EXPERIMENTAL AND SIMULATION-BASED ANALYSIS OF OUTDOOR THERMAL COMFORT CONDITIONS IN URBAN ENVIRONMENTS

ATA CHOKHACHIAN

Technische Universität München
TUM School of Engineering and Design

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Ata Chokhachian

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Vorsitzender:

Prof. Dr. -Ing. Frank Petzold

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1. Prof. Dipl. -Ing. Thomas Auer

2. Prof. Dr. -Ing. Christoph Reinhart

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ABSTRACT

In recent years, we have witnessed a growing public awareness of the impacts of the natural and built environment on well-being and health in cities. Although this is an encouraging sign, there is still a lack of good evidence and objective measures on how urban microclimate affects people's perception of outdoor thermal comfort in urban environments. In the global context of climate change and its impact on the public life of the urban population, there is an urgent need to better understand the current and future characteristics of urban microclimate and environmental qualities on an anthroposphere scale.

The impact of thermal comfort in outdoor activities is a complex issue that involves climatic and behavioral aspects, which demands both numerical approaches and field measurements, to understand, design, and achieve more comfortable, healthy, and livable urban environments.

In this context, the major contribution of this dissertation is the development of experimental and simulation-based analysis methods to quantify the effects of the built and natural environments on the outdoor thermal comfort of pedestrians. The experimental approach is used to better understand the interdependencies of urban microclimate and urban morphology and their impact on the subjective and physiological responses of the pedestrians. The developed method has shown that the geo-referenced outdoor comfort data collection technique can assist in understanding microscale interactions of environmental parameters and their impact on pedestrians' perceived temperatures.

The simulation-based approach extends the methodology from just understanding the urban environments to predicting the outdoor comfort in cities and informing the design process. The thesis compares two different tools for modeling radiant environments, with the results demonstrating the importance of accurate estimation of the mean radiant temperature and the need for a tool for annual estimation of outdoor comfort that includes the vegetation canopies. To achieve this goal, the study develops a numerical process-based tool (PANDO) to simulate individual trees for their radiation fluxes, water uptake, canopy interception, and cooling potential to plan and design urban greenery more efficiently in cities considering the benefits and future paybacks. The developed tool has been validated and implemented as a plug-in for the Rhino Grasshopper3D environment and applied to estimate the benefits of urban forestry on annual pedestrian thermal comfort in 270 cities throughout the world.

ZUSAMMENFASSUNG

In den letzten Jahren konnte ein zunehmend wachsendes, öffentliches und gesellschaftliches Bewusstsein für die Auswirkungen der natürlichen und gebauten Umwelt auf Gesundheit und Wohlbefinden in Städten beobachtet werden. Obwohl dies ein ermutigendes Zeichen ist, fehlen weiterhin Belege und objektive Messwerte wie das Stadtmikroklima die Wahrnehmung des thermischen Außenkomforts der Menschen in städtischen Umgebungen beeinflusst. Im globalen Kontext des Klimawandels und seiner Auswirkungen auf das öffentliche Leben der Stadtbevölkerung, besteht der dringende Bedarf, die aktuellen und zukünftigen Eigenschaften des städtischen Mikroklimas und der Umweltqualitäten auf der Ebene der Anthroposphäre besser zu verstehen.

Die komplexe Problemstellung des Einflusses der thermischen Behaglichkeit auf Aktivitäten im Freien umfasst sowohl klimatische als auch verhaltensbezogene Aspekte und erfordert neben numerische Ansätzen auch Feldmessungen, um komfortablere, gesündere und lebenswertere städtische Umgebungen zu verstehen, zu entwerfen und zu schaffen.

In diesem Zusammenhang ist der Hauptbeitrag dieser Dissertation die Entwicklung von experimentellen und simulationsbasierten Analysemethoden, um die Auswirkungen der gebauten und natürlichen Umgebung auf den thermischen Außenkomfort von Fußgängern zu quantifizieren. Der experimentelle Ansatz wird verwendet, um die gegenseitigen Abhängigkeiten des städtischen Mikroklimas und der städtischen Morphologie und deren Einfluss auf die subjektiven und physiologischen Reaktionen der Fußgänger besser zu verstehen. Die entwickelte Methode zeigt, dass die georeferenzierte Datenerfassung für den Außenkomfort dabei helfen kann, mikroskalige Wechselwirkungen von Umweltparametern und deren Einfluss auf die von Fußgängern wahrgenommenen Temperaturen zu verstehen.

Der simulationsbasierte Ansatz erweitert die Methodik vom reinen Verständnis der städtischen Umgebung hin zur Vorhersage des Außenkomforts in Städten und zur Gestaltung eines komfortoptimierten Planungsprozesses. Die Arbeit vergleicht zwei verschiedene Werkzeuge für die Modellierung von Strahlungsumgebungen. Die Ergebnisse zeigen, wie relevant eine genaue Schätzung der mittleren Strahlungstemperatur ist und dass ein Werkzeug für die jährliche Einschätzung des Außenkomforts benötigt wird, das die Vegetationsdecke mit einbezieht. Um dieses Ziel zu erreichen, entwickelt die Studie ein numerisches, prozessbasiertes Werkzeug (PANDO) zur Simulation einzelner Bäume für deren Strahlungsflüsse, Wasseraufnahme, Kronendachabfangung und Kühlungspotential, um städtische Begrünung in Städten unter Berücksichtigung der Vorteile und zukünftigen Amortisationen effizienter zu planen und zu gestalten. Das entwickelte Werkzeug wurde validiert und als Plug-in für die Rhino Grasshopper3D implementiert. Schließlich wurde es in 270 Städten weltweit angewendet, um den Vorteil von Stadtbegrünung auf den jährlichen thermischen Komfort von Fußgängern abzuschätzen.

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We live in a world in which the tree is worth more financially dead than alive, for so long our economy works in that way even though we know it is destroying the planet and we know that it's going to leave a worse world for future generations. This is short term thinking based on this religion of profit at all costs that needs to be changed.

The Social Dilemma
2020 Documentary

C H A P T E R O N E

INTRODUCTION

Summary

Driven by climate emergency and its effect on urban environments - which accommodate various activities and improve the livability of the cities - there is an urgent need to better understand current and future characteristics of urban climate and environmental qualities on an anthroposphere scale. Addressing this gap, future actions for urban climate mitigation and sustainable development of urban territories should not only seek innovative computational methodologies and tools but also with an exploration of new sources of information and open data platforms, contemplating the human itself as the inseparable dimension of design and urban planning. Within this context, this study develops tools and methods to quantify the effects of the built environment on pedestrian outdoor thermal comfort outdoors.

1

1 INTRODUCTION

1.1 URBAN MICROCLIMATE

Climate is one of the primary factors that define how frequently people use the public space and outdoor environments. The built and natural environments shape their surrounding microclimates that vary in spatiotemporal resolution. The urban microclimate is a shared domain between climatologists and urban designers, however looking at the history of urban climate research, we can see that they have dealt with this topic differently in terms of scale, relevant variables, metrics, and resolution. The climatologists were more interested in Urban Heat Island (UHI) phenomena on a mesoscale but the urban designers have been more concerned about the environmental forces on and/or between the buildings. Despite that, over the recent years, the urban climatologists are also moving progressively to microscale as the urban form and surface air energy exchange between the urban canyons have become the core of such studies. As an example, the PALM model is one of the recent advancements to expand the application for urban environmental modeling and calculating human thermal comfort and thermal stress coupling micro and mesoscales [1, 2].

Additionally, one can notice that over the past several years, measures related to public space and urban health like outdoor comfort, air quality, and acoustic pollution have become the core of several tool developments and studies between climatologists, computational designers, and urban planners. As an example, platforms like Eddy3D [3], InFraReD [4], Giraffe [5], GreenScenario [6], and UMI [7] are all addressing the gap between urban design decision making and environmental performance, and recently, they are even more and more convinced to include microclimate analysis in their workflows. Even though there are efforts from both fields of climatology and urban design to address microclimate-related questions, however, there should be further steps to bridge not only sophisticated but theoretical results of urban climatologists with empirical and design-oriented findings of urban planners.

One of the main difficulties faced by the designers in shaping the streetscape microclimate is the conflicts in the seasonal needs. Like the required protection from the sun in summer and the need for solar exposure in winter with compactness and openness to the sky, respectively. We can find traditional and contemporary examples providing solutions for comfort opportunities according to the climate, however annual quantitative statistics based on scientific methodologies are still required. This thesis tries to address the above-mentioned gaps by developing new tools and workflows to build a communication between urban design and pedestrian outdoor thermal comfort.

Another main deficiency of currently available tools to model outdoor comfort is the limitations in modeling vegetation canopies and their impact on annual perceived temperatures. This is important because while the benefits of urban forestry are well understood in the climate community, still the application of this knowledge has been limited in urban planning. In other words, the current body of research does not address how urban greenery should be implemented in cities in terms of distribution and density. Therefore, a suitable and fairly detailed modeling tool is needed to provide a solid quantitative assessment of the value of trees in terms of heat mitigation and microclimate improvements in urban environments [8]. In Addition, further empirical research is necessary to efficiently guide the design and planning of urban green space, and specifically to investigate the importance of the abundance, distribution, and type of greening [9].

1.2 AIM AND OBJECTIVES

Addressed by several scholars, the integration of urban microclimate in design decision-making processes can be beneficial on an urban scale to enhance people's presence outdoors [10-13] and on a building scale, it can have seasonal positive and negative relevancies on energy demand and daylight measures [14, 15]. One of the key parameters to assess and quantify environmental measures in cities is people's exposure to extreme conditions. Likewise, it is closely linked to both climate change and urban morphology meaning that any effort to mitigate the former may further improve the latter. Successful implementation of health measures demands innovative tools and reliable methods addressing common issues of wellbeing and quantifying urbanites' exposure to thermal discomfort as they walk through the urban context.

Addressing this gap, this thesis is approaching the problem not only through innovative computational methodologies and tools but also with an exploration of new sources of information and data collected on-site, considers the human itself as the inseparable dimension of design and urban planning. In this context, this thesis develops computational methods and sensor kits to model and gather data as a process to generate and extract microclimatic information respectively. The main objective of the study is to offer a set of toolkits to enable the user to quantify and map outdoor thermal comfort and vegetation potential for the representative cities and climate conditions. These tools and workflows would be beneficial to inform the planning processes at the street scale supporting 'human-powered transportation' such as cycling and walking for healthy communities.

1.3 RESEARCH HYPOTHESIS

The main hypothesis underlying this thesis addresses that, it is feasible to develop new tools to quantify the outdoor thermal comfort within the anthroposphere for pedestrians using simulation-based and sensing techniques that will inform the design process in urban planning.

Feasibility

- Sensory data can help to understand the dependencies of microclimate on human thermal perception and urban morphology taking into account the transient nature of outdoor environments.
- It is possible to develop a numerical process-based model to simulate the cooling and shading effect of trees in urban environments and couple it with the existing transient simulation tools for modeling human thermal comfort in outdoor spaces.

- Experimental methods can expand the understanding of outdoor comfort conditions in cities and simulation-based analysis can better inform the design of urban environments.

Justifiable effort

- Having tools to gather geo-referenced microclimate data on a human scale and finding correspondences between the anthroposphere and thermal perceptions, will underline the necessity of thinking more on a human scale and understanding human physiology and perception in outdoor environments.
- Offering a tool able to simulate the effects of urban greenery in cities will help the planners to quantify the benefits of such investments and also plan them more related to the climate, water resources, and morphology of the specific site or development.
- The recent developments in the application of urban CAD models to quantify outdoor thermal comfort in cities make it manageable to include detailed vegetation models in their workflows to have a more sensible estimation of seasonal and spatial variation of outdoor thermal comfort conditions.

Relevance

- The improved modeling methodologies can inform the decision-making processes with microclimatic knowledge which can improve the design quality of urban environments in terms of thermal comfort and encourage people to use them on a daily basis.
- There is a correlation between well-planned urban forestry and the active use of public spaces. Well-designed pedestrian pathways with trees can define how people choose to commute in cities according to comfort conditions and promote human-powered transport modes.

1.4 RESEARCH QUESTIONS

1) How can we measure spatiotemporal outdoor thermal comfort variations in transient conditions?
2) How and to what extent people adapt to dynamic conditions in outdoor space?
3) What is the contribution of materiality and urban form to outdoor thermal comfort measures?
4) How can we model tree canopies in annual outdoor thermal comfort simulations?
5) To what extent trees can save us from heat stress over the year in different climate zones?

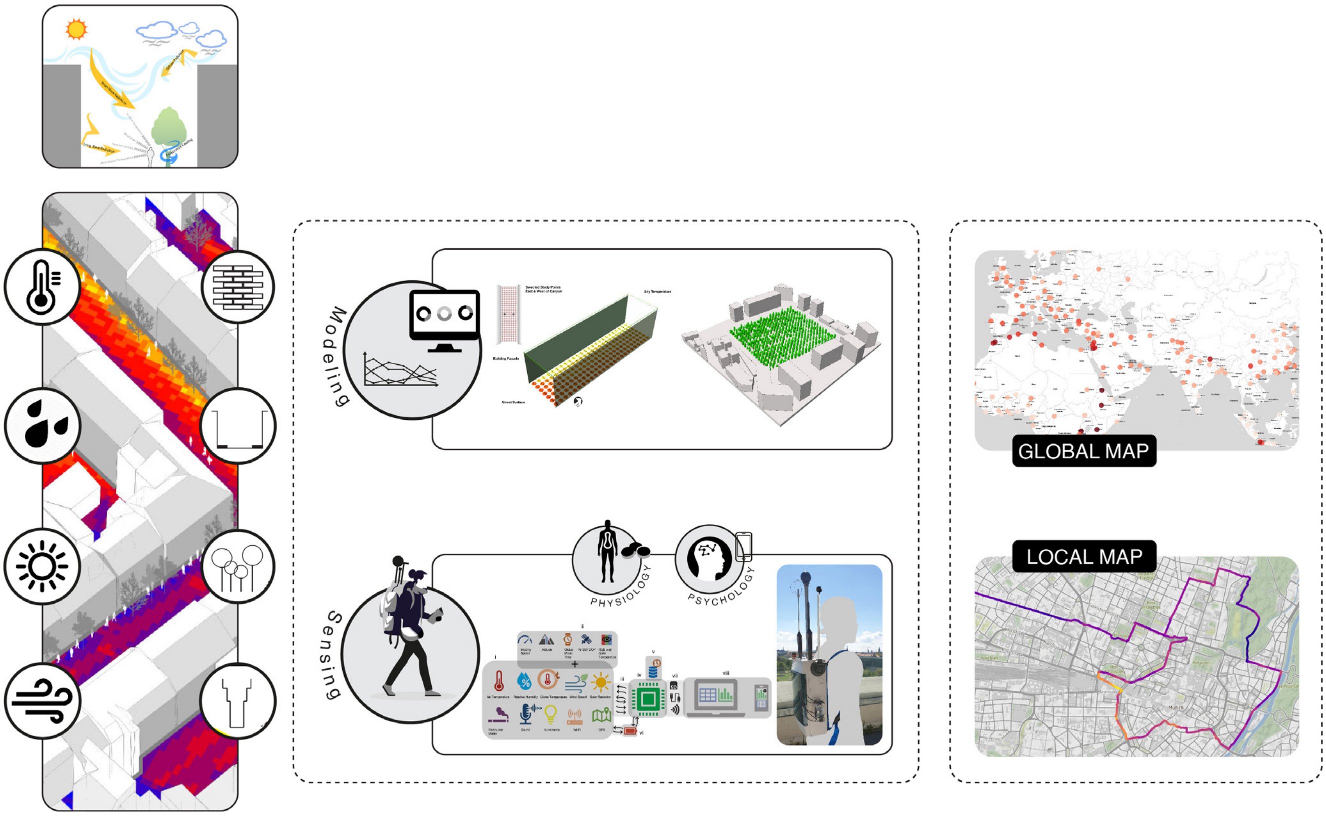

Figure 1.1
Graphical representation of the research methods.

1.5 METHODOLOGY

Methodologically, there are two main approaches to evaluate and estimate thermal comfort conditions in cities, one is a simulation-based approach and the other is based on sensing techniques. The simulation-based methods have been always dependent on computational power available on the hardware system, however, with the advent of cloud computing resources, it is possible to simulate complex and multi-scale urban models with reasonable time effort [16]. Despite that, the current efforts to simulate perceived pedestrian thermal comfort in urban settings is enormous, since the environmental conditions are highly localized and involve phenomena that are time and calculation-intensive to simulate, plus requiring substantial urban data inputs.

Since the goal of this study is the development of tools, each method (modeling and sensing) comes in a separate chapter with specific methodology development and applied case scenario. Figure 1 illustrates the research method for both sensing and modeling. The scope of the two methods that are developed in this thesis is briefly explained below.

1.5.1 Geo-referenced Comfort Sensing

Studies on the microclimate of cities have already demonstrated that pedestrian thermal comfort is a function of the built environment and it is fundamental to understand this phenomenon both with numerical techniques and field measurements to achieve comfortable, healthier, and more livable urban space. There has been a wide variety of methods to approach the question of how people react or behave in transient (unsteady) outdoor conditions, since most of the thermal comfort study methods perceive pedestrian thermal comfort as a “static” phenomenon.

The application of thermal comfort monitoring in transient conditions is limited due to the complexity of the task and instrumental setup which leads to a lack of understanding of how pedestrians compensate heat loads. In this regard, this study develops and applies an experiment to measure environmental parameters and human thermal behavior in urban space by relating individual and subjective responses to environmental conditions and adaptation. The developed method can provide an understanding of the responses of pedestrians when walking in an outdoor environment using a geo-referenced method for monitoring and mapping of microclimate. It also uses a longitudinal survey to obtain the thermal responses of pedestrians, for improving the “climatic knowledge” of the urban context. Chapter 3 builds a full spectrum of the method and describes in detail the equipment setup, data collection approach, mapping method, and outcomes.

1.5.2 Outdoor Comfort Modeling

Besides the sensing techniques, numerical modeling of urban environments has become a useful tool for analyzing detailed urban climates both in meso and micro scales. To simulate urban climate, atmospheric models need to have an adequate representation of the influence of the city on the exchanges with the anthroposphere [17]. In other words, to fully describe the thermal sensation of a person walking or sitting under a tree, needs multiple interdependent simulation models. Over the last years with the increase in the necessity of research on urban climate, several urban modeling tools have evolved such as ENVI-met and RayMan [18, 19]. Both tools require significant calculation time and cannot be readily employed at an urban or neighborhood level especially for annual calculations including vegetation covers in terms of shading and cooling benefits. This study addresses this gap by introducing a stand-alone simulation tool for the soil-plant atmosphere that can be coupled with existing process-based numerical simulation engines and quantify the benefits of urban forestry on human thermal comfort in annual cycles.

1.6 THESIS OUTLINE

Chapter 1, provides an overview of the scope, motivation, methods, and limitations of the study and follows with a summary of the necessity for further research and development in the outdoor thermal comfort domain. Further, it briefly explains the developed and applied methods in this thesis.

