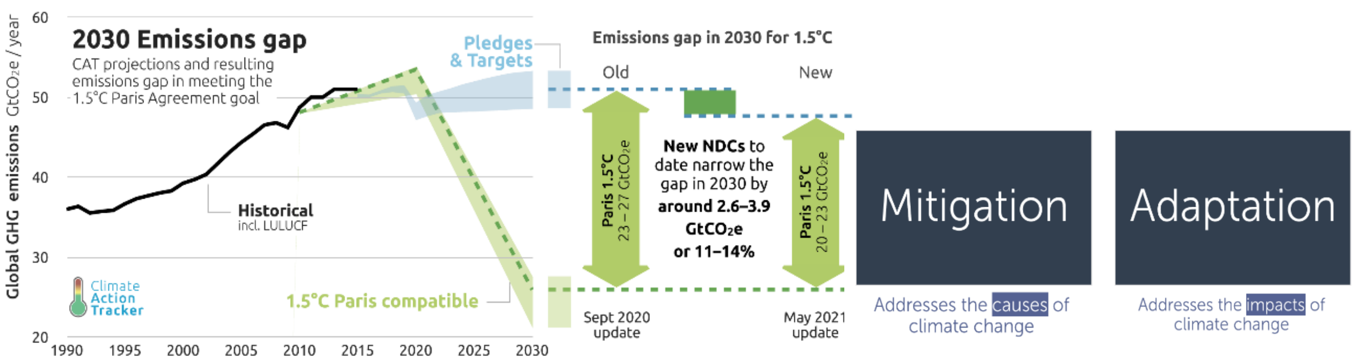


Fig. 7. CAT Projection and resulting emissions gap in meeting 1.5°C Paris Agreement goal. Source, CAT 2020 [3]

2.2. Climate Change Mitigation and Adaptation

Inter-relationship between mitigation and adaptation of climate change through an integrated approach which about actions that reduce both carbon emissions and the impact climate risk. In another word mitigation strategies are about reducing the source of the problem or the Causes of climate change, but adaptation strategies addressed about reducing the Impacts of climate change.

Climate actions and strategic planning should involve both mitigation efforts to lower greenhouse gas emissions and adaptation plans to orient systems toward the impact of climate change by implementing climate mitigation and adaptation strategies through incorporation way. As the separation has led to the misinformed view that addressing climate change means pursuing either mitigation or adaptation. The climate crisis is massive and urgent. Given limited funding, resources and attention from governments and communities that can be allocated to solving it, policymakers need to prioritize such integrated efforts with spreading awareness towards the importance of the situation. [15]

3. Urban Climate and Spatial Form

3.1. Space form, or three-dimensional shape of a space is the result of the shape of the land, plus the shape of the built environment on it. In this context, the built environment comprises the buildings themselves and the open space between them, which are all of equal design importance. It refers to the physical characteristics of a built-up area. Creation of living environments has always been led by strong ideas guided by social or environmental objectives. Thus, urban form has been influenced by safety, order, hygiene and health. [8] During regeneration of cities on this concern, it should overtake the need to create places that are attractive and comfortable to live into adaptable spaces with climate challenges (Fig. 8).

3.2. Urban Dynamics, is the urban skeleton that continue to be the subject of renewal and change as patterns of development are shaped by the shifting currents and emerging influences within political, social, technological, aesthetics and economic spectrums additional to climate change parameters. Urban morphology has proved a successful approach to analyze the characteristics of urban environments the possibility and potential of using morphological techniques to identify the key factors to take into consideration that influence microclimate in cities and inform urban design to provide a maximum cooling effect. [8] Urban space can be classified at a range of scales (Fig. 9).

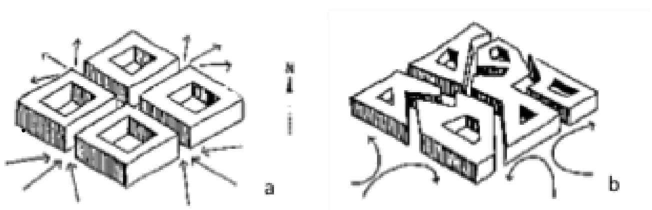
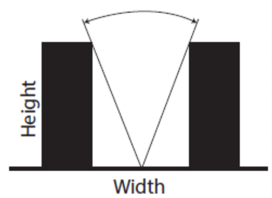


Fig. 8. Different form typologies of urban space have different responses to the environment also, Aspect Ratio & Sky View Factor have an impact on wind flow and Urban Heat Island. By Author



Aspect Ratio & Sky View Factor (SVF)

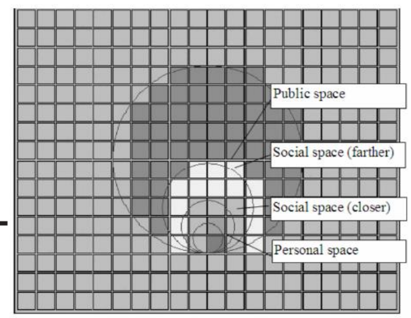


Fig. 9. Urban Space Scales

3.3. Efficiency of Urban System Contributes Mitigation of Urban Heat Island Effect

When cities replace natural land cover with dense concentrations of pavement, buildings, and other sealed surfaces that absorb and retain heat to the atmosphere. This effect increases energy costs, air pollution levels, and heat-related illness and mortality. Climate change will likely lead to more frequent, more severe, and longer heat waves during summer months. Cities officials worry that intense summer heat could lead to uncomfortable conditions for residents and will has an impact on the economy as well. So, it's important to study the contribution of achieving the efficiency of urban system in order to reduce the impact of climate change and mitigate urban heat island effect. Extreme heat events often affect our most vulnerable populations first. Trees, green roofs, renewable energy and vegetation can help reduce urban heat island effects by shading building surfaces, deflecting radiation from the sun, and releasing moisture into the atmosphere, this would help to create spaces that are more comfortable for residents. [19] (Fig. 10)