Chapter 2, starts with the history of research on outdoor thermal comfort since 1934 exposing the reader to the question of how over time, the scale and focus of such a research field has shifted from the atmospheric environment to the anthroposphere. More specifically, this study focuses on the air layer between the buildings and the ground up to a height of 2 meters. The chapter continues with an overview of biometeorological indices and explains the available tools to quantify outdoor thermal comfort explaining the limitations as well, to set the stage for addressing the gaps in the field of urban microclimatology.

Chapter 3, introduces the reader to the developed tool that measures human thermal comfort in transient environments. It reviews the already existing methods for ground-based environmental sensing and summarizes the pros and cons of each one. Further, it explains the sensor kit setup and the step-by-step improvement of the devices and platforms used in the experiment. After explaining the methodology and data processing steps, the applied scenario follows up with a detailed description of the case study, experiment design, results of analysis, and discussions.

Chapter 4 addressed the second method on quantifying human thermal comfort with the comparison of CFD-based and transient simulation models to expose the limitations and benefits of each method. The focus of the study is specifically on the modeling of a radiant environment as one of the main drivers for perceived temperatures outdoors. The chapter follows up with a further investigation of façade material choice and its contribution to the final perceived temperatures on the street canyon. The limitations found in this chapter are explained in the next chapter with the tools developed to model tree canopies as the missing piece for dynamic and annual simulation of human thermal comfort in cities.

Chapter 5 introduces a parametric tool for simulating the soil-plant atmosphere of tree canopies in Grasshopper3D, a visual programming language, and environment that runs within the Rhinoceros 3D computer-aided design (CAD) application [20]. The chapter builds a discussion on the benefits of urban forestry in cities and follows up with a detailed explanation of the radiation model, phenology model, tree templates, and model validation. Further, to demonstrate an applied case, 270 cities are simulated for their comfort improvement potential with urban forestry. The results are illustrated on maps showing how much trees can save us from annual heat stress in the respected cities and climate zones.

Chapter 6 summarizes the results and discussion of the thesis and provides an outlook on how this research can be further developed and applied in future research and practice.

1.7 IMPACTS

For administrators, policymakers, designers, and planners, it is crucial to determine effective performance indicators to predict and evaluate the environmental quality and implement the gathered information into design decision-making processes. This aspect is fundamental since the usage of public space is the most relevant measure to evaluate its performance and guaranteeing continuity through time. To achieve this target, the frequency at which residents are walking down a certain street can be used as an indicator of the quality and attractiveness of the urban environment. In this regard, this thesis aims to develop simulation and sensing workflows to forecast outdoor thermal comfort in cities that can be used by urban planners and designers as a decision-making tool to understand and design livable outdoor environments and contribute to the health and wellbeing of the citizens. Therefore, the outcomes are comfort maps that reveal the impacts of the built and natural environments on human outdoor thermal comfort including urban forestry potential based on their climate, and seasonal behavior of trees. These maps combined with detailed simulated canyon models could be valuable source of information for urban planners to consider urban forestry in direct connection with human comfort and wellbeing in their design processes.

1.8 LIMITATIONS

- This thesis does not intend to address the questions and topics related to mesoscale studies nor UHI-related topics.
- All the findings and discussions are only valid for the microclimate and outdoor comfort-related subjects within the defined scale, climate, resolution, and temporality.
- Some of the findings might not be scalable especially the ones related to the subjective thermal experiences in terms of physiological and psychological findings and discussions.
- The methods and tools developed and used in this thesis need to be further validated to be applied in different contexts and climate zones.

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C H A P T E R T W O

URBAN MICROCLIMATE AND OUTDOOR COMFORT

Summary

This chapter reviews the literature on microclimate and outdoor comfort-related research from 1934 to today and exposes the reader to the chronological evolution of the terms and raises the question of how it evolved based on new developments and necessities of the climate and era.

2

2.1 INTRODUCTION

In recent decades, several studies have focused on the link between microclimate and urban settlements indicating that improved outdoor thermal conditions are in direct connection with how people conceive and use outdoor space. Designing a place with optimum comfort level may lead to positive urban development such as encouragement for cycling and walking, attracting more people to comfort zones in the city, and turning this opportunity into business and tourist attractions to shift the area economically profitable [1]. Comfortable outdoor spaces could be designed with a set of strategies according to the context like, planting trees with the advantage of evaporative cooling plus shading effect or adding man-made canopies using local materials are some of the possible solutions.

The subjective human sensation of feeling thermally comfortable is generally understood to depend on several factors and parameters. Air temperature, humidity, wind speed, and radiation are the four basic physical environmental parameters impacting the body's heat balance [2]. However, perceived temperature gradients, fluctuating wind, and solar radiation spatiotemporal changes are the key differences between outdoor and indoor thermal environments. At the same time, the comfort perception differs from one person to another, but physiologically if the body reaches thermal equilibrium with the surroundings, then the feeling should be close to comfort. Thermal comfort is a psychological interpretation of the physiological state of the body and should not be confused with temperature sensation. Especially, temperature and comfort sensations do not behave the same way with changing environments. Temperature sensation changes more rapidly than comfort sensation and, cold discomfort changes more rapidly than does warm discomfort.

Research and practical efforts to quantify numerically the effects of heat and thermal discomfort is a widely discussed topic indoors and outdoors. Initially the topic was used to examine the effects of heat on industrial workers back in the 1960s. Also, it is known that high environmental temperatures affect health, and prolonged exposure to high temperatures associated with summer heatwaves can result in death either as a primary cause or as a contributing factor in heart disease, strokes, and pulmonary disorders [3].

The initial research on urban climate dates back to the work of Luke Howard, an alchemist who also presented the first description of the cloud types, conducted the first known urban climate analysis in 1833. He identified temperature variations up to 1.6 K over the day and 3.7 K over the night between London and its surrounding countryside under the varying circumstances of different sites and different instruments.

During the second half of the 19th century cities like Paris also found similar conditions and in the early 20th century Schmidt [5] first time talked about the urban climate in Vienna and the influence of large cities on the microclimate. After the appearance of these topics among the meteorologists, it took several years before urban climate research ventured out into the fields of urban planning and microclimate studies.

Microclimate topic regardless of scale is of interest not only to climatologists but also to biologists, crop scientists, geographers, hydrologists, and urban planners. There are different explanations of microclimate in terms of scale and applications depending on whether the narrator has a meteorology background or urban planning. If the background is tied to climatology, microclimate finds its definitions within the atmospheric boundary layer and the upper soil. As Barry and Blanken [6] explain, microclimate is an atmospheric zone where the climate differs from the surrounding area normally from 10 meters to 1 kilometer. However, the urban planning approach limits itself in between the buildings and only a couple of meters above the ground.

Manley [7] distinguished three fundamental subjects of urban microclimatology with comprehensive implications for architecture and landscape architecture: the microclimate of the plant cover, the microclimate of the topography, and the microclimate of buildings. This chapter is diving into the literature and historical developments of the term microclimate of buildings, trying to understand the evolution of the term in literature based on the applications and questions that research overtime was trying to find answers for. It starts with the definitions of microclimate and continues to make a dialog with outdoor comfort linking to human health and wellbeing.

2.2 ATMOSPHERIC ENVIRONMENT TO ANTHROPOSPHERE

1934 - 1948

Searching for the initial footprints of research on microclimate-related topics from the web of science takes us back to 1934 where Ramdas [8] defines microclimate as the 2 meters distance between the surface of the ground and the adjacent air layer. 77 years later Rodger Fleming and Jankovic [9] with the same spatial resolution describe this layer as:

> *"The layer of air within two meters of the ground, the noosphere, that is the most important of all in Earth's atmosphere. It is located in what meteorologists have come to call the anthroposphere, nestled in the "boundary layer," a turbulent, well-mixed zone at the very base of the sublunar realm. "*

They continue,

> *"This is a space in which the "natural" atmosphere gets entangled with human energy. This is the anthropocentric layer is the interdisciplinary sphere of human affairs, the most influential layer of our planet's atmosphere. This layer has not been fully or even adequately explored, which is unusual, since it is so accessible to us—as intimately close as our next breath. Indeed, it has been consciously excluded from environmental analysis."*

What we're reading here will take us on a journey over 77 years where the first and the most recent definition of microclimate match very comparably. Also, we can see that the term microclimate appeared much earlier than outdoor comfort in literature but not specifically related to urban climate.

There have been years of research on microclimate in the field of agriculture, plant physiology [8], and medical sciences. In 1948, for the first time, the term microclimate emerged in connection with urban planning where Graham [10] in his thesis for the diploma in town planning investigated the influence of microclimate and considered topography, prevailing wind, areas of water, and soil conditions as drivers of microclimate. Before that the key factors to shape microclimate were related to smoke pollution or smoke drift of industrial cities.

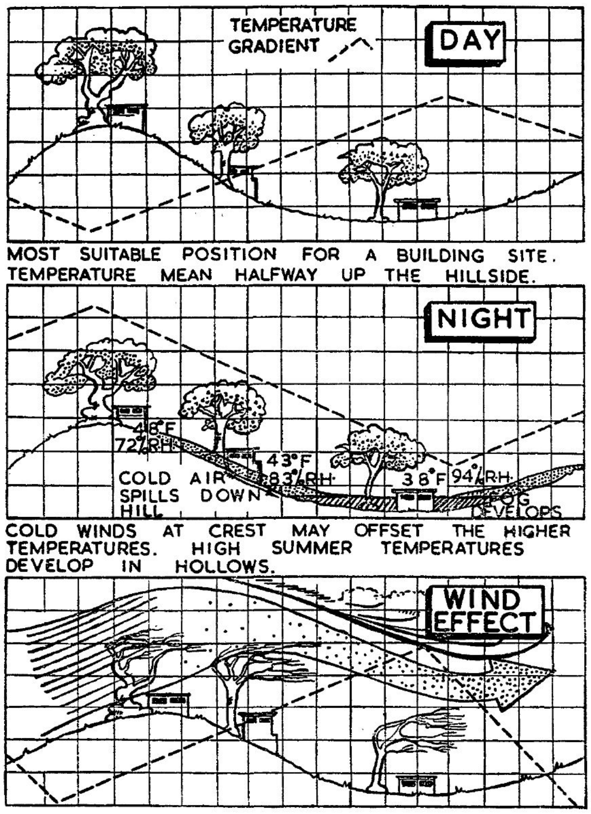
Graham uses the microclimatic parameters as a core driver for urban planning which was not specifically about thermal comfort but more on air pollution and dust concentration as a function of industrialization. He concludes:

> *"The increase in air temperature due to the smoke and dust haze and the radiation of heat from the inorganic surfaces all tend to raise the urban temperatures of exposed surfaces—indeed to such an extent that on some man-made surfaces exposed to the sun it is almost possible to fry an egg."*

Graham for the first time points out the scale and how different could be the microclimate in a few meters saying:

> *"Planners are no doubt aware that the climate of Manchester differs from that of Torquay or Dumfries. Seldom do they realize, however, that the climate of their own town possibly even their own garden varies sharply in less than a mile of distance or a change in elevation of a few feet."*

Figure 2.1
Diagrams showing the effect of topography on microclimate [10].



Even if the term microclimate was not widely spread like today, architects like Gamier, Wright, and Corbusier all provided large areas of vegetation in their urban planning scenarios to create a pleasant environment in their designs and they called it "ventilating the town" and this was a suitable term because the presence or absence of vegetation is a primary factor in the quality of the microclimate. Most probably they were aware that these phenomena are based on science but they just chose to not study them. Today, this science is known as microclimatology and the following pages attempt to evaluate its relation to planning and how the term has been applied and evolved through time.

One of the valid points about Graham's work to describe drivers of microclimate was topography. He narrates that microclimatic variations are generally caused by local topographic differences. Even a small elevation change can cause large changes in the air temperature. What we see in his illustration, the temperature difference is not only about built and unbuilt, it is also about altitude and landscape (Figure 2.1). Obviously, at that time, the necessity of thinking about microclimate was not essentially connected to human comfort but rather locating the building on the site (settlement choice) in terms of having natural ventilation and protecting from stormwater. Or finding the proper altitude for the vineyard which is still a valid discussion nowadays with climate change and the effect of shifting microclimates on wine production.

1966

Eighteen years later, in 1966 a study done by Budd [11], for the first time addressed human physiology and its connection to thermal comfort outdoors in the context of Antarctica. The study of thermal comfort in extreme cold conditions was one of the early steps about human health and comfort because it was believed that first nations in polar regions are unlikely to acclimatize to cold weather because their clothing keeps them warm. Budd collected 400 observations of medial thigh skin temperature, thermal comfort, sweating, clothing, activity and environmental conditions. He found out that Sweating, and thermal comfort, were directly related to both skin temperature, and activity, however the skin temperature did not change with the level of activity. The main aim of the study remained to assess the thermal stress of Antarctic sledging. Additional aims were to study the inter-relations of thermal comfort, sweating, skin temperature and activity, and to make an estimate of energy expenditure.

1967

A year later, in 1967, Green [12] in his paper titled “HOLIDAY METEOROLOGY: Reflections on Weather And Outdoor Comfort” for the first time introduced the term outdoor comfort and used the term “what the weather feels like” as an individual and subjective phenomena in the context of finding holiday spots and also people walking on daily basis. He also introduced an equation (heat balance model) to estimate the skin temperature and measure the deviation from the neutral thermal comfort considering the environmental factors, clothing, metabolic rate, and skin temperature. He also used the model to calculate the required clothing factor based on desired skin temperature and actual weather conditions.

1969

Since 1969 we observe a systematic movement on research in the climate of cities by introducing the concept of UHI by Oke [13] as climatic and geomorphic phenomena. He formulates 5 main factors controlling UHI: urban fabric, city structure, artificial heat production, urban water balance, and urban air pollution which has been widely studied in the last 50 years in different cities and climates. Most of these studies have already pointed out that microclimatically, the cities are becoming drier, denser, less pervious, and more rigid surfaces due to higher conductive capacity.

1971

One of the very first studies that was based on UHI principles but also addressed human thermal comfort was done by Clarke and Bach [14] in 1971. In their study, they introduced the concept of microenvironments in the context of urban development but mainly talking about UHI and the annual temperature differences with suburban areas. However, their attempts to numerically quantify the microenvironments are substantial since they explicitly talk about the thermal comfort and health of the inhabitants' heat exchange between the human body and the environment. They conclude that:

> *“The microvariations of meteorological parameters are strongly influenced by the physical characteristics of the location in which they are measured and consequently the comfort conditions in the different microenvironments will have strong variations.”*

They also evaluated the material performance of pavements comparing grass with concrete where they found 1.5 K difference in air temperature and 5.9 K in globe temperature concluding that comfort sensations in the microenvironment are influenced by physical factors such as surface cover, elevation, air pollution, time period, and location. During the day, the surface cover appears to be dominant. The microclimate above grass surfaces was consistently more comfortable than the adjacent paved surfaces and the differences were greater at the urban sites than at the suburban sites.

During the same time period Gehl [15] in his seminal work, ''Life Between Buildings: Using Public Space'' for the first time studied the influence of microclimate on outdoor activities by counting people sitting on sunny and shady benches. He showed that local sunny or shady conditions significantly impact the desire of people to either stay or leave. And as a solution, he directly points to urban planning saying:

> *"If the effects of the urban structure on the climate are considered in the urban planning process, climate modification can be purposely controlled rather than allowed to inadvertently develop."*

1975

In that period, the increasing number of research and the relevance of addressing research questions concerning the future of urban environments led to a conference in 1975 about metropolitan physical environments in New York. In this event, 160 scientists and planners came together to discuss the use of vegetation, space, and structures to improve the environments for people who live in metropolitan areas and design more comfortable urban environments through the manipulation of urban forest systems and open space.

In the session for microscale meteorology in metropolitan regions, topics like the outdoor comfort of pedestrians and the design of outdoor urban spaces were intensely discussed. Even if these perspectives were mainly meteorology driven, the connection to urban design and proposing design solutions could be the key factor to pinpoint this event as the scientific turning point of microclimatic research and practice.

Arens and Ballanti [16] in their paper titled "Outdoor comfort of pedestrians in cities" argued that the outdoor comfort of pedestrians had been neglected so far by architects and planners because of difficulties in determining comfortable and uncomfortable climatic conditions in cities and predicting the climatic characteristics of a planned urban site because of:

1. Complexities in determining what climatic conditions are comfortable or uncomfortable, meaning lack of proper metric or index.
2. Difficulties in predicting the climatic characteristics of a planned site translate to the lack of tools and methods to quantify such effects.
3. Lack of design criteria based on pedestrian outdoor comfort.

Today, all of the above-mentioned problems remain valid to a certain extend. Concerning the metrics, even if there have been considerable developments to quantify the climate in outdoor environments, because of the increased range of climatic variables outdoors, and spatiotemporal variations, still predicting the perception of outdoor thermal comfort needs further work. Regarding the tools and methods, there has been a considerable amount of developments to quantify outdoor thermal comfort bringing all the players and parameters into the equation, however detailed vegetation models or understanding of transient behavior of thermal comfort models need further research as well.

1977

In 1977 Arens and Ballanti [16] introduced the idea of predicting annual discomfort frequency which has a direct impact on decision-making processes in urban planning based on factors like time of the day, day of the year, expected type of human activity, and expected level of clothing. They proposed a methodological workflow illustrated in Figure 2.2 which could be used directly to inform the design process. Moreover, they implemented the concept of wind factors, today known as wind matrix, based on wind tunnel measurements. They used the non-dimensional wind speeds obtained in the wind tunnel with the reference wind speed to estimate the threshold wind speed on the site for each wind direction and the result is the probability of discomfort occurring based on different wind speeds and directions.

1983

In 1983 Rosenberg, Blad [17] gave another scalar definition of microclimates which described the climate near the ground in which plants and animals live. The layer within the first few tens of millimeters from

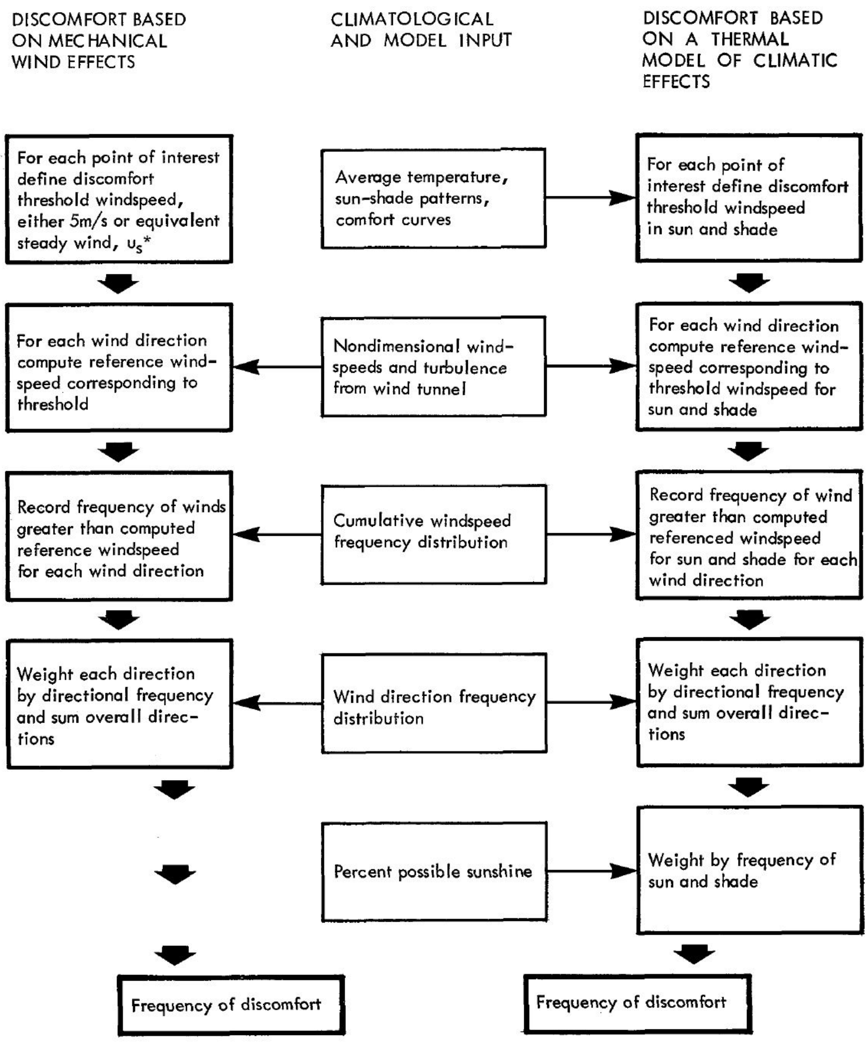


Figure 2.2
Calculation process of defining discomfort frequency [16].

the surface into the soil or the air (biologically). The observation of the microclimate has changed over the years including the human factor and introducing the anthroposphere which expands the microclimate layer to the height of pedestrians.

Regardless of how many meters or centimeters from the ground we set the boundary for the microclimate, physically speaking, changes in environmental measures are greatest near the surface. Very large quantities of energy fluxes are in transfer with evaporation, condensation, wind speed decrease, and radiation exchange. The rate of these exchanges with time and space makes the microclimate so different from the climate just a few meters above where the climate is driven by the atmospheric mixing processes and is more moderate and stable.

To sum up, as natural or technical phenomena, microclimates are thermal zones with site-specific physical and thermodynamic characteristics. They are affected by temperature, moisture, rain, wind, fog, snow, insolation, cloudiness, air quality, and other factors [18]. Microclimates are natural or man-made “thermal places” with various cultural, social, and political meanings. The physical variables that impact outdoor comfort are the same as indoor conditions. However, since people are used to describing “the weather” based on the ambient temperature, outdoor thermal comfort conditions are typically expressed in the form of a biometeorological index that summarizes the impact of different variables in an equivalent temperature [19, 20].

2.3 BIOMETEOROLOGICAL INDICES

The heat balance between the human body and the environment is a complicated combination of temperature, humidity, wind force, and different radiation exchanges. There is a great number of empirical formulas (biometeorological indices), that have been provided up to now, which can express the scale of comfort and discomfort of the human beings in relation to the weather conditions.

One of the very first attempts to index outdoor comfort (weather comfort) dates back to 1959 where Hendrick [21] introduced the “outdoor weather index” for the summer season. The index combines Temperature, relative humidity, wind speed, and solar radiation (increase in air temperature equivalent to the solar-heat load on human) into a single numerical expression for outdoor weather comfort in Hartford.

$$I = (0.5 + 0.0001U^2)(T^* - 80 + 0.11U) - 0.35(0.5V)^{0.5}(20 + 0.05U - 0.2T)$$

Where I is comfort index, U is relative humidity, V is wind speed (mph), T* is defined as the air temperature plus the increment due to direct solar radiation, or where $T^*=T+R(0.5-0.007(V-3)^{0.5})$ in direct sunshine, and where T*=T on cloudy days or in the shade.

Hendrick concludes, since a large part of public interest in weather forecasts relates to weather comfort, a comfort index is potentially an important contribution to meaningful communication of weather information from meteorologists to the public. However, what we see now even with the appearance of metrics like Universal Thermal Climate Index (UTCI) or feels like temperature, the communication of weather information cannot be fully conveyed to the public and one can always argue that the relative sense of weather comfort varies within and between individuals and depends upon personal factors as well as the direct weather influences.

Moreover, it has been already discussed more than 60 years ago that besides air temperature which partially explains the comfort story, other parameters like humidity, wind speed, and solar radiation also play important role in determining outdoor weather comfort. However, due to its simplicity of concept and measurement, the temperature has remained the standard index of comfort for a long time for the outdoors.

Since the appearance of the Effective Temperature (ET) index in 1923 by Houghton and Yaglo [22] which was for indoors, there has been close to one hundred thermal comfort indices developed over the years which historically have been divided into indoor and outdoor thermal comfort metrics [23-25]. Among those indices, in 1985 Rodriguez, Mateos [26] for the first time introduced the concept of biometeorological comfort index for a walking man outdoors as a necessity to take into account the scale of sensations to express human climatic well-being. The biometeorological comfort index is a 'temperature' that combines the cooling effects associated with wind, atmospheric humidity, and radiant exchanges which in itself offers a measure of the corresponding sensation of comfort or thermal well-being.

Driven by considerable research in outdoor comfort, the most recent and well-known biometeorological index, UTCI was introduced in 2000 to predict how a human would physiologically react to a given set of environmental conditions based on thermo-physiological modeling of human response to meteorological conditions including the acclimatization phenomenon [27]. UTCI is an internationally accepted assessment procedure based on scientific progress in human response-related thermo-physiological modeling over the last four decades. It is a physiologically relevant assessment model of the thermal environment to significantly enhance applications related to health and well-being as the core issues of human biometeorology. It is based on Fiala's 340-node thermoregulation model, a regression approach using the outcome of some 100,000 simulations covering all of the most extreme combinations of the meteorological input variables on the global scale [28]. This model simulates phenomenon of the human heat transfer inside the body and at its surface taking into account the anatomical, thermal and physiological properties of the human body.

UTCI considers people's clothing behavior (how much insulation they put on) dependent on just air temperature in a non-linear way in the range of 0.4 clo to 3.0 clo. In other words, it considers firstly the behavioral adaptation of clothing insulation by the general urban population with the actual environmental temperature, secondly the distribution of clothing over different body parts providing local insulation values for the different model segments, and thirdly the reduction of insulation caused by movement and wind speed. UTCI considers the "typical" walking speed as 4 km/h which corresponds to a metabolic rate of 2.3 MET.

UTCI as a biometeorological index originally designed to address the needs of the following communities:

1. Public weather service (weather forecast for outdoor activities)
2. Public health system (warning about heat waves and cold spells)
3. Precautionary planning (urban and regional planning, tourism industry, and climate researchers)
4. Climate impact research in the health sector (epidemiological studies based on cause-effect related approaches)

This thesis also uses UTCI as the biometeorological index to quantify the feels like temperatures both in sensing campaigns and simulation workflows.

2.4 PEDESTRIAN OUTDOOR THERMAL COMFORT

While indoor environments are man-made and often highly controlled, outdoor thermal comfort (OTC) conditions rely on a series of physical phenomena that vary spatially and temporally. The human outdoor thermal comfort is the function of microclimate boundary conditions and these conditions could be affected or driven by climate change, UHI, or local cooling (e.g. from shading or evapotranspiration under the trees).

Thermal comfort is a long-established field of research that lies at the intersection between environmental psychology and building science. It deals with the question, under what particular set of environmental conditions and activities, individuals will express a subjective feeling of thermal well-being [19, 20]. Thermal comfort is a subjective but adaptive phenomenon. The adaptive opportunity (the degree to which the environment enables people to adapt) is important for thermal satisfaction [1] and outdoor spaces can foster this opportunity with adequate design choices and by giving pedestrians the opportunity to recover from heat or cold stress.

One of the main reasons that we see an increasing body of research and literature in outdoor comfort, is the connection to urban planning and the interest to predict how comfortable people feel in outdoor space and to develop reliable and practical outdoor thermal comfort models to predict "when" and "where" people are going to be and for "how long". Several studies have been done to explore this question. As an example, to overcome the traditional limitations of transversal and longitudinal studies, a study at MIT relied on Wi-Fi data, collected in a public courtyard in Cambridge, MA, USA to measure under what environmental conditions close to 700,000 individuals frequented the public courtyard over a period of ten months [29]. The study method was again applied in a similar setting in the United Arabic Emirates [30]. Both studies concluded that the estimated UTCI values were a strong predictor of both, the number of residents frequenting an outside space as well as their dwell time.

This information is in turn of interest for the municipal governments that may try to encourage residents to walk or cycle as suggested by Paris mayor Anne Hidalgo for the concept of the 15-minute city. Encouraging people to walk and use public spaces on daily basis, needs proper investments in facilities and infrastructure to motivate people and give them opportunities to prefer walking in favor of their health. One of the strategies to promote walkability and have a positive impact on the health and wellbeing of citizens is to give them comfort opportunities with trees and urban vegetation [31]. Respectively, the primary purpose of street trees has changed over the last 30 years from an aesthetic role of beautification and ornamentation to one that also includes the provision of services such as stormwater reduction, energy conservation, and improved air quality [32, 33].

In the following, the study elaborates more on the available tools and methods to quantify outdoor comfort conditions in cities and highlights the need for predictive tools in design and planning.

2.5 TOOLS TO QUANTIFY OUTDOOR COMFORT

As discussed before, microclimate and outdoor comfort in terms of scale and application are very different. Microclimate can easily be connected to the atmospheric layer, however, the outdoor comfort is directly addressing the layer of air where humans have the most interaction with the built environment. We can see this clear division in the application of tools and methods to quantify microclimate and outdoor comfort as well. The studies on microclimate normally address the mixed layer of urban roughness layer up to urban boundary layer which extend normally double as the height of the buildings. In contrast, outdoor comfort studies zoom in on the urban canopy layer in between the buildings. Including the boundary layer conditions in outdoor comfort studies are also highly recommended but due to the complexity and scale of the modeling, we rarely see such an integration. Moreover in OTC studies, the local effects of shading from buildings and trees have the most impact on shifting the equivalent temperature which indirectly has an impact on microclimate as well.

It is pretty difficult to draw a clear line around which tools and methods could or would be used separately for microclimate and outdoor comfort studies. At least, this is true for modeling methods [34] however, for the sensing part the methods that are based on remote sensing are dealing with microclimatic phenomena and all the other ground-based techniques address the comfort-related questions.

This thesis addresses both methods of modeling and sensing trying to introduce toolkits to quantify perceived temperatures. One can also divide the tools for comfort assessment into steady-state and non-steady-state methods where generally the simulation tools fail to model non-steady-state outdoor thermal comfort, especially in transitional conditions. That is where the sensing techniques become handier to bridge this gap.

2.5.1 Modeling

The current efforts to model outdoor comfort including all the effective measures of the physical domain are fairy complex since environmental conditions are highly localized and involve phenomena that are time-intensive and computationally expensive to simulate. To fully describe the thermal sensation of a person on an urban plaza or walking under a tree on a sunny day with moderate wind, requires a series of interrelated models. The topic of outdoor comfort has been a question to be addressed by urban planners and bio-meteorologists and it gained even more visibility for cities and policymakers since 2003 following the extreme heatwave events in Europe. It has been also proven and widely accepted that the main drivers of the changing climate are human activities and anthropogenic environmental degradation. To understand the physical domain, measure the intensity and provide robust answers for pedestrian thermal comfort in cities, there has been a considerable amount of work done to model the urban environments considering different effects and resolutions.

Even though the subjective perceptions and reactions of people to the urban environments are diverse and not yet well known, in the context of assessing outdoor comfort, simulation methods are often of special importance because they provide a medium for information integration from different perspectives and comparisons of different design scenarios [24]. Computer simulations have been developed hand-in-hand with the rapid growth of the computer, and nowadays it is not anymore a privilege to set up a quick simulation model to estimate PV potential or Energy Use Intensity (EUI) of an entire district. In outdoor comfort studies, the appearance of ENVI-met [35], RayMan [36], and other models have been the base for more than 1000 scientific publications over the last 10 years. However, both tools require significant calculation time and cannot be readily employed at an urban or neighborhood level for annual simulations.

This is important due to the need to design urban space that enable human beings to balance their heat budget to optimize their comfort, performance, and health during daily activities [37]. In other words, to quantify the thresholds and human thermal behavior in response to varying climate conditions, there is a necessity to have an adequate modeling tool that considers all the exchanges with the environment. In microscale, considering the combined cooling effect of a tree (evapotranspiration from leaves) and local wind, requires coupled models that combine raytracing for direct shading, computational fluid dynamics for wind distributions, and evaporative cooling based on local moisture content in the air. Addressing the gap, this thesis aims to overcome the mentioned limitations and offers a hybrid method integrating process-based model (PBM) for simulating annual and seasonal behavior of trees on UTCI and pedestrian outdoor thermal comfort.

As mentioned before, the simulation models are based on the assumption that comfort is achieved in steady-state conditions [38, 39]. However non-steady state methods can provide additional information about temporal courses of thermophysiological parameters such as skin and core temperature, which are more relevant to human thermal sensation [40]. This study addresses the non-steady behavior by introducing the sensing techniques.

2.5.2 Sensing

Sensors increasingly permeate our lives and generate a plethora of data, which has transformed the way we live in cities. Planners have also been using sensory data to improve our understanding of urban environments. Additionally, the recent developments in remote sensing and ground-based measurements to understand processes behind spatial patterns have increased the application of such methods in microclimate studies.

Mobile measuring methods have been of great importance in climatology since the first experiments of this type began more than 100 years ago with the first measurements of the atmosphere using kites and balloons [41]. Nevertheless, compared with the technological advancement of remote sensing and ground-based measurements methods, mobile measurement techniques have received comparatively limited attention for a long time. This could be partially due to the advanced modeling developments giving the impression that accurate in situ measurements are less needed. However, the need for a better understanding of processes underlying spatial patterns in urban environments has grown over the last decade and also has become an effective tool to improve the computational models.

In addition, recent advancements in emerging technologies such as GPS, wireless, and cellular data transfer offered prospects for innovative approaches addressing climate-related topics. Around the same time, as new sensors with improved functionality and precision appeared on the market, lightweight and portable devices became even more affordable supported by the advanced data processing techniques. This study with the developed microclimatic sensor kits explores a unique source of in situ data for local climate mapping with adequate temporal and spatial resolution to understand the characteristics of the microenvironments near the grounds. The detailed toolkit prototypes and applied case study is explained in Chapter 3.

2.6 BIBLIOMETRIC ANALYSIS

To better understand the patterns and chronological development of this research domain, this section introduces a bibliometric study of literature for the domain of urban outdoor comfort and microclimate. The analysis is based on a database downloaded from the Web of Science core collection for the articles published between the years of 1945 to 2020 including the term "outdoor comfort" in the topic of the publication meaning containing the selected word either in the title, abstract or keywords. The analysis of the database includes 3079 publications using VOSviewer platform [42]. The extracted database is analyzed with confronting other related keywords to see the clustered patterns for each topic and also the shifting pattern of the trends over time.

Figure 2.3
Co-existence analysis of "microclimate" and "outdoor comfort" in literature between 1945 - 2020.

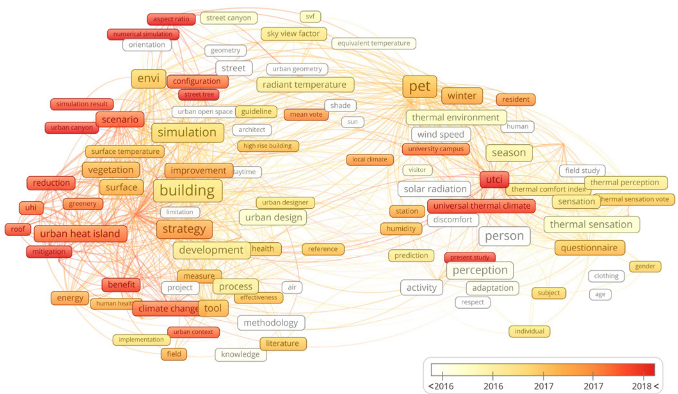


Figure 2.3 shows the cluster analysis with correlating "microclimate" keyword to the main dataset putting into evidence that over the years, we see very clear division on studies focusing on human and thermal perception on the right, and research dealing with the structure of the cities and the built environment on the left. This gap clearly illuminates how studies on human-related topics are detached from the field of urban design.

Figure 2.4 shows the co-existence of the "outdoor comfort" keyword in the literature between 1967 to 2020, colored chronologically. What we read here, is the fact that topics like

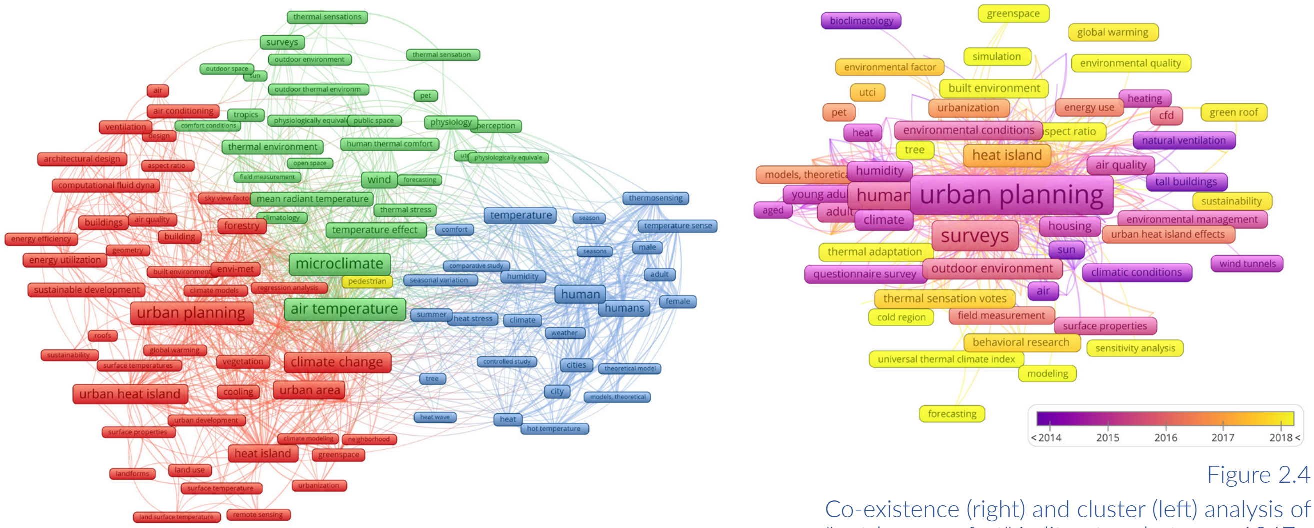


Figure 2.4
Co-existence (right) and cluster (left) analysis of "outdoor comfort" in literature between 1967 - 2020.

urban planning or human are occurring less in recent literature where keywords like forecasting, modeling, or sensitivity analysis appearing more frequently. This can raise a flag to direct the research in the future more into health and design-related topics and connecting to impacts on everyday urbanism.

Clustering analysis of the same dataset (Figure 2.4, left) shows a clear division of 3 main research domains of human, microclimate, and urban planning. These 3 clusters find themselves around the word pedestrian as a core, showing the importance and underlying trend in outdoor thermal comfort research even if chronologically over the past years we see less focus on human-centered topics.