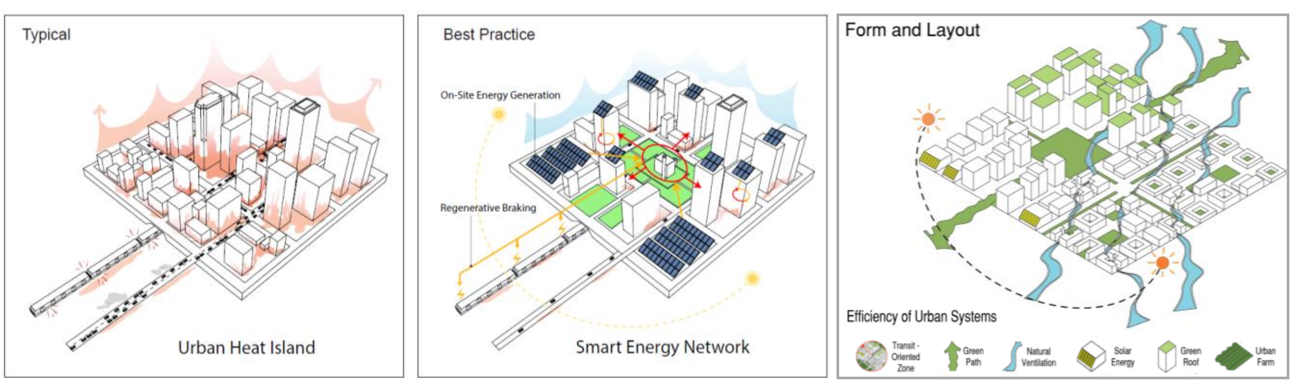


Fig. 10. Urban Heat Island Best Practice. Source, Urban Climate Lab- NYIT School of Architecture and Design, spring 2017 [12]

4. Outdoor Thermal Performance Indicators

Urban climate is distinguished from those of less built-up areas by differences of air temperature, humidity, wind speed and direction, and amount of precipitation. These differences are attributable in large part to the altering of the natural terrain through the construction of artificial structures and surfaces. For example, tall buildings, paved streets, and parking lots affect wind flow, precipitation runoff, and the energy balance of a locale, as well human behavior and the real feeling temperature.[2]

4.1. UTCI - Universal Thermal Climate Index

The assessment of the thermo physiological effects of the atmospheric environment is one of the key issues in human biometeorology. Meteorological input data, particularly radiation data, influence the output of comprehensive heat budget models and the question of data availability in various geographical regions needs to be addressed. [17] UTCI provides an assessment of a felt temperature based on human response to the outdoor thermal environment. It considers air temperature, wind speed, solar radiation and relative humidity. Thermal stress classified in the range from extreme cold to extreme heat stress (Fig. 11) and it's relative from country in climate zone to another.

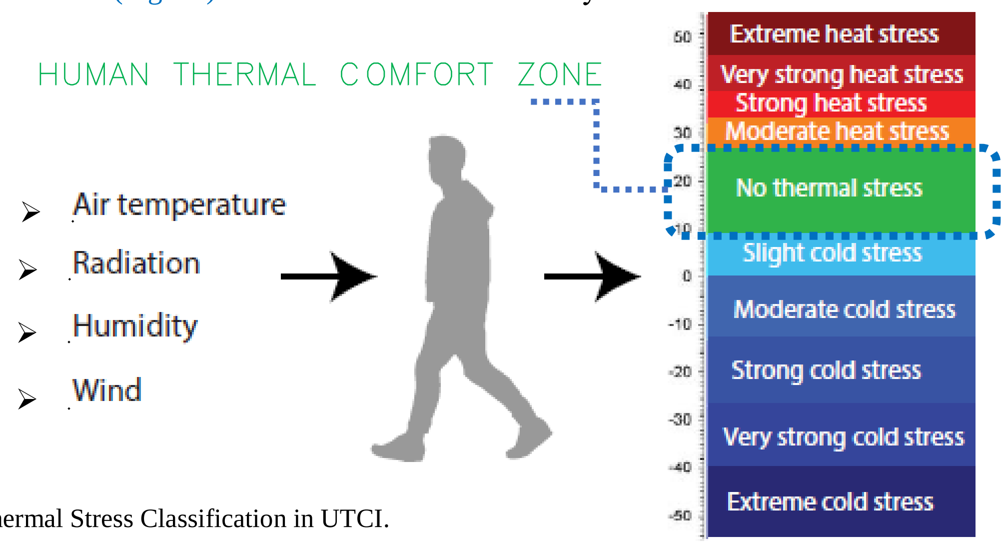


Fig. 11. Thermal Stress Classification in UTCI.
Source, Urban Climate Lab- NYIT School of Architecture and Design, spring 2017 [12]

4.2. PET – Physiological Equivalent Temperature

The physiological equivalent temperature, PET, is defined as the air temperature at which, in a typical outdoor setting with cumulative calculation of wind speed and direction with solar radiation, the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. "PET, is a thermal index derived from the human energy balance. It is well suited to the evaluation of the thermal component of different climates. As well as having a detailed physiological basis, PET is preferable to other thermal indexes like the predicted mean vote because of its unit (°C), which makes results more comprehensible to urban or regional planners, for example, who are not so familiar with modern human-bio meteorological terminology". [6]

PET results can be presented graphically or as bioclimatic maps. The temporal behavior of PET, whereas spatial distribution is specified in bioclimatic maps could express the feeling temperature and the effects of the thermal environment on human beings and evaluate human thermal comfort range. Through analyzing the case study of this research, PET will be calculated in simulation results.

5. Urban Microclimate Modeling

Urban climate model handles the intangible physical environment. It manages meteorological conditions at the simulation area as well as the induced physiological comfort for different types of activities. The meteorological information stored is based on data from feasible meteorological station as well as the urban morphology. The urban form, due to the mass, distribution and material, would affect local microclimate, making it different from what was obtained from the meteorological stations. For example, building blocks would redirect air flow and block direct sunlight. Meanwhile, the combination of different activities and microclimatic conditions would yield different comfort conditions. The different comfort levels for different activities in the studied areas are stored as comfort maps in the microclimate model which would then provide useful information to individual virtual users for decision making in urban design process through indicating the areas of problems. [7]

5.1. Collective effects of microclimatic factors

To study the collective effects of microclimate, multiple regression analyses were used. This is because microclimate consists of different factors and the various combinations could produce the same or different thermal sensation. Meanwhile, according to ASCE (2004), thermal sensation, wind chill, and wind force have to be considered together in determining outdoor comfort the same for, MRT - mean radiant temperature, Humidity percentage and AT - Air temperature which all together comprehensively express PET. By using multiple regressions, the effects of different microclimatic factors could be determined together based on the corresponding correlations. That is, how much the factor is affecting the spatial behavior could be determined. Multiple regressions also helps to derive simple regression equation based on the correlation of the various factors and the inter-correlation between the involving factors. [7] ENVI-met simulation model usage and output example (Fig.12.).

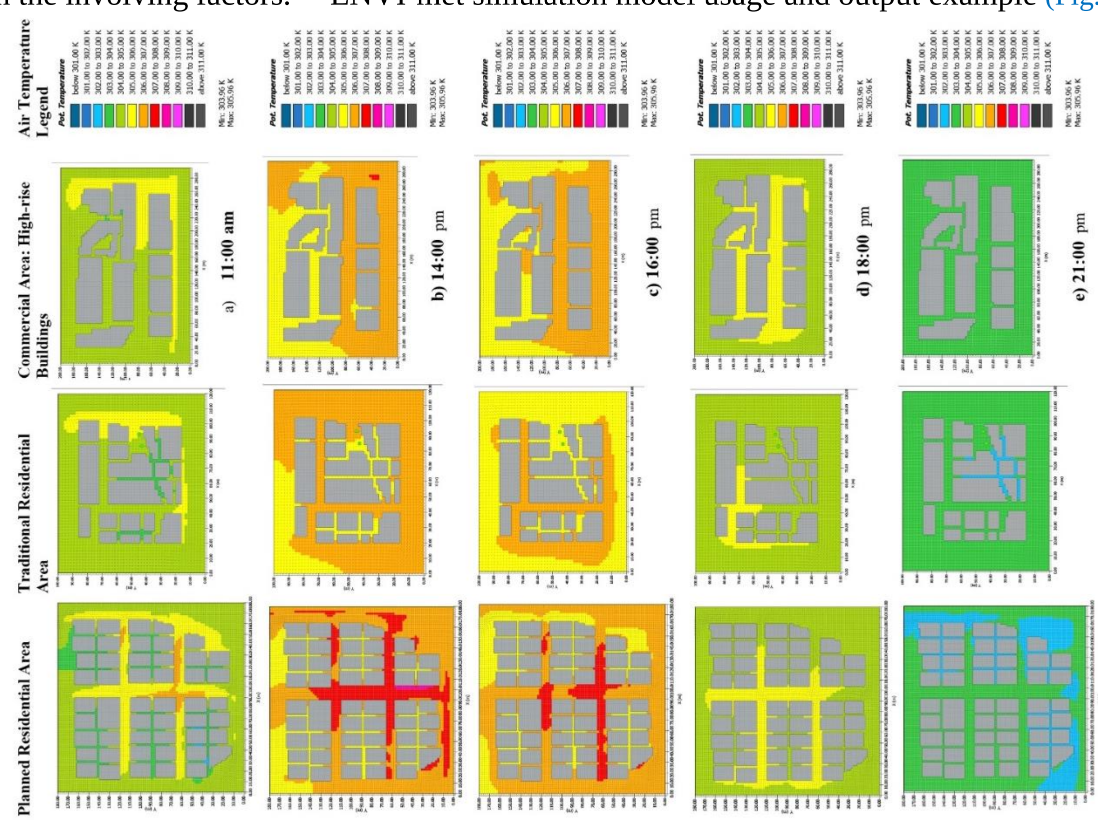


Fig. 12. Visualization of air-temperature at different urban areas with different land use and different urban form & density. Simulated in different times, using ENVI-met simulation. Source, Effect of Canyon Geometry on Outdoor Thermal Comfort [14]

5.2. Microclimate Digital Simulation Models

Computer modeling software should be included in the study programs for environmental control and urban design. All projects submitted to municipalities, neighborhoods, or agencies, must include a good environmental impact study that explains the appropriate plans with the expected climate change adaptation, this will augment the importance of digital simulation in urban design process.