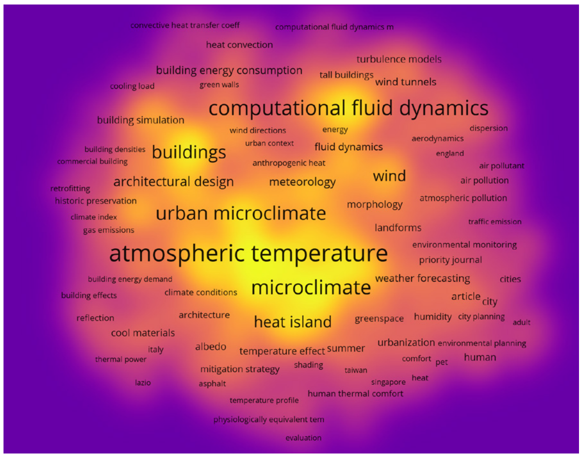


Figure 2.5
Co-existence analysis of "UTCI" in literature between 2000 - 2020.

Figure 2.5 zooms into the database with focusing on the simulation approach. Analysis of 1248 papers including the term UTCI in co-existence analysis puts out the computational fluid dynamic (CFD) methods as one of the main tools to study microclimate and outdoor comfort. This can be directly linked to ENVI-met where it has been extensively used for urban planning reasons for thermal comfort analysis. However, the tool due to its computational needs would not be very suitable for extracting design-based solutions which should contain annual statistics on thermal comfort and heat/cold stress measures.

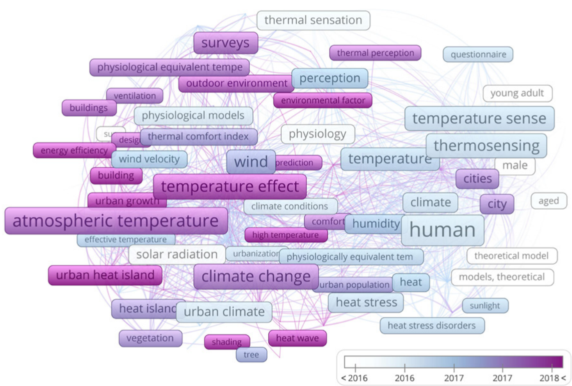


Figure 2.6
Co-existence analysis of "OTC" and "UTCI" in literature between 2000 - 2020.

Figure 2.6 shows an increasing trend over the last 2 years toward UHI which might not be the correct direction to address the topics related to OTC and UTCI. Also, we see a fading trend for thermal sensation and physiological studies. Addressing this gap, this thesis provides methodologies to improve the use and integration of such methods in OTC experiments.

2.7 URBAN HEALTH

The urban environment has long been recognized as an important determinant of health and well-being. According to the World Health Organization (WHO), health in cities is not a status to achieve, nor defined based on current health infrastructure, however, it is a conscious process of improving physical and social environments. Over the last years, we have witnessed an increasing public awareness about the effects of the natural and built environment on wellbeing and health in cities [43]. Despite being an encouraging sign, good evidence and objective measures remain lacking for how environmental aspects impact the individual behavior of people in urban contexts.

One of the key parameters to assess and quantify environmental measures in cities is people's exposure to extreme conditions since prolonged exposure to high temperatures associated with summer heatwaves can result in physical and mental disease. Likewise, it is closely linked to both climate change and urban morphology meaning that any effort to mitigate the former may further improve the latter.

The microclimate is known as a local phenomenon of the built environment that can directly affect the wellbeing of people and can be used as an index for urban livability. Additionally, successful implementation of health measures demands innovative tools and reliable methods addressing common issues of wellbeing and quantifying urbanites' exposure to thermal discomfort or pollution as they walk within the urban context.

Driven by climate emergency and its effect on outdoor spaces - which accommodate various activities and improve the livability of the cities - there is an urgent need to better understand current and future characteristics of urban microclimate and environmental qualities at the anthroposphere scale [24]. Most of the studies on urban climate consider UHI as a measure for urban health [44] which might not be the suitable approach since heat islands do not reflect the urban canyon level human interaction and spatiotemporal

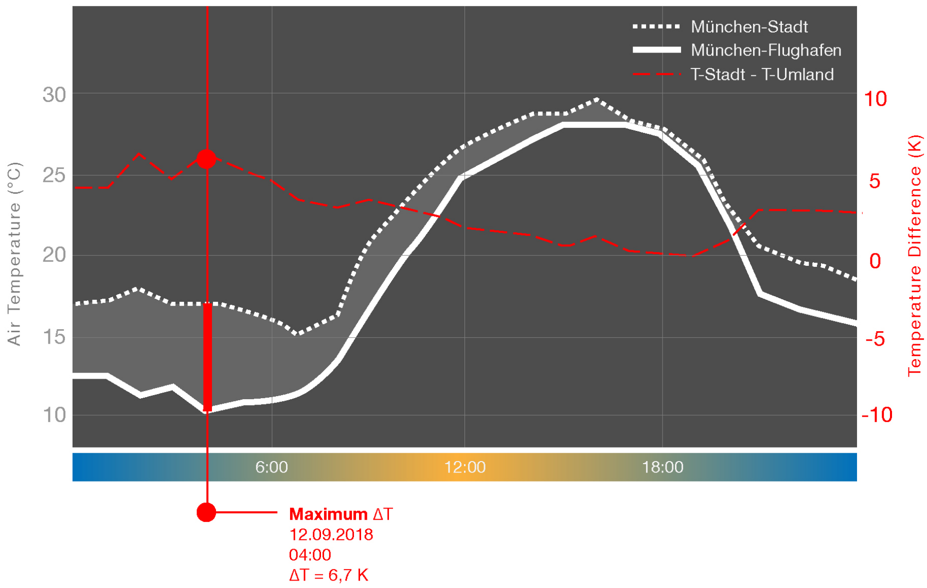


Figure 2.7
Temperature comparison between airport and city of Munich on August 22nd.

microclimatic variations. Additionally, UHIs reach their peak in cities at night which could be more relevant for the health of people indoors rather than outdoors (Figure 2.7).

This study does not aim to propose new health measures based on outdoor thermal comfort, however, it believes that the developed tools and workflows would help further to study and understand the effects of the built environment on people's exposure time to heat or cold stress connecting to human physiology and subjective measures.

2.8 CONCLUSIONS

Reviewing the literature on the topics of outdoor comfort and microclimate studies for the last 8 decades gives the impression that the questions that the research community was trying to answer remained almost the same. However, today compared to 80 years ago, we have more computational power and a deeper understanding of the microenvironments. Does this lead us to better urban environments? This is the question that needs to be answered not only by physics and simulations, but it is the question for the disciplines dealing with cities as a package of interrelated ecosystems. Meaning, this is a question that should be answered by design and not only with engineering way of problem-solving.

Scientific research in the 20th century has thoroughly engaged with microclimates in their thermodynamic profiles. Among other parameters, temperature, humidity, and radiation exchanges became central to how microclimates are measured and defined. By setting up a mutual relationship between climate and architecture, between weather and human activities, urban climate research both challenged and transformed the causal approach of architecture and climate [45]. As Roesler and Kobi argue, the crucial task of today's microclimate research consists of understanding and describing the man-made materiality of the microclimate as a human artifact, even though it appears to be a natural, non-material and physical phenomenon.

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C H A P T E R T H R E E

OUTDOOR COMFORT SENSING AND MAPPING

Summary

Studies on the microclimate of cities have already proven that pedestrian thermal comfort is the function of the built environment and it is fundamental to understand this phenomenon both with numerical techniques and field measurements to achieve comfortable, healthier, and more livable urban spaces. There has been a wide variety of methods to approach the question of how people react or behave in transient outdoor conditions since most of the thermal comfort studies perceive pedestrian thermal comfort as a “static” phenomenon. The application of thermal comfort monitoring in transient conditions is limited due to the complexity of the task and instrumental setup which leads to a lack of understanding about how pedestrians compensate heat loads. This chapter contributes in two directions, first to set up geo-referenced environmental monitoring equipment as a methodology and second to use the toolkit to have a better understanding of dynamic thermal comfort and the thresholds for tolerance to thermal discomfort.

3

Partial results of the presented work in this chapter have been published in:

Ata Chokhachian, Kevin Ka-Lun Lau, Katia Perini, Thomas Auer (2018): Sensing Transient Outdoor Comfort: A Georeferenced Method to Monitor and Map Microclimate. Journal of Building Engineering; 20., DOI:10.1016/j.jobe.2018.07.003.

3 OUTDOOR COMFORT SENSING AND MAPPING

3.1 INTRODUCTION

In cities and public space, transient conditions are experienced when people move between conditions that are situated in spaces with a wide range of varying environmental conditions [1]. This includes step changes, temperature drifts, and cyclic variations that influence thermal sensation and comfort. The transient nature of thermal comfort has been widely discussed in indoor studies [2-4]. However, such understandings of outdoor environments are generally lacking.

Most of the studies that are addressing the effects of microclimate on pedestrians have used thermal budget models in which it is assumed that comfort results from the thermal balance between the body's heat production and heat losses to the environment. These models assume equilibrium heat flow, which in reality occurs only after 1 to 2 hours of constant exposure to the surroundings [2]. One of the first studies to capture transient conditions of the physical and psychological response of people to changing thermal environments was done for nude subjects in indoor laboratory conditions in 1967, where they found out that discomfort increases more rapidly below 28°C than above 30°C for transient changes when the subject goes from comfortable to uncomfortable conditions [5]. Later on, in 1977, Arens and Ballanti [6] claimed that applying the steady-state model to a transient situation underestimates the discomfort threshold wind speed. They found out that in areas with shade, the model is so oversensitive to wind that almost any wind would cause discomfort which was resulting in unrealistic discomfort frequencies of wind. Another shortcoming of such study was pointed out in 1972 by Landsberg [7] arguing that:

> *"We try to assess the sensations caused in the human body by the atmospheric environment and one of the major difficulties in judging the physiological factors involved in the problem has been the fact that most data and experimentation have been concentrated on healthy, young men under laboratory conditions."*

Thus in such studies, many questions concerning realistic representation of the natural environment and lack of a broad age spectrum of the real population afflict the data and findings. It is also well accepted that pedestrians tend to adjust their behavior or walking routes to achieve better thermal comfort in cities [8]. Plus, outdoor heat discomfort discourages activities involving elevated metabolic rates while outdoor cold discomfort has the same effect on sedentary outdoor activities.

To overcome the limitations of transient outdoor thermal comfort studies, there have been several measurement methods based on remote sensing available for boundary layer investigations, local or microscale measurements, however their potentials are not very well studied. Meanwhile, many of the resolution and spatiotemporal gaps in time and space can be filled with mobile measurement methods. Within this context, this chapter demonstrates the concept, realization, and application of mobile measurement instruments with the following objectives:

- Collecting geo-referenced (location-based) microclimate data.
- Mapping outdoor comfort spatially and temporally.
- Assessing the effects of thermal history on the dynamic comfort responses of pedestrians.
- Getting a better understanding of the correlations of urban morphology and outdoor thermal comfort.
- Measuring how and to what extend people compensate for thermal stress physiologically during outdoor activities.

This is possible based on the fact that the combination of methods of social sciences and sensory studies can enhance a complementary understanding of human thermal comfort. Operating through human-centered approaches, these methods unveil the individual behaviors, collective practices, and intimate perceptions connected to the specific microclimate of a particular space and time.

Figure 3.1
Argus, the first mobile setup to capture geo-referenced high dynamic range images.

3.2 GROUND-BASED MEASUREMENTS

Most commonly available meteorological data are derived from static stations which can provide valuable information on the climate of cities and UHI by comparing downtown stations with suburbs. However, such data do not allow spatiotemporal evaluation of microclimate conditions on street level. One may argue that the alternative method could be the simulation approach, however, due to the complexity of such models and high dependence on detailed physical input models of urban artifacts, computational modeling tends to have limited resolution at the pedestrian level. Moreover, those models are limited in predicting human perception under certain microclimatic conditions.

Collecting data on a human scale within the anthroposphere layer is not a novel approach. There have been several prototypes with different scopes to gather data trajectories on a microscale to understand and put into evidence the interactions of people with the urban environments.

One of the very first portable instrument systems to measure environmental parameters is the work of Herrington and Vittum [9] in New York in 1977 combined with the physiological responses of human users of the spaces. In their study, they concluded that human thermal comfort can be highly controlled and improved with site design. This finding is nothing new nowadays however, still many developments do not consider such a measure as part of their design process.

Driven by technological advancements 'Argus' in the 1990s was one of the first devices to capture omnidirectional, geo-referenced high dynamic range images (Figure 3.1). It was built as part of the city scanning project at MIT, the forerunner to later outdoor image-based mapping efforts such as Google's StreetView. Following the concept of geo-referencing the environmental data, there have been several prototypes with different sensors answering different questions in their experiments. As an example, Nakayoshi, Kanda [10] employed a mobile measurement system that records microclimatic conditions experienced by individuals and the corresponding physiological responses along a designated pedestrian route that consists of various urban morphology and surface environments. The variations in thermal sensation are attributed to the cutaneous thermoreceptors which respond to subtle microclimatic changes [11]. It indicates that pedestrian thermal comfort under outdoor transient conditions is highly associated with their physiological response and thermal history. Table 3.1 summarizes mobile microclimate monitoring techniques and sensory developments (Figure 3.2 a-c).

Figure 3.2a
MaRTy a portable 6 directional MRT monitoring device [12].

Figure 3.2b
MIT's CITYSCANNER, mobile sensing platform for smart city services [15].

Table 3.1: Review of mobile microclimate monitoring techniques.

Name	Year	Air Temperature	Relative Humidity	Solar Radiation	Wind Speed	Sky View Factor	Globe Temperature	GPS Coordinates	Noise Level	Air Quality	Measure	Mode	City	Platform	Reference
MaRTy	2019	•	•	•	•			•			PET UTCI	M	Tempe	Industrial sensors	[12]
-	2019	•	•	•	•		•				PET	M	Amsterdam	Industrial sensors	[13]
-	2018	•						•			UHI	M Auto	Doha	T type Thermocouple wire	[14]
City Scanner	2018	•	•					•	•	•	-	M Auto	Cambridge	Open source sensors	[15]
-	2018	•	•	•	•			•			Tair	M Bike	Tokyo	Platinum resistance thermometer	[16]
CityFeel	2017	•	•	•	•	•	•	•			PET	B	Geneva	Industrial sensors	[17]
-	2016	•						•			Tair LST	B	Vancouver	Industrial sensors	[18]
Urbmobi	2016	•	•	•				•				M Bus	Aachen		[19]
-	2015	•	•	•	•		•				UTCI	M	Strasbourg	Industrial sensors	[20]

Backpack (B), Movable (M), Wearable (W)

Figure 3.2c
Portable UTCI monitoring device [20].

As we see in the table, there are different scopes in terms of sensor setup and mode of data collection in any of these studies but they are all using the measures and indices intending to quantify the perceived temperatures for people. Besides, mounting a sensor kit on top of a car or bus to capture microclimatic data is the question for big data and crowdsourcing specialists to see how accurate and effective these methods could be.

Collecting of spatiotemporal datasets of urban environments can empower advanced analytics and technology solutions for local governments and urban planners. However, in many environmental use cases, the data gathered is limited in a spatial and/or temporal resolution, restricting the information that can be retrieved. Generally, we can mention two main limitations for mobile measurement and this study is not an exception. First, obtaining accurate positional data is essential during sampling. However, because building surfaces reflect carrier waves, Global Positioning System (GPS) data collected in urban areas tends to have a large degree of error. Second, there is relatively little published data and discussion regarding mobile measurement methods, such as the sensor lag, and the uncertainties associated with mobile measurements.

3.3 METHODOLOGY

3.3.1 Monitoring Equipment

The development of a mobile sensor kit had been an ongoing process with 3 different prototypes. The base prototype was built with industrial sensors that are summarized in Table 3.2. The equipment setup is based on two sets of data loggers with different functionalities. The first set is a TESTO480 Digital Microclimatic Sensor kit for the measurement of Air Temperature, Relative Humidity, instantaneous Wind Speed, and Globe Temperature with Type K Thermocouple, class 1. The second set is LI-COR LI-1500 light sensor logger kit with embedded GPS tagging and LI-200R Pyranometer for solar radiation records. To capture skin temperatures at specific points, an infrared camera was used.

Figure 3.3
Geo-referenced portable microclimate monitoring device (developed by the author).