ENVI-met is a computer program that predicts micro climate in urban environment. They describe it as “a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution of 0.5–10 m in space and 10 s in time. ENVI-met is a prognostic model based on the fundamental laws of fluid dynamics and thermodynamics. The model includes the simulation of flow around and between buildings, exchanges processes of heat and vapors at the ground surface and at walls, turbulence, exchange at vegetation and vegetation parameters, bioclimatology, particle dispersion”. [5]

ENVI-met is validated by many research studies and proven reliability for many meteorological parameters. It has been validated for solar radiation, and for the RH. In addition, ENVI-met has been combined with field measurements to represent types of urban trees in the vegetation database.

In the following sample, study showing the relation between PET and outdoor thermal acceptable or uncomfortable range, also the effect of vegetation on simulating PET in urban area for enhancing Human Thermal Comfort shown in a comparative analysis for the different values between a base case and upgraded scenario by adding more vegetation it will be used as a deductive method for the case study of this paper in Berlin, Germany using ENVI-met digital simulation tool (Fig.13).

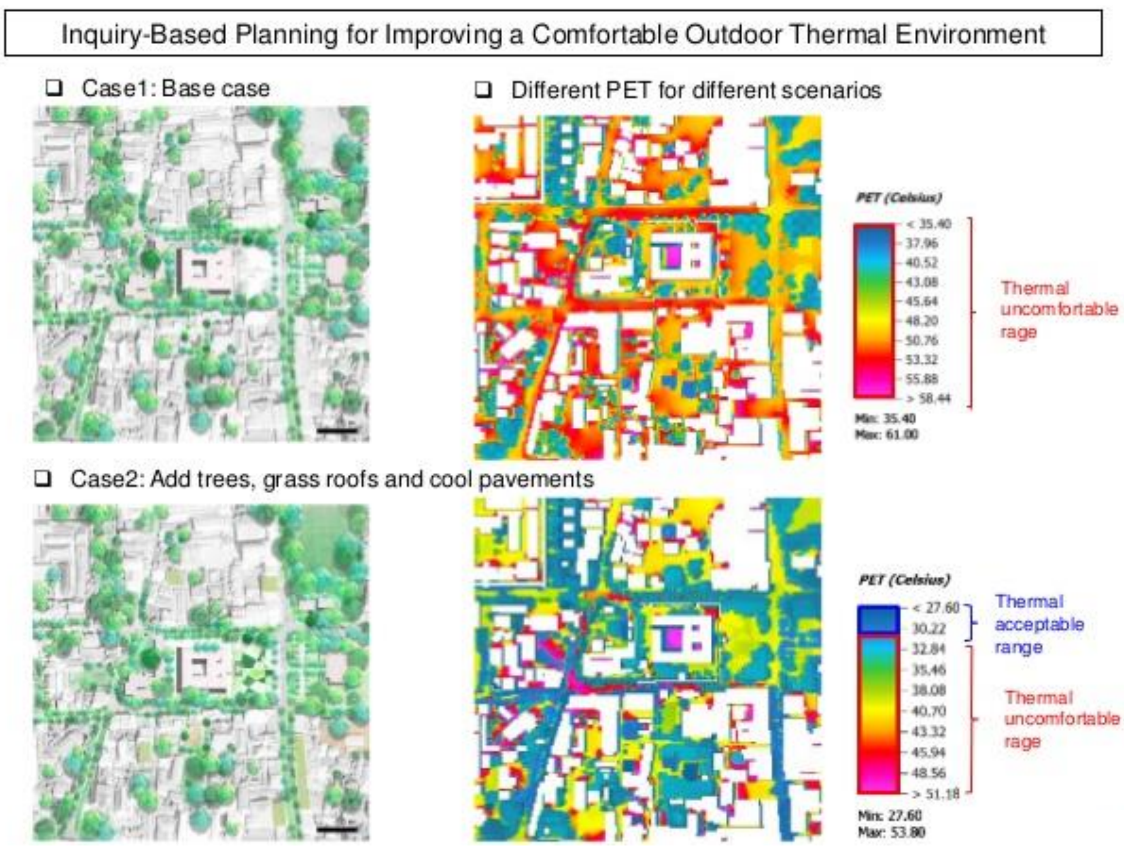


Fig. 13. Example for the effect of increasing Vegetation on PET, using ENVI-met simulation. Source, Thermal comfort conditions of urban spaces in a hot-humid climate [9]

6. Case Study – Berlin, Germany 2018

6.1. Description

Location is in: Schillerstraße 120, 10625 Berlin, Germany. Oberstufenzentrum (OSZ) Körperpflege School, in the center of Berlin for the professions of hairdresser, beautician, make-up artist, specialist for spa companies and dental technicians are taught at this school.
Climate Zone Classification: Berlin's climate is classified as warm and temperate. Berlin is a city with a significant rainfall. According to Köppen and Geiger (Weatherbase), this climate is classified as Cfb. **North direction:** Vertically Slight West (as shown in the drawings).