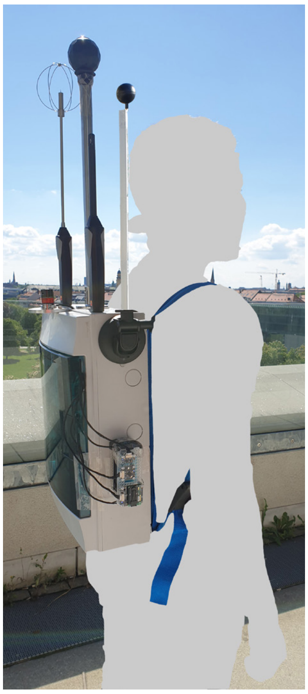
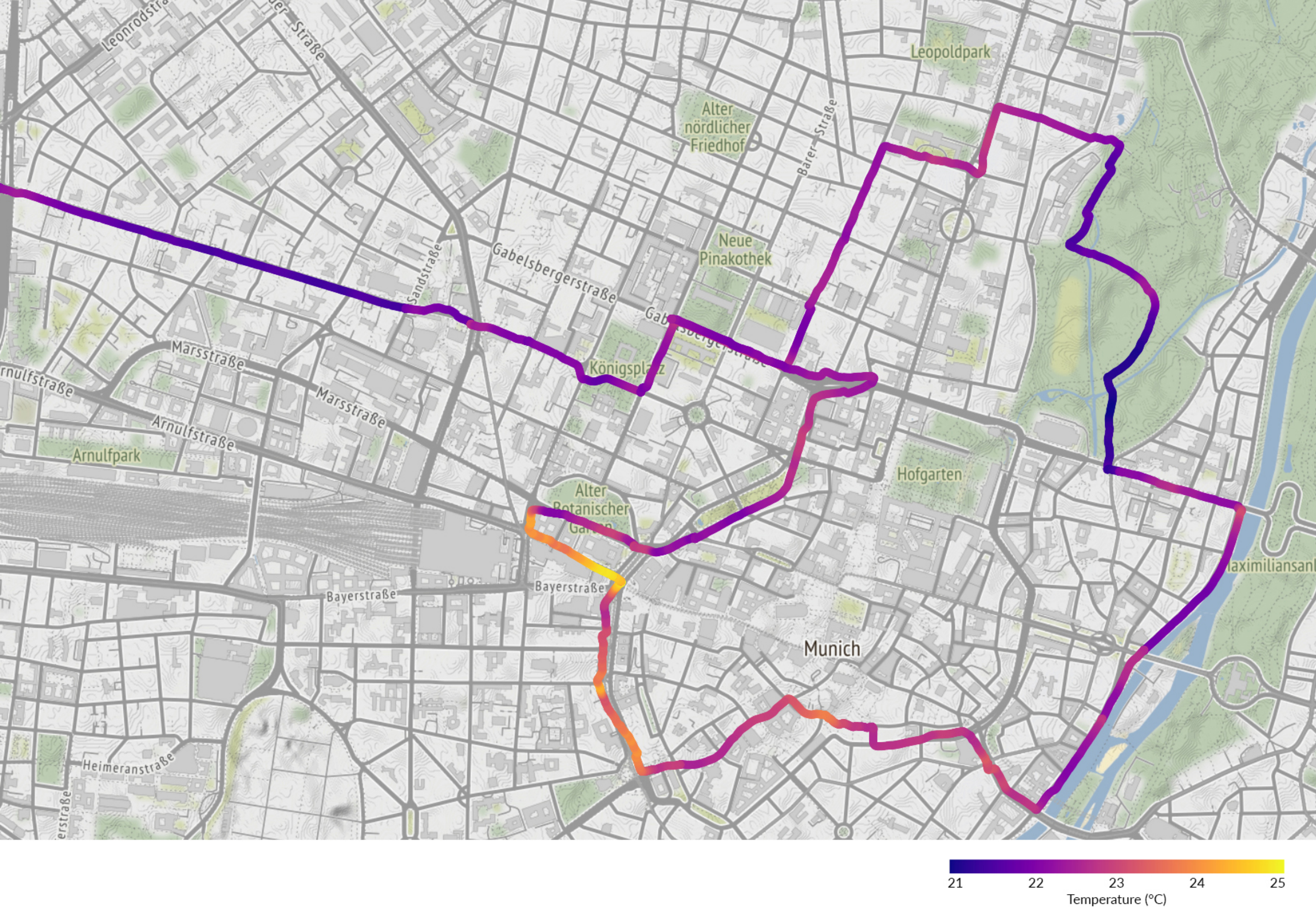


Table 3.2: Technical details of the experiment instruments

Logger	Parameter	Sensor	Model	Accuracy
TESTO480	Air Temperature	Testo Air Temperature Probe	0628 0143	± 0.5 °C
	Wind Speed	Testo Air Flow Probe	0628 0143	± 0.03 m/s
	Relative Humidity	Testo Humidity Probe	0636 9743	± 1.0 %
	Globe Temperature	Testo Globe Thermometer (D = 150 mm, E = 0.95)	0602 0743	± 1 °C
LI-COR	Global Solar Radiation	Pyranometer	LI-200R	0.183 w/m²
	GPS Coordinates	RADIONOVA	RF Antenna	2.5 m
	Tilt Angle	Pendant G Data Logger	UA-004-64	± 0.1 g; 1 m/s²

The second version was developed based on the open-source Arduino platform with the aim of reducing the cost of the kit into a more scalable and affordable version. The incentive was also to construct a prototype that could be easily deployed in the field. The detailed description of the prototype and comparison results are described in Nouman, Chokhachian


Leonrodstraße
Straße
Leopoldpark
Alter
nördlicher
Friedhof
Barer Straße
Neue
Pinakothek
Gabelsbergerstraße
Sandstraße
Marsstraße
Arnulfstraße
Königsplatz
Arnulfpark
Hofgarten
Alter
Botanischer
Garten
Bayerstraße
Maximiliansanl
Munich
Heimeranstraße
21
22
23
24
25
Temperature (°C)

[22]. The main limitation of the second version was the stability and validity of the sensors which restricted further development.

The third version is developed based on the concept of bricklets with the Tinkerforge platform (Figure 3.3). The prototype showed very stable and reliable data frequencies plus a wide range of environmental sensors and an accurate GPS logging system. As an experiment, these sensors are deployed on a bike to map microclimate variations in terms of air temperature in the city of Munich which was able to capture significant variations comparing the downtown and outer shell of the city up to 4 K. Also, the immediate temperature drops passing through the park and green areas is visible due to high sensitivity of the sensors and accurate GPS signals (Figure 3.4).

3.3.2 Measuring the Radiant Environment

The Mean Radiant Temperature (MRT) is one of the essential parameters for determining outdoor thermal comfort and it is the function for the amount of human body thermal exposure to the surrounding surfaces. According to Fanger [23], MRT is defined as:

> *"The uniform temperature of a surrounding surface giving off blackbody radiation (emission coefficient ε = 1) which results in the same radiation energy gain of a human body as the prevailing radiation fluxes which are usually very varied under open space conditions".*

There are different methods and tools to measure and calculate MRT depending on the complexity of the equipment setup and the relevance of outputs for the objectives of the experiment. To calculate MRT, (in °C) the relevant properties and dimensions of the radiating surfaces and the visible section of the sky must be known. Moreover, the posture of the human body (e.g. seated or walking) is also important. In the developed sensor kit, the MRT is estimated from the global radiation which is captured with a pyranometer and a globe thermometer that measures the initial radiant temperature. The first step is to estimate MRT from globe thermometer, using the equation from Thorsson, Lindberg [24]:

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \times 10^8 \times V^{0.6}}{\varepsilon\, D^{0.4}} \times \left(T_g - T_a\right)\right]^{1/4} - 273.15 \qquad (1)$$

Where Tg is the globe temperature (°C), V is the air velocity (m/s), Ta is the air temperature (°C), D is the globe diameter (mm) and ε is the globe emissivity (0.95 for a black globe).

MRT indoors usually corresponds to the air temperature, but at sunny locations outdoors, it can be more than 30 K higher [24]. In this case, Tmrt is incremented to T*mrt, if there is also direct solar radiation [25] because:

- Due to rapid and continuous varying conditions (radiation and wind field) outdoors, the globe has no time to reach its equilibrium in a walking mode (the standard black globe needs ca. 15 min). This can be improved by smaller globe diameter.

Figure 3.4
Microclimate map of Munich district on July 22nd collected by bike.

- Due to the shape and dimensions of the globe, the resulted Tmrt cannot represent perfectly the radiation load on a walking person.
- The globe is black and it absorbs too much short-wave radiation compared to the clothed human body.

So the adjusted MRT is calculated based on:

$$T^*_{mrt} = \left[T^4_{mrt} + \frac{f_p \times a_k \times I^*}{\varepsilon_p \times \sigma}\right]^{1/4} \quad (2)$$

Where I* is the radiation intensity of the sun on a surface facing the incident radiation direction, εp is the emission coefficient of the human body (standard value 0.97), ak is the absorption coefficient of the irradiated body surface area for short wave radiation (standard value 0.7), fp is the function of the incident radiation direction and the body posture, σ is Stefan-Boltzmann constant = 5.67×10^{-8} W/(m^{2}K^4).

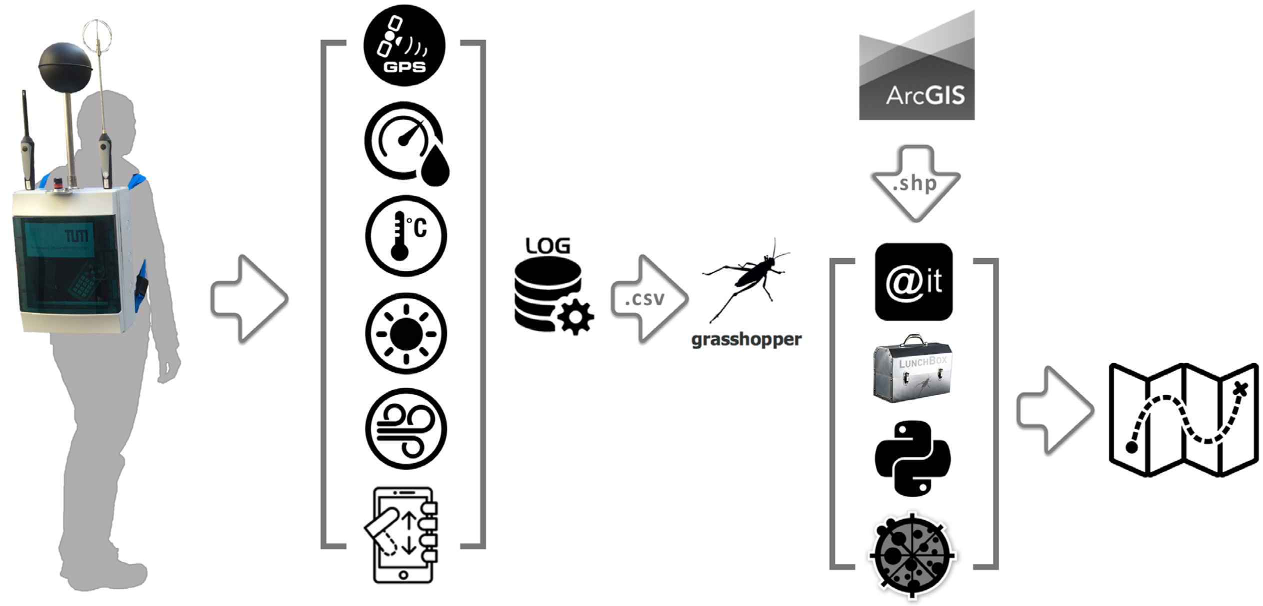
A detailed description of the approach and the angle factor estimation is given by Fanger [23]. The projected area factor is also calculated for a rotationally symmetric human based on the elevation of the sun considering solar declination, altitude & azimuth of the sun, and local standard time [26]. Having an elevation of the sun (γ) we can estimate the hourly projected area factor for every step of the measurements using the following equation:

$$f_p = 0.308 \cos\left[\gamma \times \frac{1-\gamma^2}{48402}\right] \quad (3)$$

3.3.3 Data Processing and Mapping

Depending on the resolution of the study, the data logging can be set from 1 second to 60 seconds, as experienced for walking campaigns,

Figure 3.5
Overview of the monitoring, processing and visualization procedure.



the appropriate sequence is 5 seconds to record all the input data with a meaningful spatiotemporal resolution. It is important to note on the GPS data that at some locations, depending on the visibility of the satellites and sky view factor the connection can be lost, but that problem is enhanced by correcting and adding the missing points using the street segment lines from OSM data in the post-processing.

For mapping the collected data, the base maps are extracted with shapefiles of the area from the Open Street Map (OSM) platform. This data was used to match geo-referenced tags with the estimated location on the streets to generate the path and also create the figure-ground map of the buildings and landscape features. Different Grasshopper plugins were used to post-process and map the data illustrated in Figure 3.5 showing the initial collected parameters up to map generation.

3.3.4 Improved Solar Radiation Measurement

Transient comfort experiments are relatively complex and due to unstable conditions of the sensor kit over the walking activity this instability can cause several errors in the measured data specifically on solar radiation because of varying tilt angles walking through the path. To enhance the problem, the sensors kit is equipped with a pendant gravity acceleration data logger to measure the tilt angle over time. The logger uses an internal three-axis accelerometer based on micro-machined silicon sensors consisting of beams that deflect with acceleration with a logging sequence of 1 second. Tilt angle is not measured directly by the logger, but is processed using the following formula:

$$\text{Tilt angle of the sensor kit} = 180° - \text{arccos (Acceleration in axis)} \quad (4)$$

Taking the tilt vector for every second of the measurement and calculating the sun vector for every hour of the tour depending on the accurate location of the subject using a GPS data logger, made it possible to calculate adjusted solar radiation taking into account the tilt angle of the device and location with the following formula:

$$\text{Adjusted Solar radiation} = \text{Incident Solar Radiation} \times \sin(\text{sun vector} + \text{tilt vector}) \quad (5)$$

3.3.5 Thermal Comfort Sensation

According to Höppe [27] in principle, there are three different approaches toward thermal comfort: psychological, thermophysiological, and based on the heat balance of the human body. The psychological definition is, “the condition of mind which expresses satisfaction with the thermal environment” [28], certainly is very hard to deal with. Due to its subjective character, it reflects a wide inter-individual variations. Nevertheless, psychological aspects are important factors, especially outdoors since the thermal history can influence the subject's assessment even more. There has been a significant number of studies on subjective thermal sensations in a variety of contexts and climates. As one example, a field study done by Kotz [29] with about 250 subjects interviewed on a hot summer day shows that even if the PMV assessment has been higher than +3 (hot), however, most of the objects stated they felt very comfortable. Asking them the reason there were two main statements: first, on the days before the

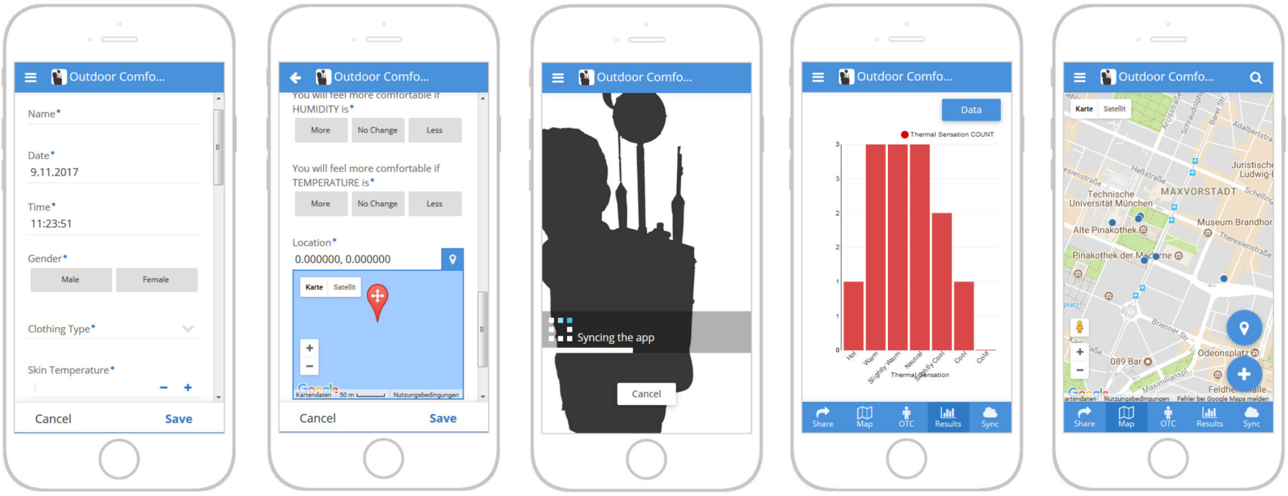
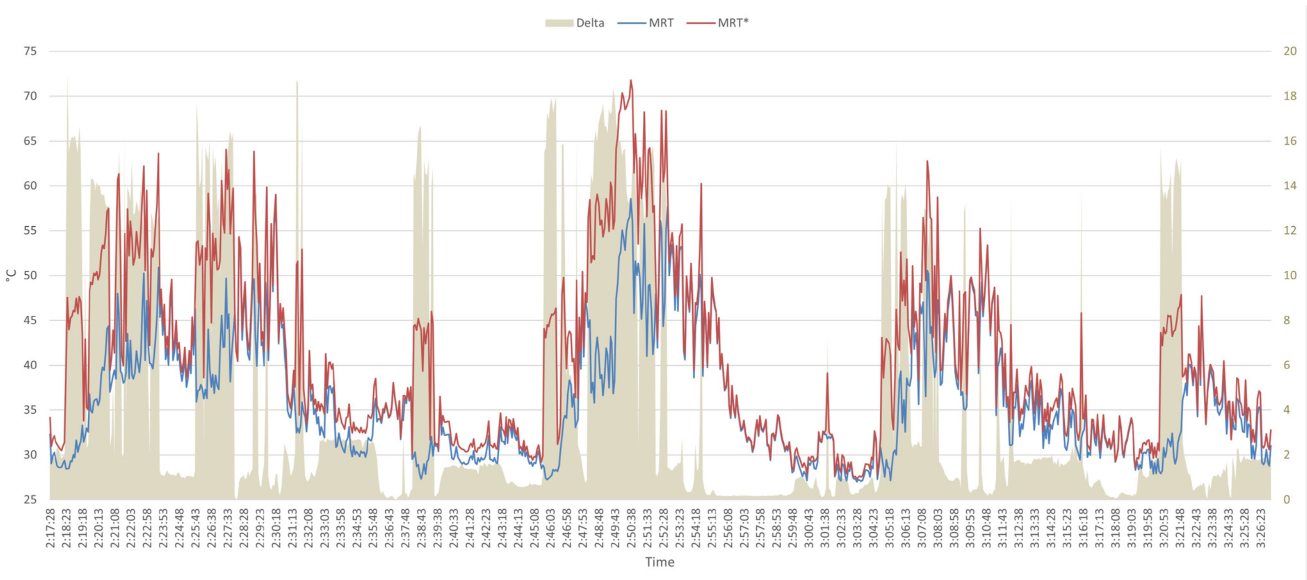


Figure 3.6
Overview of the outdoor comfort app.

weather was unseasonably cold and now they were glad to have sunshine again and the second reason was that they had time off and enjoyed easy living to get some suntan. This example reveals the importance of subjective assessments of thermal comfort especially for outdoor studies and how personal expectations can alter numerical assessments.

In this study as well, there was a consideration for psychological aspects through a designed app. The OTC survey app was developed to record subjective votes of people in terms of thermal sensation and thermal satisfaction. It is enabled with GPS location tags to pin exact survey locations in urban environments (Figure 3.6). Over the experiment campaign, the participants were asked to install the app which was created with a structured questionnaire to be answered every 10 to 15 minutes through the walk. Since the cellphones are also embedded with GPS trackers, it was manageable to trigger exact locations of the survey through the route and overlap the measured microclimate data with subjective responses of the participants in the locations of interest. The developed experiment setup has been tested and applied in different cities and climate zones and here the Genoa experiment is explained and discussed in detail as one of the very

Figure 3.7
Variations of MRT and MRT* through the path.



first attempts to use the developed method to analyze outdoor comfort in urban environments.

3.4 APPLICATION SCENARIO - CITY OF GENOA

The Genoa experiment took place on the 28th of September 2017 from 2 pm to 3 pm. Through the experiment, the participants including 5 female and 6 male subjects, were exposed to varying environmental conditions walking through diverse urban contexts from the old town (compact and dense) to the harbor (open and clear) routes. The concept was based on field measurements to achieve a better understanding of comfort modes on a microscale including people's behavior.

Figure 3.7 shows considerable spatiotemporal variations in meteorological conditions along the route and the delta between MRT and MRT* over the walking route. The measurements show that MRT without considering solar radiation varies between 27 °C to 58 °C where MRT* diverges between 27 °C to 70 °C with an average of 40 °C. This highlights the importance of including solar radiation in MRT calculations in outdoor environments to capture the immediate shifts where the subjects are exposed to the sun or moving to shade. This is also important because the GPS trajectories cannot give the location of the subjects to know which side of the street they are walking as it was shaded or exposed.