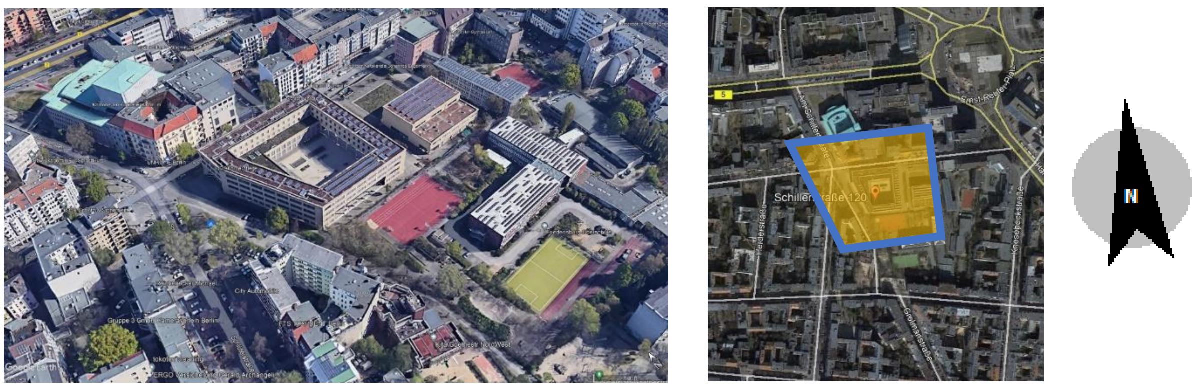


Fig. 14. Case Study Location - Schillerstrasse, Berlin, Germany. Source, Google Earth Satellite Maps

6.2. Scope of Study

The aim of studying this case is to analyze the relation between the form of space and urban context of the area of study with climate parameters. The research focused on urban micro scale as a form of open space at social scale range and study the correlation with urban climate parameters and the limitation is on microclimate scale by using digital simulation models to analyze the impact for different Air Temperature values in different time periods with PET validation through detecting the problem between metrological measurements and real feeling. The results of PET will show how the form of the courtyard space affected the simulation.

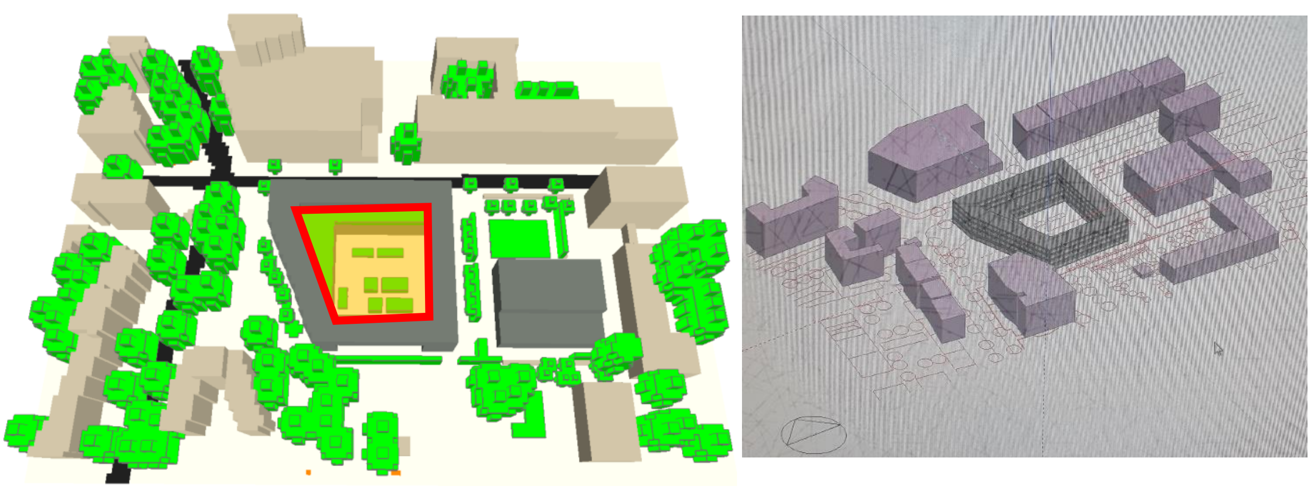
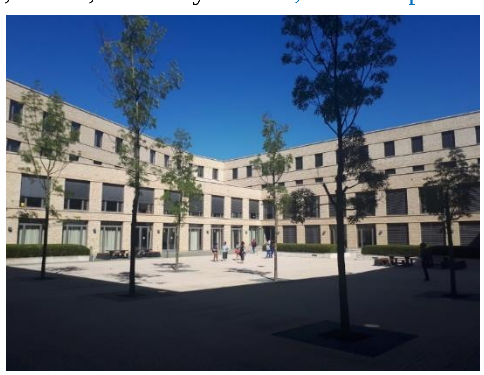