3.4.1 Walking Routes and Survey Points

The walking path for the experiment was defined for a maximum period of 1 hour within a closed-loop walking distance of approximately 2.5 km. Walking through the path, every 10 minutes there was a shortstop to fill the questionnaire app answering subjective responses on thermal sensations. Also, the skin temperatures for every subject were measured during the survey with an infrared camera. Using the GPS tags it was possible to locate the walking route and the

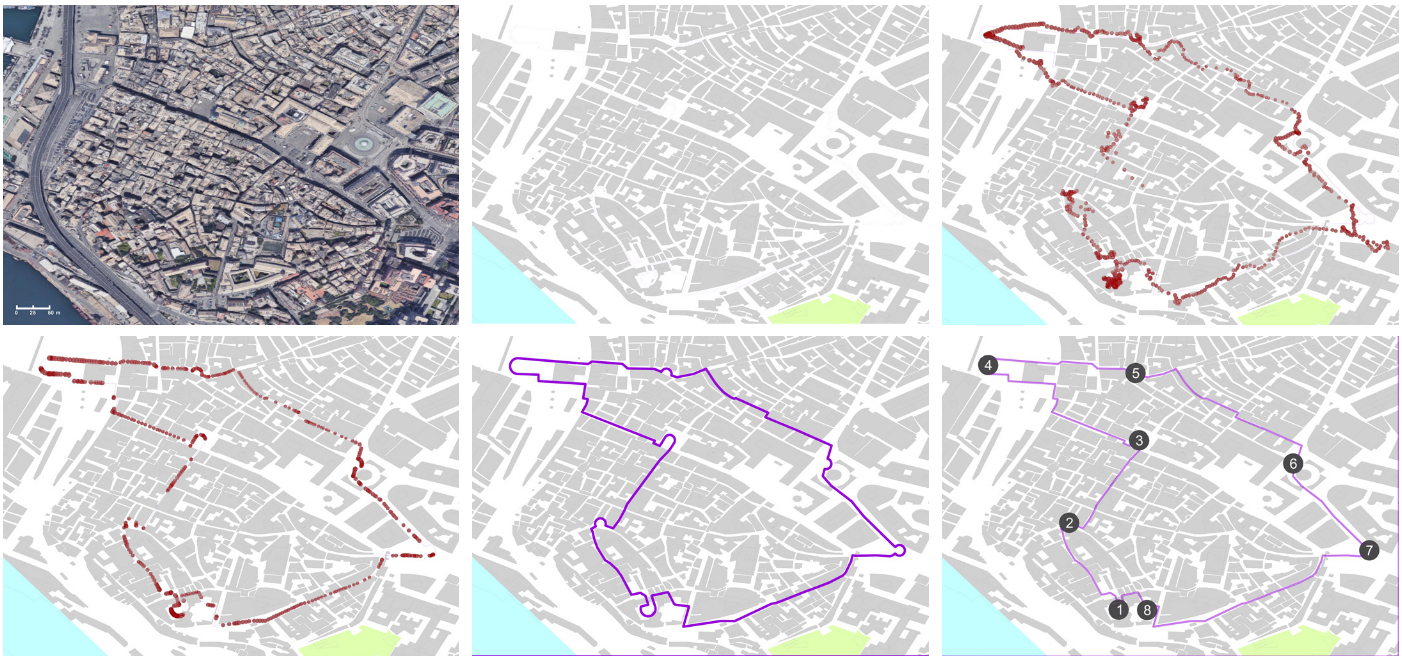
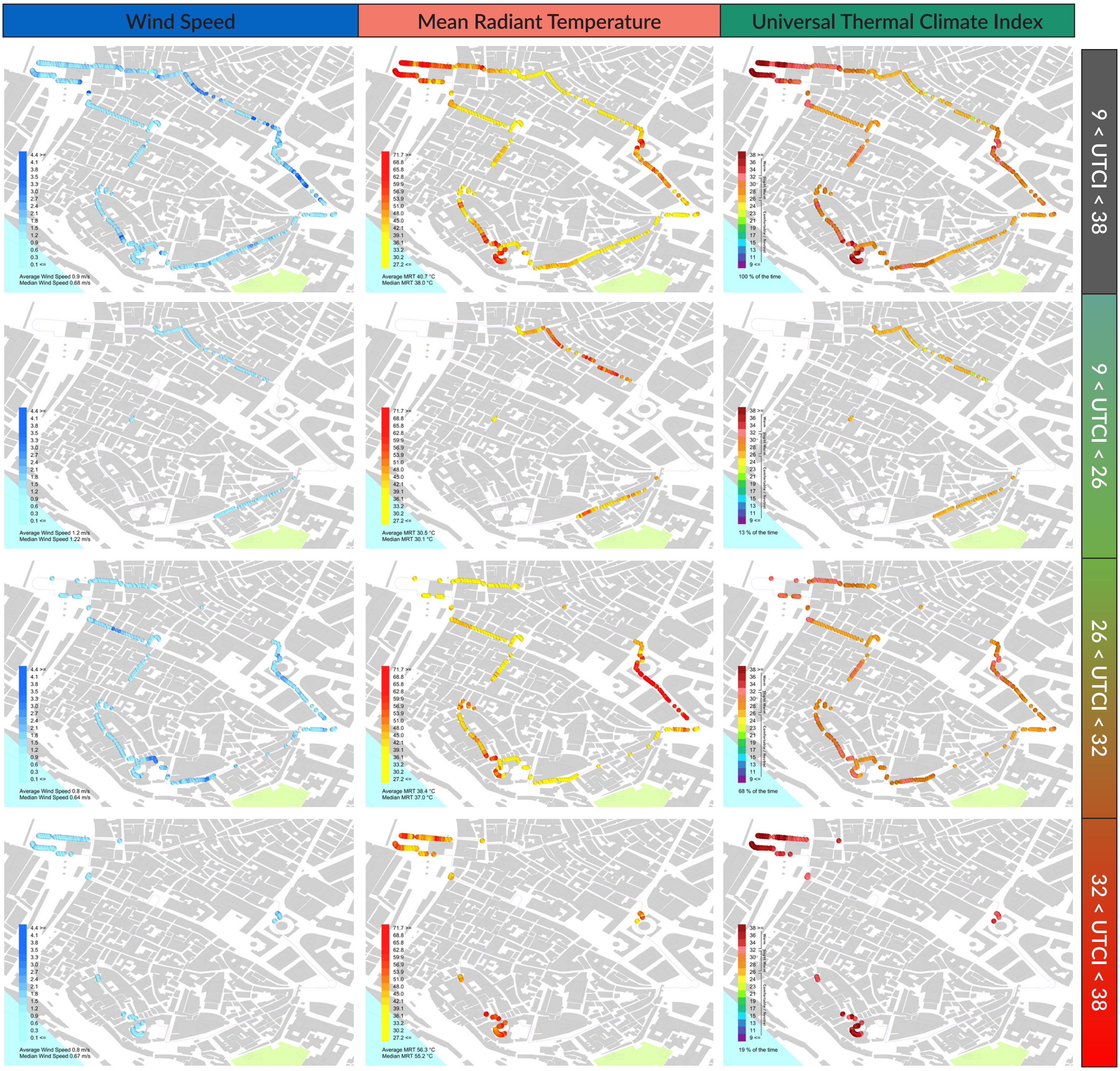


Figure 3.8
The location of the experiment and correction process of exact walking route.

stop points since we see a point cloud on these stops representing the number of people and duration of stay in the specific location. The data later overlapped with GPS signals of the survey app to get the exact location of the surveys. Figure 3.8 shows the steps of data processing from generating the base maps from OSM data to locating the GPS points and extracting the correct path of the walk and the survey points.

3.4.2 Thermal Comfort Results

One of the successful approaches toward physiological assessment of the outdoor thermal environment was UTCI by COST Action 730 with the



goal of applicability in different thermal environments, climates, seasons, and scales [30]. This study also uses UTCI as an outdoor thermal comfort metric. For the collected data, all of the values fall into the range between 9 °C to 38 °C (no thermal stress to strong heat stress). Figure 3.9 illustrates the UTCI maps clustered into different thermal comfort ranges. The first row shows the results for the entire route and the following rows are filtered based on different thermal comfort thresholds as 9-26 (no thermal stress), 26-32 (moderate heat stress), and 32-36 (strong heat stress). The outcomes show through the path, 19% of the time people were exposed to slightly warm conditions, 68% of the time experienced moderate heat stress and the rest of the time (13%) had no thermal stress. On the maps, the strong heat stress happens where there is an increase in SVF resulting in more solar exposure and it has a direct link with the morphology of the street and its aspect ratio. The other spot on the south part of the map with strong heat stress is in the courtyard of the university which due to its compact urban form does not necessarily align with the previous statement of compact morphology less heat stress. However, this effect reflects the exposure time of the people to microclimatic conditions in the courtyard due to the experiment setup and briefing of the subjects that translates to higher MRT values. The results show that the experiment can capture spatiotemporal variations of microclimatic conditions.

3.4.3 Pedestrian Wind Comfort

Based on the initial concepts of wind comfort there is a general agreement that the most appropriate approach for assessing or predicting pedestrian wind comfort is to use wind speed thresholds depending on pedestrian activities considering acceptable frequencies within a certain duration of time [31-33]. The wind speed measurements in this study vary between 0.1 m/s to 4.4 m/s and interestingly the points that we see with strong heat stress through the path, the wind speed never reaches more than 0.6 m/s, however for spots within the comfort range the wind speed rises to 1.2 m/s. High wind speed frequencies do not happen at the harbor with more openness, but it happens in narrow corridors of the old town which can act as wind tunnels sucking in the fresh air. In Figure 3.9 the second row shows the comfort range for UTCI and the median wind speed is the highest compared to other categories. This means narrow streets with minimized solar exposure and maximized wind effects can positively contribute to less heat stress (up to 10 °C) on pedestrian level.

Additionally, the adaptive model of comfort tells us that warm outdoor climates which would be regarded as uncomfortable concerning air temperature, are acceptable where elevated wind speed is happening. The wind maps show higher wind speeds in narrow canyons and corridors (up to 4 m/s) where the solar exposure is limited and this phenomenon shifts the thermal sensation to comfort range on these spots.

According to Penwarden [34], wind speeds above 5 m/s are more likely to give unpleasant disturbance. The wind speed is supposed to fall less than 5 m/s for 80% or more of the exposure time. If it goes upper than 5 m/s for more than 20% of the time, then remedial actions should be taken into account. These considerations are also dependent on the type of activity which means the tolerance for higher wind speeds is higher in case of

Figure 3.9

Maps of UTCI, Wind and MRT within different thermal comfort ranges.

increased metabolic rates. For example, in the case of fast walking, a mean wind speed of more than 10 m/s should not happen more than 5% of the time however, for the sitting position this rate is 3.5 m/s. For this study since the highest recorded wind speed was 4.4 m/s for walking activity, it was always below the discomfort line, however, it is important to keep the thresholds in mind for further studies especially for cold seasons.

3.4.4 Sky View Factor Approximation with GPS

One of the frequently used indicators to study environmental qualities in cities is the Sky View Factor (SVF). SVF at a point in space represents the ratio between the visible sky and a hemisphere centered over the analyzed location and the values can vary between 0 to 1. SVF can directly impact the radiant exchange between the human body and the built environment. Increased SVF over the day can cause more solar exposure which can translate to heat stress in urban canyons. There are different methods of SVF estimation available, based on graphical and geometrical modeling of canyons [35] or fish-eye lens photographs [36]. More advanced methods were recently implemented based on data proxies like google street views analysis [37, 38] or GPS receivers [39]. The GPS method despite the other methods, which are based on the direct calculation of SVF, is used in this study to measure SVF in real-time using proxy data. The method was shown to generate good results in urban environments but had a reduced explanation power in suburban and rural environments, which was consistent with the expectation that the variation in tree cover would produce noise in signal processing [40].

Chen, Ng [41] argues that GPS methods due to several features are more appealing than the traditional methods to estimate SVF: first, they are rapid and comparatively inexpensive; second, the method is not dependent on atmospheric condition at all in contrast to photographic methods; and third, they can be easily linked with geo-referenced datasets. Despite that, this method still has restrictions that limit the applications. First, they might not be suitable when accuracy is essential; second, the prediction equations are unique for each GPS equipment which means validation is necessary and it is not possible to derive a universal equation; and third, the performance of the method is good only for urban areas which was not the issue for this study.

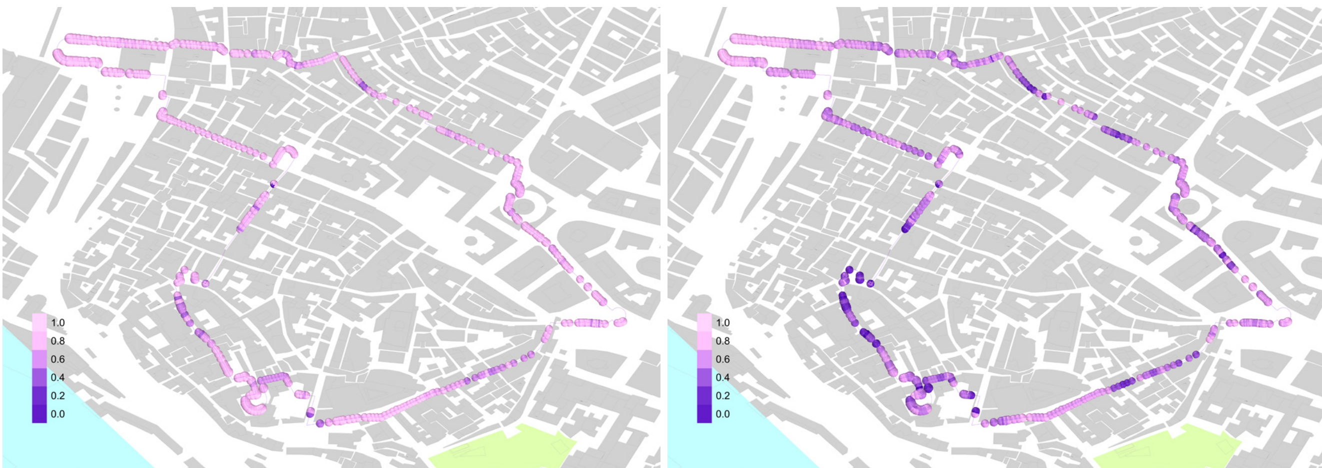


Figure 3.10
SVF map of the walking route from GPS data, calculated separately with HDOP (left) and N (right)

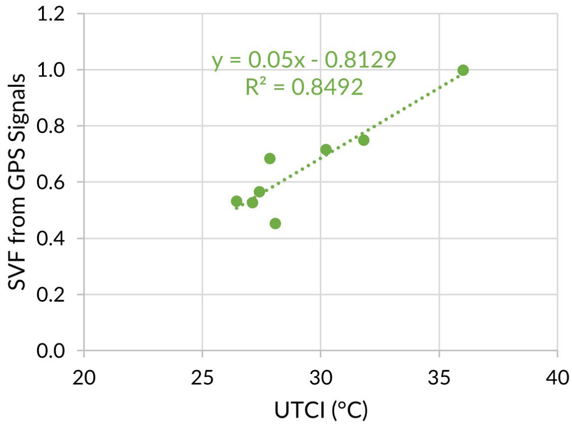
In the Genoa experiment, a GPS receiver was used to acquire raw data of satellite visibility including the number of visible satellites (N); Horizontal dilution of precision (HDOP), which is a measure of geometric quality of the configuration of a satellite in the sky (the lower the number the better the configuration and the better the fix quality); and strength of satellite signal were used in multiple regression analysis to derive an equation for the prediction and mapping of SVF based on Chapman, Thornes [40]. Figure 3.10 shows the SVF variation over the path calculated with HDOP and the number of visible satellites where the second method shows more reasonable variations compared to the first one.

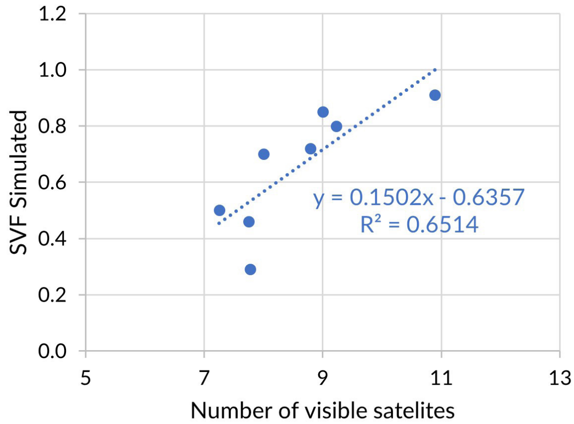
Since the prediction equations are unique for each GPS equipment, the method is also validated with the simulations of SVF using 3D models of the survey points. The correlation results of simulated SVF and the number of visible satellites from each point converge with R^2 = 0.65. The results show in our case the number of visible satellites has the most accuracy for predicting SVF through the walking path. After validating the regression model to calculate SVF from the number of visible satellites, the maps of SVF are plotted for the whole route, and for survey locations, UTCI is correlated as well. The results shows a strong correlation between the measures UTCI and calculated SVF from GPS data at the survey points with R^2 = 0.84 (Figure 3.11).

Figure 3.11

Simulated SVF and number of visible satellites (left)

Estimated SVF from GPS loggers and measured UTCI (right)

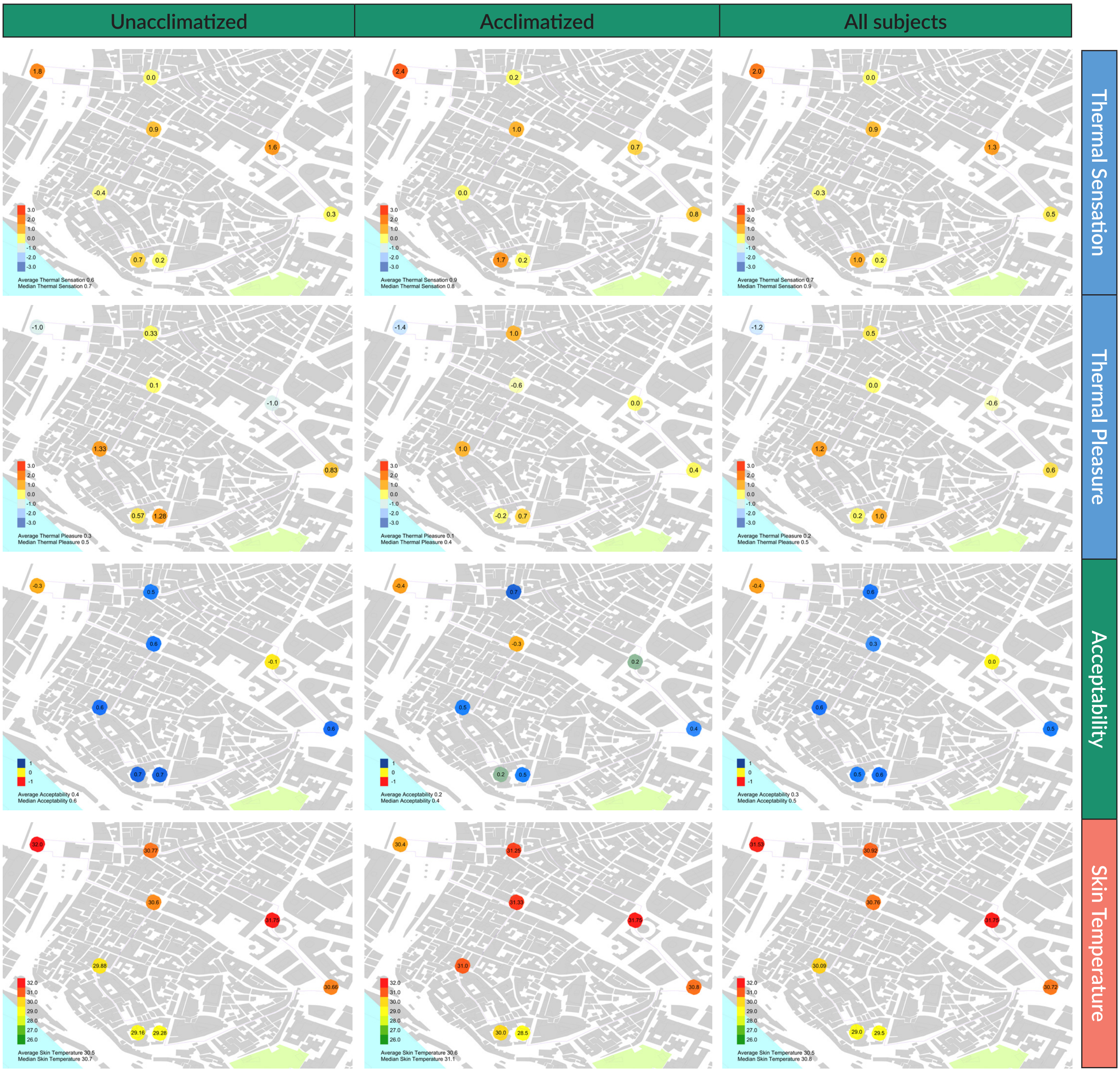




3.4.5 Subjective Thermal Responses

The thermophysiological definition of comfort is based on the firing of the thermal receptors in the skin and the hypothalamus. Comfort in this sense is defined as the minimum rate of nervous signals from these receptors [42]. Additionally, mean skin temperature (Tskin) plays a dominant role in the comfort perception and is widely known to be responsive to changes in different ambient temperatures [43, 44]. It was also observed in this study that Tskin is closely associated with changes in environmental parameters. The results for Tskin variations in Figure 3.12 show that it gradually increases from point 1 (courtyard of the university) to Point 4 (waterfront) due to the high exposure to solar radiation and the UTCI values follow the same trend. Tskin remains at a relatively high level in the latter half of the route because of the increasing level of metabolic activity and continuous exposure to a warmer environment [45]. This confirms the 20 minutes time that the body needs to compensate for heat stress. In addition, the results show slightly higher Tskin for female subjects compared to the male respondents through the walking route under same environmental conditions.