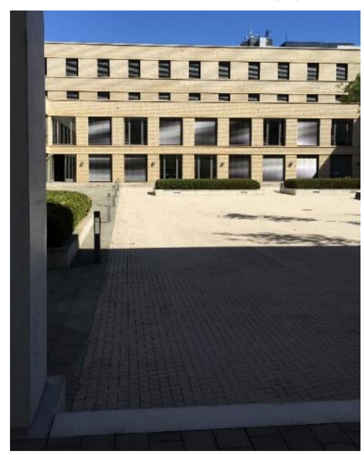
Fig. 15. Case Study Scope - Schillerstrasse, Berlin, Germany. Source, by Author using ENVI-met & DesignBuilder Models

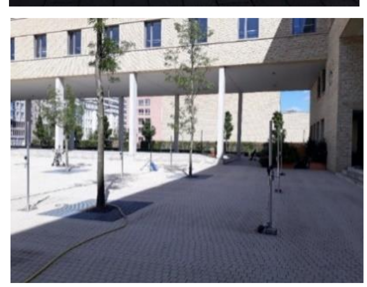
6.3. Site Analysis

The area of study is in the range of 500*300 m with an area about 300 m radius centered from the targeted project of the case study. Site description for the heights of the surrounding buildings shown on the below map, School building is in 4 floors with green roof above 1st floor. The surface of the courtyard is primarily covered by paving stone, in the middle part of the area there are only a few trees, which are too young to provide relevant shades. From site visit investigation, thermal uncomfortable detection is in sitting outdoor.

Case Study Site description - Schillerstrasse, Berlin, Germany. Source, Site visit photos by Author and the working group







6.4. Tools & Empirical Study

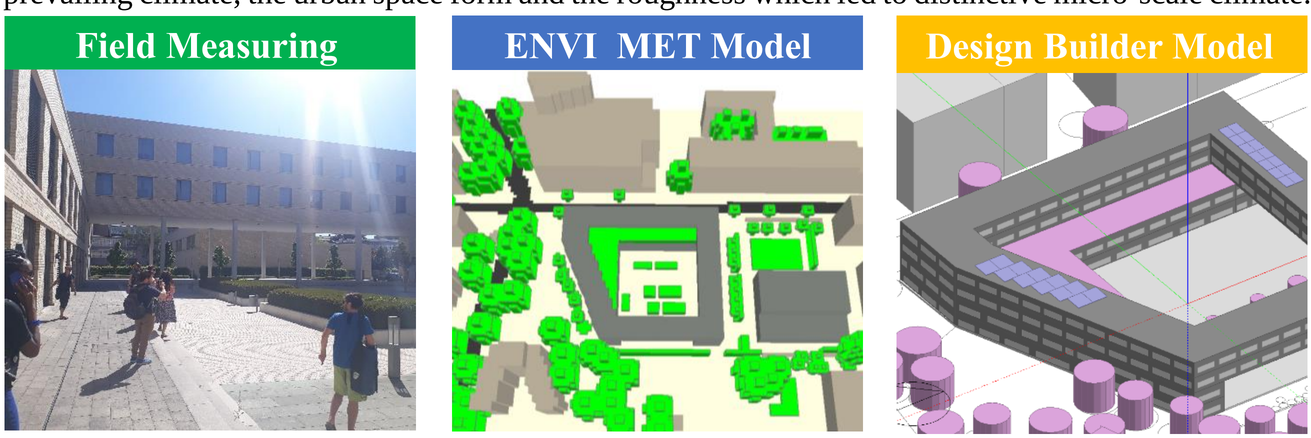
Field Measuring: The measuring campaign has been held on 15th of July 2018 at 8:00 a.m. till 10:00 p.m.

- The weather this day was Humid warm summer day the sky was clear with clam winds.
- The school Courtyard has been divided to into 29 Grid points for measurements at 1.1 meters height. A measure of the Globe Temperature (Tg), Air Temperature (Ta), Relative Humidity (RH) and Infrared radiation (IR) have been measured at each point per hour referred to the bio climatological reference height.
- We were divided into number of groups in this measuring campaign each group has 3 people.
- In the morning and early afternoon hours considerable part of the area is exposed to the direct sunlight.
- Hand-held wind meter comes with a cup anemometer. It operates completely independently of the wind direction, measures wind speed, and calculates wind velocity also measures (Ta) and (RH).
- Multifunction data-logging thermometer used to measure in/outdoor TG, TA, RH and others, it's an ideal device for evaluating heat stress risks in different work environments.

Hand-held wind meter and Multifunction data-logging thermometer. Source, Site investigation by measuring campaign.

The study has been conducted in three main phases:

The School Courtyard was the main focused investigation area of the case study in order to achieve outdoor thermal comfort for the users. It is important to understand the interactions between the prevailing climate, the urban space form and the roughness which led to distinctive micro-scale climate.