It was also found that Tskin over the entire path did not correlate with UTCI very well which can be explained by the complexity in determining skin temperature and the limitations of the measurement method of the forearm at each point of the walking route, which may not be representative of human physiological response to the thermal environment. The transient nature of outdoor environmental conditions is another reason for the low



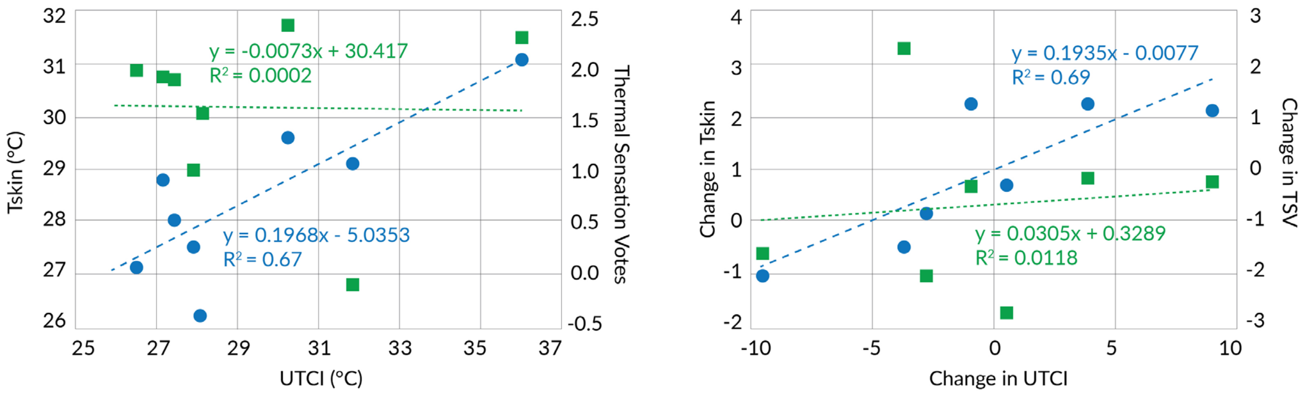


Figure 3.13
Scatterplots of Tskin, TSV and UTCI (left), and changes in Tskin, TSV and UTCI (right).

correlation between UTCI and Tskin. Nonetheless, Thermal Sensation Votes (TSV) correlated with UTCI reasonably well, especially for the changes in both values between survey points which further confirms the dependence of human thermal sensation on the meteorological conditions of the surrounding environment and UTCI (Figure 3.13).

Over the experiment, three peaks of UTCI were observed at more exposed locations along the walking route, i.e. Point 1 (courtyard of the university), Point 4 (waterfront), and Point 6 (De Ferrari Square), which coincide with high TSVs reported by the respondents. The intense solar radiation at Points 4 and 6 were predominantly the reason for the warm sensation while the transition from indoors to outdoors imposed a warmer sensation to the respondents even the air temperature and solar radiation are not as high as in the open locations.

Similar TSVs were reported by both male and female respondents with the presence of the three peaks in open and exposed locations. However, Thermal Pleasure Votes (TPVs) reported by female subjects were found to be slightly higher than the male counterpart, suggesting that female respondents are likely to be more tolerant to a warmer environment. Previous studies suggested that women tend to feel warmer in the outdoor environment but the tolerance of warmer conditions is higher than of cooler conditions [46-48].

The difference in TSV between local (acclimatized) and non-local (unacclimatized) subjects was larger than the gender difference. In general, TSVs reported by local respondents were higher than those reported (0.3-1.0) by non-local respondents. Regardless of the acclimatization of local respondents, the diversity of non-local respondents' backgrounds resulted in lower TSVs. .

3.5 DISCUSSIONS

As discussed before, most previous comfort experiments were conducted either in controlled climate chambers or in air-conditioned indoor environments under steady-state exposures. However, in outdoor settings, people tend to move through diverse and dynamic microclimates, exposing them to experience spatial gradients and temporal transients in temperature as well as other climatic parameters including humidity, wind speed, and solar

Figure 3.12
Psychological responses mapped over the survey points.

radiation. These inhomogeneities in outdoor thermal environments provide more opportunities for alliesthesia like walking between sun and shade or shortstop in a pocket park compared to static and relatively homogeneous environments like a straight sidewalk with no variations in SVF. Parkinson and de Dear in 2015 proposed that alliesthesia may be the underlying mechanism to explain why warm or cool can be perceived pleasantly [22]. They also differentiated two types of thermal alliesthesia: temporal and spatial [25]. To capture these immediate variations the developed toolkit and designed experiment can be used in the future to quantify the concept of positive spatial and negative temporal alliesthesia in outdoor environments.

The developed methodology needs improvement regarding the thermal sensation data collection method. As we know, if we consider alliesthesia outdoors then the concept of "neutral" range in the one-dimensional scale to represent the thermal comfort is inadequate. In one of the very recent studies on thermal sensation in outdoor space, Liu, Nazarian [49] build discussion based on the fact that the psychometric tool known as the thermal sensation scale has been extensively used in outdoor thermal comfort research. However, this one-dimensional descriptive scale was originally developed for indoor assessments and therefore has certain shortcomings in outdoor settings. As a solution, they propose a six-dimensional semantic framework for outdoor thermal comfort assessments comprising four descriptive - 'thermal sensation', 'humidity', 'wind' and 'solar radiation,' plus two affective - 'thermal pleasure' and 'thermal intensity' dimensions. Besed on this, it is recommended to consider the limitations of 7 point scale for future outdoor thermal studies.

3.6 CONCLUSIONS

This chapter proposed an innovative methodology to measure and evaluate outdoor comfort including pedestrian's response which enables us to find correlations between urban morphology and environmental parameters. The experiments of outdoor comfort in urban settings are more complicated and unpredictable compared to indoor contexts due to the non-steady and transient nature of the outdoors. However, dealing with this challenge was one of the main objectives of this research. We can summarize the outcomes of the study in two clusters:

1. The first outcome is more context related to the city of Genoa when we compare different genders, locality, and expectations. Results show that there are considerable spatiotemporal variations in the meteorological conditions and the corresponding thermal sensation reported by subjects which confirms that the outdoor thermal comfort studies cannot be deployed in test chambers under controlled environments.

2. The second outcome is the meteorological backpack and the designed experiment with all the data transfer platforms and visualization codes enabled with a geolocating system that can be used in the future for any context and climate zone to collect data and elaborate information on outdoor comfort and microclimate studies bringing together environmental, psychological and physiological data on the pedestrian level.

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C H A P T E R F O U R

OUTDOOR COMFORT MODELING

Summary

In urban areas, the impact of the built environment on wellbeing and human health should be considered as a measure to encourage walking and active use of public space. This chapter compares two different methods for modeling the radiant environments using a CFD-based model and a transient tool. The aim is to identify the limitations of each model and explore an accurate estimation of mean radiant temperature to simulate the effects of urban form and vegetation on pedestrian outdoor thermal comfort. Further, the chapter explores the possible OTC simulation workflow that can inform the urban planning processes.

4

Partial results of the presented work in this chapter have been published in:

Ata Chokhachian, Katia Perini, Mark Sen Dong, Thomas Auer (2017): How Material Performance of Building Façade Affect Urban Microclimate. PowerSkin2017, Munich, Germany.

Katia Perini, Ata Chokhachian, Sen Dong, Thomas Auer (2017): Modeling and simulating urban outdoor comfort: Coupling ENVIMet and TRNSYS by grasshopper. Energy and Buildings; 152., DOI:10.1016/j.enbuild.2017.07.061.

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4 OUTDOOR COMFORT MODELING

4.1 INTRODUCTION

As a result of population growth all over the world, the environmental issues deriving from land-use conversion and anthropogenic activities are gaining increasing attention due to their impacts on human health and wellbeing. The last 20 years clearly showed an intensified frequency of extreme weather events with frequent summer heatwaves throughout the world, where the estimated number of people affected by the heatwave in the world was 125 million each year [1].

This is more evident in densely populated cities, where the effect is intensified by the density and materiality of the built environment. Consequently, the increased summertime discomfort frequencies can increase the EUI of buildings for cooling purposes most commonly using HVAC systems that can negatively contribute to intensification of UHIs. In this context, appropriate modeling tools are needed to support the urban planning processes to quantify the effects of the built environment on microclimate and pedestrian outdoor thermal comfort. One of the main challenges in microclimate modeling is to quantify the frequency of extreme

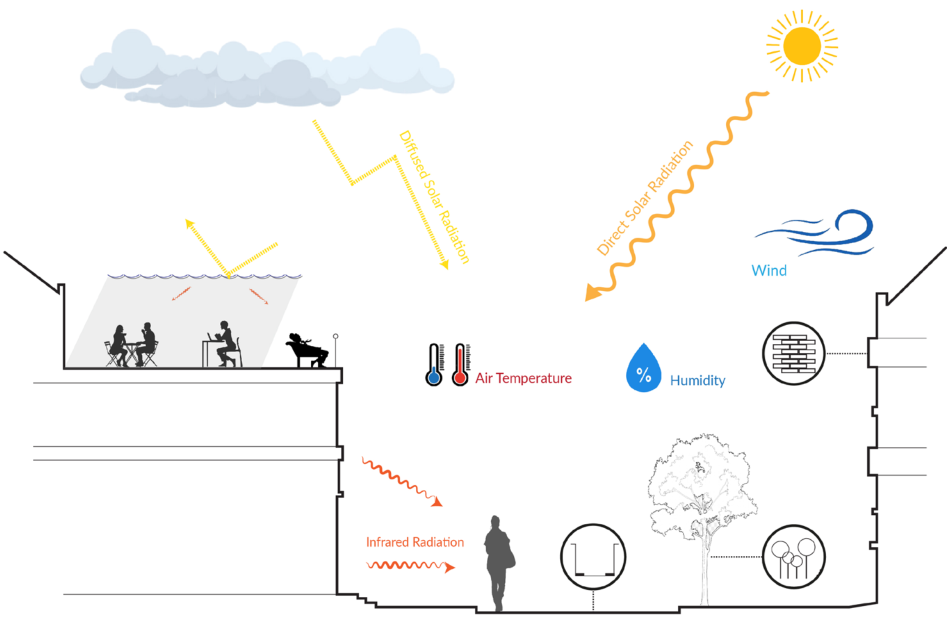


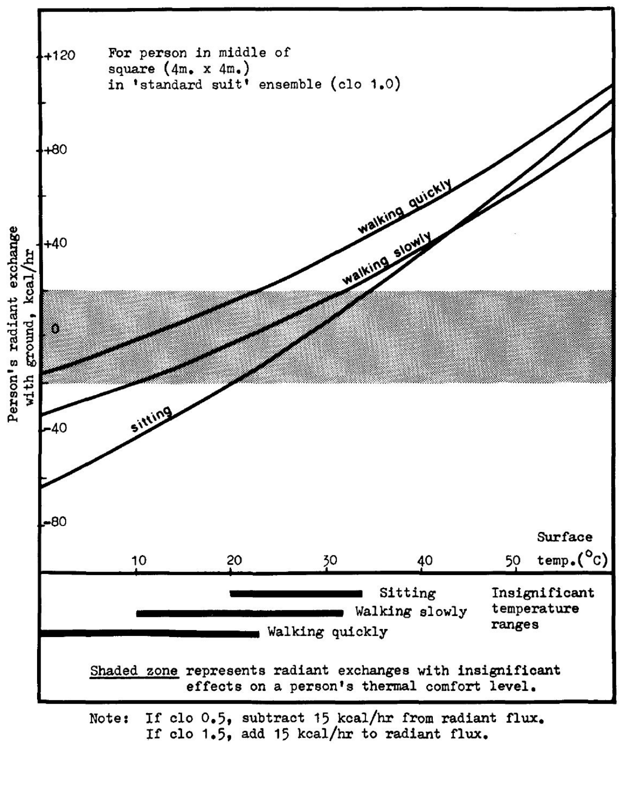
Figure 4.1
Conceptual sketch of outdoor comfort and effective parameters.

events and predict the consequences of such phenomena on outdoor comfort and provide context-related design solutions and maintain desirable outdoor conditions despite rising air temperatures and increasing extreme heat events.

The contributing parameters in assessing the perceived temperatures for a person walking on the sidewalk are fairly complex that need information about wind flow, solar radiation, temperature, and humidity profiles between the buildings including vegetation surfaces and water bodies (Figure 4.1). In this regard, while measurements can deliver highly accurate data, they are rather expensive and time-consuming endeavors that can only inform us about specific thermal conditions that exist at a given segment and time. In contrast, numerical modeling allows us to evaluate alternative urban design scenarios, as well as to study the spatial and temporal variability of outdoor thermal comfort conditions on pedestrians..

Simulation tools have been able to model the urban environments dynamically and over longer periods of time to inform the design process for urban massing and landscape development. Urban morphology, density, materials properties, and vegetation cover can create varying patterns of microclimate within a couple of hundreds of meters in cities. That is why built environments are known as one of the main microclimate modifiers [2-4]. This connects directly to human thermal comfort and the design of urban space to increase awareness among architects and urban developers to be aware of the bilateral impact of the built environment on the wellbeing of our cities. Consequently, improved outdoor comfort conditions will enhance the city in several aspects like the encouragement of cycling and walking, attracting more people to the cold spots in the city, and on the other hand, increasing the business and touristic potentials of the area [5]. Given the complexity of the urban domain, modeling such environments need inputs from building geometries, climate, materiality, vegetation covers, and anthropogenic sources as part of the built and natural environment to drive design in favor of less discomfort exposure for pedestrians [6].

Figure 4.2
Effect of surface temperature on human radiant exchange and activity range [7].



It is valid to claim that research on outdoor comfort has the same history as indoor comfort. At the same time, Fanger started to numerically evaluate human thermal comfort, there have been studies on outdoor thermal comfort as well and we can find most of them placing themselves in the core of urban design and urban planning. One example dates back to 1977 with the work of Plumley [7] who adopted Fanger's human thermal comfort model to determine comfortable levels of radiant-heat exchange for various activities, clothing types, and climatic conditions. One of the innovative aspects of this work was estimating radiant heat exchange with the surfaces based on the activity of a person (Figure 4.2). He also proposed that the comfort outdoors can be altered with artificial radiant sources from the surfaces with very local design solutions. For example for Syracuse, New York, he proposed that in cold conditions if a person has a large sky view, solar radiation should be maximized (seats facing the sun and ground materials that are moderately reflective to the sun). Or in warm conditions, if the direct sun is desired, a breeze is necessary and a reduced sky view is desirable.

In 1974, Morgan and Baskett [8] did a review on the energy balance approaches to generate models for man-environment coupling. They reviewed 8 models and concluded that most of the current models are designed for indoor situations, not being able to handle the solar radiation effects of the outdoors. They conclude that some models contain very sophisticated treatment of the physiological processes of energy transfer to the skin while treating the environmental factors in a sketchy manner. The few models which treat the environmental factors with some depth are in general naive with respect to the physiologic processes. As Buettner [9] contended over 50 years ago, the need of current research in biometeorology is to extend this type of analysis of man-environmental relations to clothed subjects in natural (outdoor) environments.

One of the reasons that the term outdoor comfort was not actively researched in the past can be explained in terms of necessity and the appearance of air conditioning which made indoors more controllable and manipulatable and the commonly used statement that people spend 90% of their time indoors, which can be true however these days studies suggest that people have spent more time than usual outdoors to get enough doses of daylight and vitamins on daily basis [10].

Even if the research community was more aligned to indoor comfort topics, in 1972 one of the very first computational models developed to describe man-environment relations quantitatively and in particular with respect to the relative physiologic comfort of clothed men in various outdoor areas within a large urban complex by Myrup and Morgan called Man Model (MANMO) [11]. MANMO was based on the average skin temperature as the dependent variable and the average skin wetness as the model outputs which could be related to human comfort.

The main question that Morgan and Baskett [8] raised and still up today is not answered yet was, where is the link between the simulation models and the subjective evaluation of thermal comfort. Or, in other words, what parameters should we model and how do we relate these outputs to the two well-accepted thermal comfort criteria of comfort pleasantness and temperature sensation which still is not very straightforward to answer with computational models.

Since then, research and development efforts to provide a tool for systematically analyzing variations of outdoor human energy budgets and thermal sensation as a result of different urban street canyon geometries including the vegetative properties, date back to 1982 with the work of Burt, O'Rourke, & Terjung [12-14]. In their substantial work, they combined three numerical models of human skin temperature and associated energy fluxes in outdoor settings (HUMAN), a detailed model of energy fluxes in urban street canyons (URBAN3), and a model to compute radiant and thermal field above, beneath, and within vegetation canopies (CANOPY). Today, given the advantages of numerical modeling and the increasing computational power of personal computers, several tools like; ENVI-met [15], RayMan [16], CityComfort+ [17], SOLENE [18], VTUF-3D [19] have emerged to facilitate the assessment of microclimate and human thermal comfort with the aim of supporting various urban design processes and planning strategies. While these tools differ both in the modeling approach and the human thermal comfort indices that they deliver, they all rely on the calculation of mean radiant temperature as one of the most critical parameters.