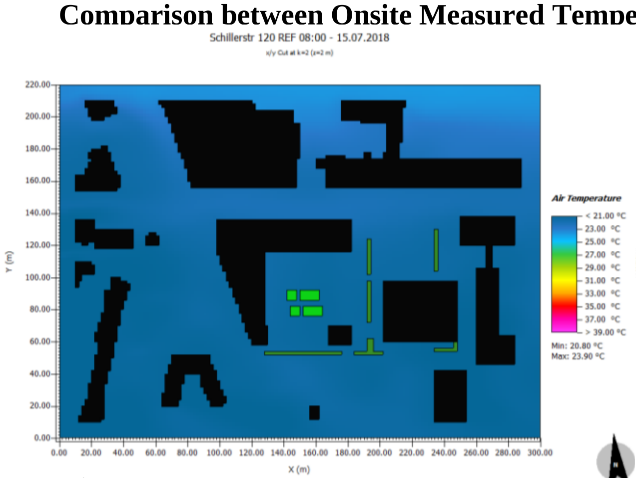
Urban micro scale climate studies and simulation modeling for this case includes programming coding (R-Studio), using the metrological measurement devices, and technical thermal models like microclimate simulation by ENVI-met software (Focused outcome), Energy simulation with DesignBuilder and RayMan model as human thermal comfort indicator tool using fish eye photos for calculating Sky View Factor, which all helpfully used in the analyzing of digital simulation implemented in this research case.

6.5. Input Parameters

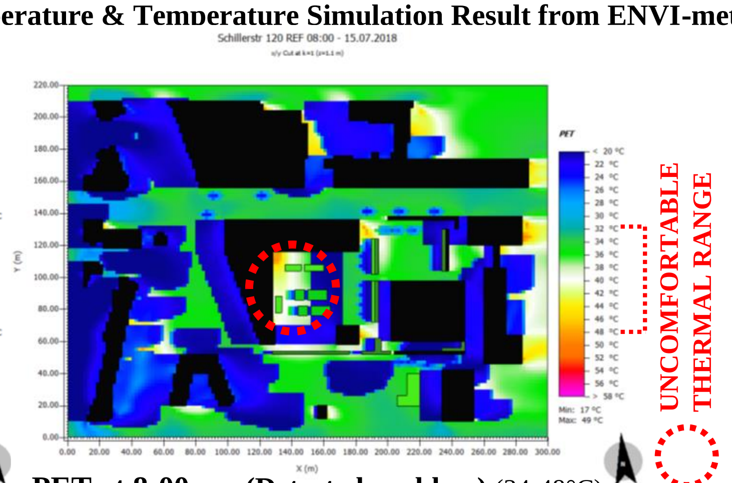
Using ENVI-met 2018 simulation program to investigate the effects of possible mitigation and adaptation strategies. As it's a Holistic Microclimate Model, in which all the different elements of an urban or landscape setting interact which each other. The model started at midnight and 24 hours were allowed to the modelled parameters to stabilize (time designations in this section refer to the timescale of the model). The simulation finished at 10 a.m. next day, therefore the total simulated time was 35 hours.

6.6. Results and Output Data Analysis (Air Temperature – PET)

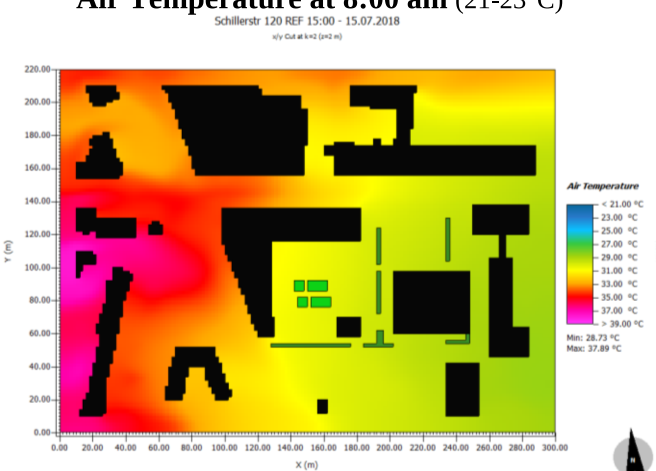
Comparison between Onsite Measured Temperature & Temperature Simulation Result from ENVI-met.



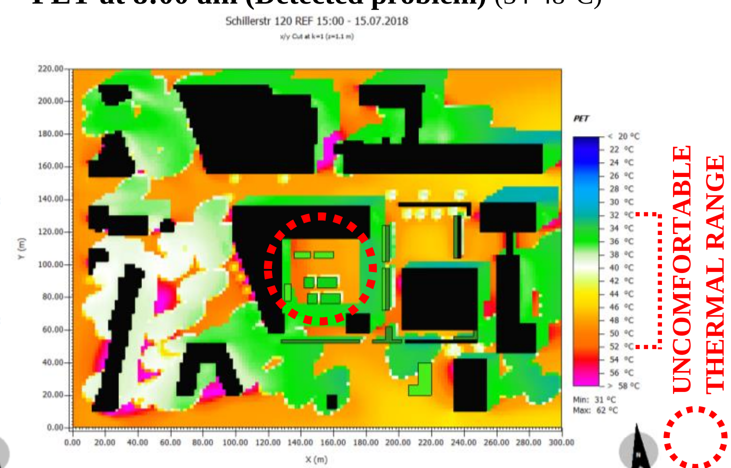
Air Temperature at 8:00 am (21-23°C)



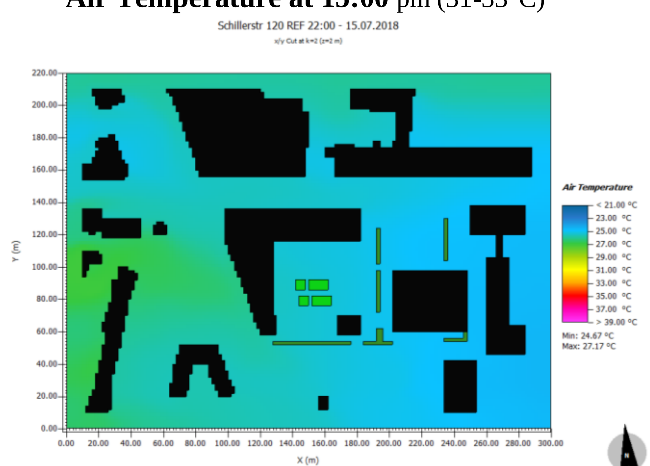
PET at 8:00 am (Detected problem) (34-48°C)



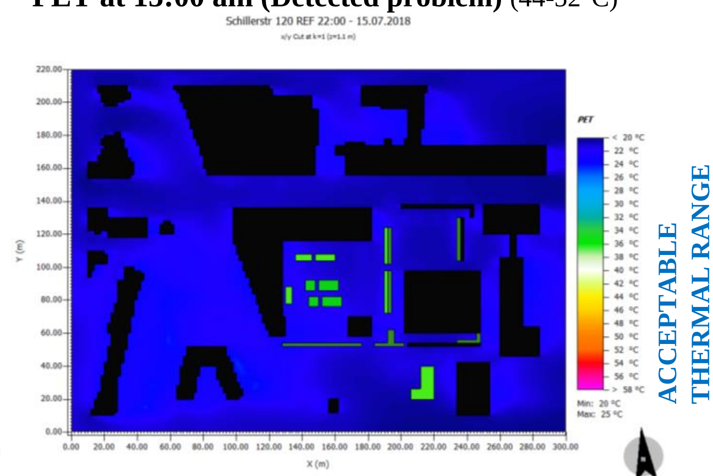
Air Temperature at 15:00 pm (31-33°C)



PET at 15:00 am (Detected problem) (44-52°C)



Air Temperature at 22:00 pm (23-25°C)



PET at 22:00 pm (22-24°C)

6.7. Findings and Solutions depending on simulation results

A. Problem in the feeling temperature inside the courtyard has been validated as uncomfortable thermal range for human wellbeing in outdoor space due to lack of shades and dark paving material.
B. Increases water areas and create high fountain as an Air cooler is a good adaptation solution.
C. Making Path flow for nice common wind, by Lift up the existing trees and adding another trees inside the court by a design way allow cool wind to reach to all floors.
D. Plant green walls as a screen to forward the air flow to almost building and outdoor space cooling.
E. Plant more Green roof and Green Facades for east and south oriented elevations as insulation to decrease the absorbed amount of Heat radiation, also to reduce CO_2 emissions to mitigate UHI.
F. Using roof solar panels and solar water heating systems to save energy, also to reduce CO_2.
G. Using light painting for building and light materials for Hardscape and road to reduce Temperatures.

6.8. Conclusion

1. ENVI-met software allows us to create sustainable living conditions in a constantly changing environment. With ENVI-met's interactive tool we can dive into any aspect of the microclimate complex and analyses how our designs perform with all parameters, orientation and Sun path.
2. The urban microclimate plays an important role in building energy consumption and thermal comfort in outdoor spaces. Nowadays, cities need to increase energy efficiency, reduce pollutant emissions and mitigate the evident lack of sustainability.
3. The growth model highlights the need to redirect the construction sector towards urban renovation using a bioclimatic approach. The public space plays a key role in improving the quality of living in today's cities, especially in terms of providing places for citizens to meet and socialize in adequate thermal conditions and comfortable outdoor context.
4. Thermal comfort affects perception of the environment, so microclimate conditions can be decisive for the success or failure of outdoor urban spaces and the activities held in them.
5. Usage of microclimate digital simulation models to generate appropriate urban forms can lead to create a better urban context for different areas in different conditions with a consideration of climate parameters in mitigation and adaptation strategies to achieve human thermal comfort in urban areas and enhance climatic efficiency which has an effect on human health and the quality of life also the productivity of the community and energy demand and energy consumption.
6. Upgrade the performance of Urban Form to be adapted with Climate factors and Climate Change in order to achieve high efficiency for Human wellbeing and quality of urban life by using digital simulation and enhance the importance of urban climate modeling and enhancing thermal efficiency and Human Thermal Comfort in open urban spaces.
7. There is a direct relationship between climate change environmental and social development for the community and it all has an impact on the economy of individuals and governance.
8. ENVI-met give the solution and scenarios of how the urban environment could be designed to give the best possible microclimate conditions to the citizens, which is very important for human health.

6.9. Recommendations

- Increasing level of vegetation in the courtyard by planting more trees with larger canopies to provide more shades and to mitigate the urban heat island effect.
- Changing the material of the hardscape with a material with high albedo to reduce absorbing heat.
- Using non-reflective glass in the windows since its reflectiveness makes the sun rays more intense inside the courtyard to achieve efficient outdoor thermal performance.
- Creating a dynamic shade to provide shade for the courtyard and to be movable upon the need.

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