Today, it is already well studied and accepted that one of the important parameters for quantifying thermal comfort in urban areas is the correct approximation of the radiant environment [20]. According to Herrmann and Matzarakis [21] mean radiant temperature (MRT), along with wind speed, are the parameters mainly influencing thermal bioclimatic conditions. In urban areas, heat transfer by radiation is the most important factor in the energy exchange processes between the human body and its environment.

There are different computational approaches to quantify the radiant environment outdoors either based on computational fluid dynamic (CFD), or transient models. In transient or process-based models, the heat fluxes are not being modeled as fluids, however, in CFD models the airflow contains the resolution to include thermal properties of the air. This does not necessarily affect the radiation models in each of the methods (which might not be identical) however it affects how each tool deals with thermal storage of the buildings and the whole radiation flux balances in the urban canyons. Both of these methods allow evaluating the effects of urban morphology and vegetation on microclimate and thermal comfort however each might come with some limitations especially considering MRT over the day and night [22].

The recent study by Gál and Kántor [22] evaluated RayMan Pro, SOLWEIG, and ENVI-met, comparing modeled MRT values with those derived from observation. The results indicate that the models significantly underestimate nighttime MRT. SOLWEIG and ENVI-met tend to overestimate MRT during prolonged periods of shade and underestimate when the sites are sunlit. RayMan underestimates MRT values during most parts of the day. The authors explicitly point out that the largest MRT errors occur at low sun elevations in all three models, mainly as a result of underestimated longwave emitted and shortwave reflected radiation fluxes by the adjacent facades. These errors indicate room for improvement with regards to surface temperature estimation and shortwave reflected radiation calculations in these models.

In another example, the study by Wang, Berardi [23], compared MRT values in different urban densities in Toronto based on ENVI-met simulations. They captured slight differences between each urban configuration during the daytime, however, after 7 pm (after sunset) the curves tend to be almost linear. The sudden MRT drop after sunset and the equilibrium with the air temperature at the same time puts into evidence the need for further investigation to study the thermal mass effect of the building surfaces exposed to solar radiation.

This was one of the main motivations to set up a Transient Systems Simulation (TRNSYS) and compare the results to see the effects of materials on MRT and translate them to the perceived temperature for outdoor thermal comfort with the following objectives:

- Understanding the limitations of the radiation models in CFD-based simulation tools for urban environments.
- Quantifying the contribution of different façade materials on mean radiant temperature.
- Developing a workflow that can simulate the radiant environment in annual cycles for design decision support purposes.
- Identifying the limitations of transient models in modeling the outdoor environments.

4.2 METHODOLOGY

The methodology of this chapter is based on the comparative study of MRT simulations in ENVI-met and TRNSYS. The simulation outputs are compared for different hours of the day concerning mean radiant temperatures to see the limitations of each model and in the next step, UTCI values are derived from each model in order to understand and quantify the contribution of material choice on pedestrian thermal comfort on a street canyons (Figure 4.3). For UTCI calculations, both models use the wind speed from ENVI-met which means the only influencing parameter on different perceived temperatures is driven by MRT.

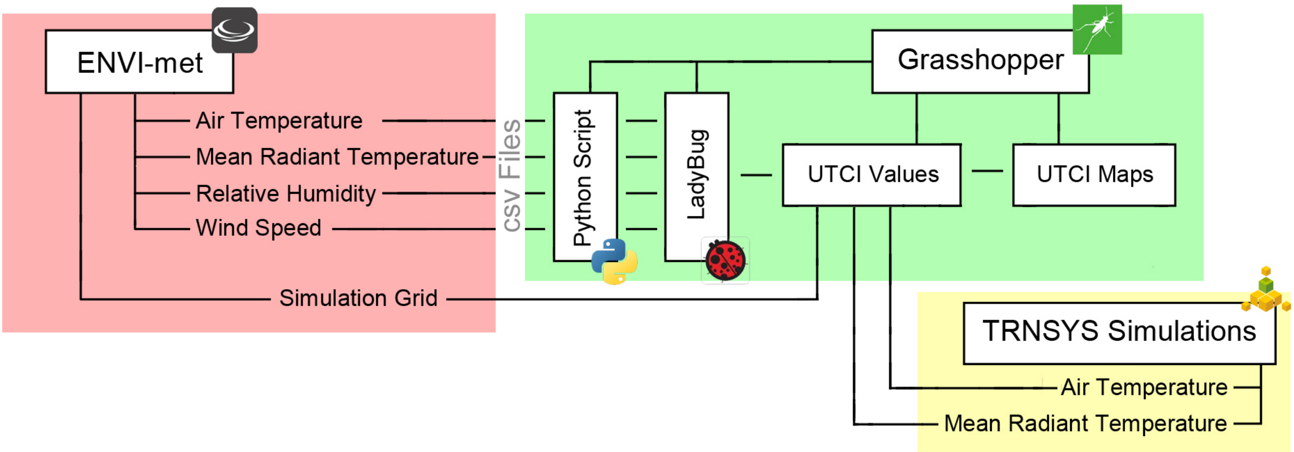
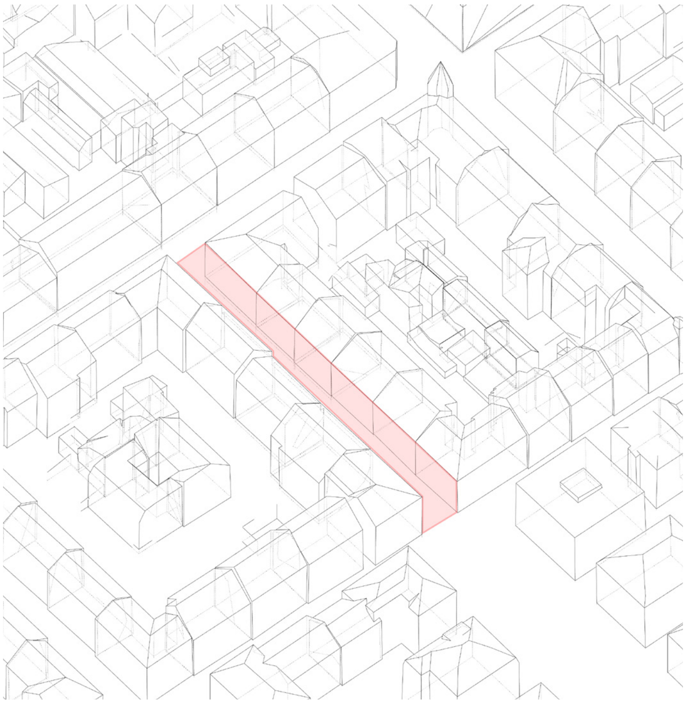


Figure 4.3
Diagram of coupling methodology for implemented tools.

4.2.1 Simulation Setup

The simulations are carried out in the following order: 1) Simulation of the canyon model in ENVI-met, 2) simulation setup in TRNSYS based on wind speed result for air change rate obtained from ENVI-met and 3) comparison of the MRT and UTCI values for different hours. It worth mentioning that TRNSYS simulations are fundamentally different than ENVI-met, but nonetheless, the boundary conditions are set to be as close as possible to make the results comparable. The geometry of the case study is based on a typical urban canyon in the inner city of Munich with mid-rise building density, surrounded by the same height buildings. The street canyon had a width of 21 meters and a length of 75 meters, with neighboring buildings of 21 meters high. The canyon is North-South oriented with concrete building construction and asphalt covering the ground surface (figure 4.4).



For all of the simulations (ENVI-met and TRNSYS), the grid resolution of 3 × 3 meters was assigned, according to AIJ Guidelines, the minimum grid resolution should be set to about 1/10 of the building scale (about 0.5–5.0m) within the region including the evaluation points around the target building [24]. The simulation period was set for a hot summer day in the city of Munich (12th August) to capture the maximum effects of both models. The climate data collected from a weather station in the city center and for both ENVI-met and TRNSYS simulations, input values were assigned hourly (Table 4.1).

Table 4.1: Summarization of climate data

	Min	Max
Air Temperature	15.3 °C	33.9 °C
Wind Speed	1 m/s	
Wind Direction	100 °	

Figure 4.4
Configuration of analyzed typical urban canyon.

4.2.2 ENVI-met

The three-dimensional microclimate model ENVI-met is designed to simulate the surface-plant-air interactions in an urban environment with a typical resolution of 0.5 to 10 m in space and 10 sec in time. ENVI-met, a non-hydrostatic, micro-climatological, and computational fluid dynamics model to simulate surface-plant-air interactions employs the standard k − ε turbulence model in closing the Reynold Average Navier-Stokes (RANS) equations for mean flow characteristics of turbulent conditions. For this study, ENVI-met V4 simulations ran for a duration of 48 hours, although only the second 24 hours outputs were used.

4.2.3 TRNSYS

TRNSYS or Transient Systems Simulation program is a simulation tool for calculating energy and climatic conditions of building environments, thermal and energy systems. TRNSYS uses a building code validated by the US Department of Energy, which certifies that the model is able to simulate: transient effect of thermal mass, long and short wave radiation model, and heat transfer. Unlike ENVI-met, TRNSYS is not a CFD-based program, so there are several diverse differences between these two models. These differences have brought both advantages and disadvantages for TRNSYS in outdoor MRT simulations. TRNSYS allows to define detailed building envelope layers and thermal properties and deploy annual simulations. In the case of this analysis, TRNSYS provided the opportunity for applying the material of the building facades and streets to a very precise level.

However, simulating MRT in urban canyons with TRNSYS can have limitations since the transient models can underestimate the wind flows especially in outdoor space considering the surface temperatures. On top of that, TRNSYS can only take one wind velocity per zone, which means the resolution of wind speed in TRNSYS cannot be compared with ENVI-met. This might cause inaccuracies in MRT calculation because wind speed affects the convective heat transfer of building surfaces. But since the effect of convective cooling will be limited in MRT calculations, this limitation should not affect the results severely.

In order to downscale the grid-based wind speed results from ENVI-met, they were averaged into a constant value per hour. The average wind speed is the total volume of air passing through the street canyon divided by the volume of the simulation space (m^3), which is the area of the street multiplied by the building height.

$$ACH = \frac{V_{air}}{Stree\ Area\ \times Height}$$

The second limitation of the energy modeling engines like TRNSYS or EnergyPlus is that they do not have native methods of describing the climatic effect of trees in simulations. This means that TRNSYS does not support the use of complicated geometric models for trees plus there is no good solution for simulating the unique shading effect due to the translucency, porosity, and distribution of the leaves. Evaporative cooling from tree leaf surfaces cannot be modeled the same way ENVI-met does. These limitations are very critical in this analysis, and most of them are addressed and enhanced with the development of the PANDO model which is explained in detail in Chapter 5.

4.2.4 Material Definition

Thermal simulations are dynamic in terms of material variation, for this reason, there is a possibility to evaluate different materials with varying solar absorption to see their impact on radiant temperature variations of the urban space. This will help to select correct materials for building façade to have less impact on the outdoor environment and pedestrian thermal comfort. Table 4.2 provides detailed information on material properties and construction variants for different simulation inputs. Three alternative materials are selected: Brick, Concrete, and exterior insulation with plaster as finishing layer. The other variant was the color of the materials with different solar absorption. For brick 35 and 68 percent, for concrete 30 and 80 percent, for wall with exterior insulation the color with 30 and 80 percent solar absorption implemented for TRNSYS simulations.

Table 4.2: Facade construction variants and specifications.

Variants	Ground	Solar Absorption	Construction	Conductivity kj/h.m.K	Capacity kj/kg.K	Density kg/m³
Concrete	Concrete 60cm	Light 30% Dark 80%	Concrete 30cm	6.12	0.88	2300
Brick	Concrete 60cm	Glazed 35% Common Red 68%	Brick 30cm	2.88	0.84	1920
External Insulation	Concrete 60cm	Light 30% Dark 80%	Plaster 2cm	0.72	1	849
			EPS 20cm	0.144	1.5	32
			Concrete 20cm	6.12	0.88	2300

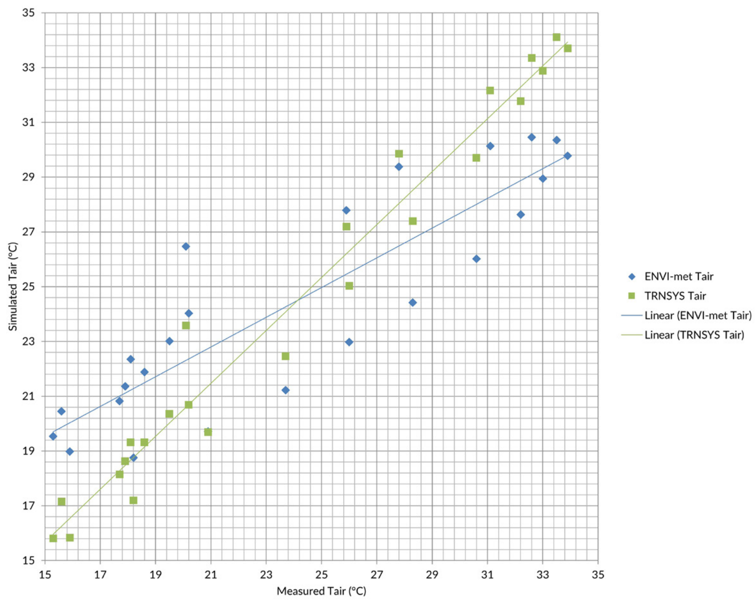


Figure 4.5
Model validation graph – comparison between air temperatures deriving from ENVI-met and TRNSYS simulations and field measurements.

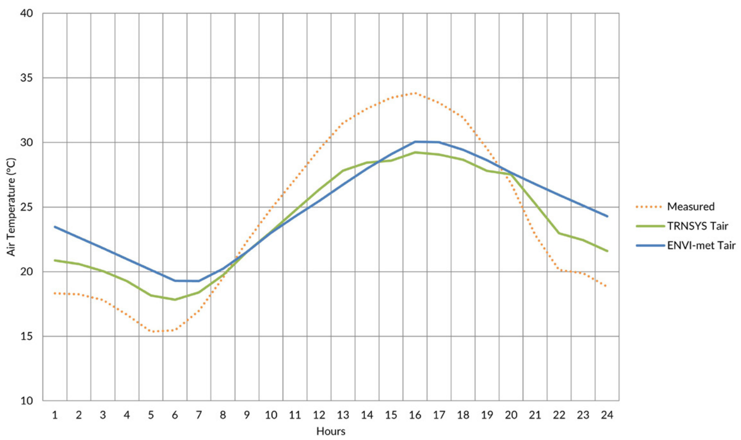


Figure 4.6
Hourly air temperature comparison.

4.3 MODEL VALIDATION

In order to verify the reliability of ENVI-met and TRNSYS models, two different validation methods are used. First, the hourly air temperature output data from both models are compared with the data recorded by a weather station in the city of Munich (Figure 4.5). The weather station operates since 1961 and is located on the LMU campus in Munich. The hourly air temperature values in the middle of the canyon at the height of 10 meters from the ground are extracted. The comparison shows a very similar temperature profile compared to the field measurements in the case of TRNSYS, while in the case of ENVI-met during night temperatures are slightly higher and during the day slightly lower (Figure 4.6). These validation results correlate with other studies, which found a reasonable agreement between ENVI-met simulated and measured diurnal data [25]. Also, we see slightly higher air temperatures over the night which can confirm that CFD models perform better in predicting the air temperature due to the fluid behavior of the model and they could be more suitable for UHI predictions.

Second, for further validation of the MRT values of the TRNSYS model, measurements in 5 different street canyons were conducted using the method explained in section 3.3.2 in the city of Munich (Maxvorstadt neighborhood) on August 15th, 2018 from early morning (7 AM) until midnight. Figure 4.7, on a figure-ground map shows the locations of the streets and Table 4.3 summarizes the specifications of each street in terms of dimensions, orientation, and aspect ratio.

Table 4.3: List of monitored street canyons and their dimensions

Street	Nr.	Height	Width	Length	H/W	Orientation	Rotation
Hiltensbergerstr.	1	18m	20m	74m	0.9	N-S	9°
Georgenstr.	2	18m	20m	122m	0.9	E-W	97°
Oskar-von-Miller-R.	3	21m	27m	75m	0.7	E-W	107°
Ludwigstr.	4	21m	38m	79m	0.5	N-S	18°
Rheinbergerstr.	5	21m	12m	87m	1.8	E-W	108°

For this validation, the simulation results were extracted and correlated for the measurement points on the sidewalk for each street over the day.

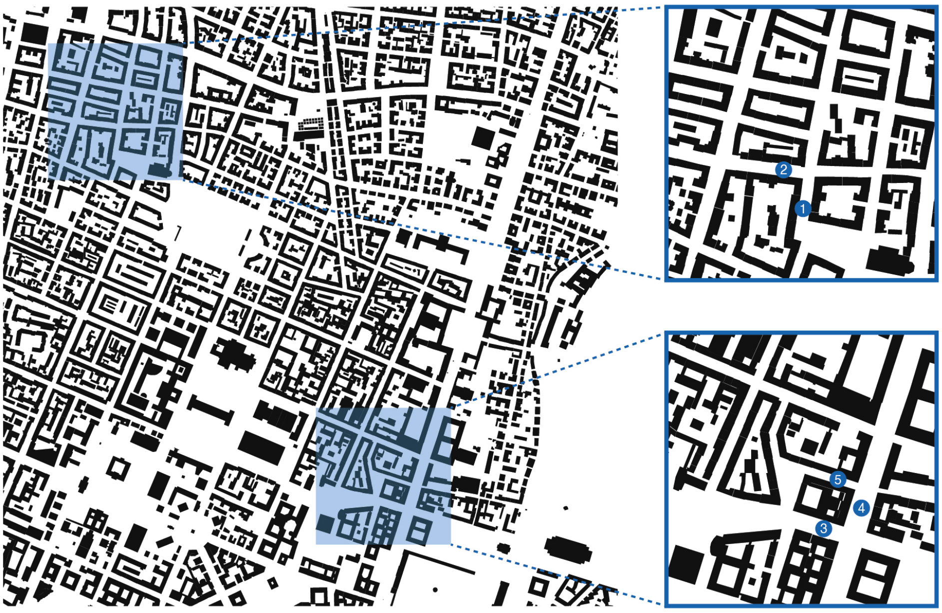


Figure 4.7
Locations of the measurements in the city center of Munich.

The results show a high correlation for all 5 streets with R^2 varying between 0.80 to 0.98 (Figure 4.8). For Rheinbergerstrasse, since the street is E-W oriented, with comparatively higher aspect ratio, and the measurement point was on the south sidewalk, the MRT values do not show any contribution of direct sun (shortwave radiation) and the they stay between 22 to 39 °C. The validation process and the results pointed out the importance of accurate modeling of longwave, shortwave, and reflected radiation from the surfaces to estimate accurate MRT outdoors. Additionally, to include the UHI effects in transient simulations, it is recommended to run the weather data with an urban weather generator (UWG) to calculate air temperatures inside urban canyons from measurements at an operational weather station located in an open area outside of the city [26].

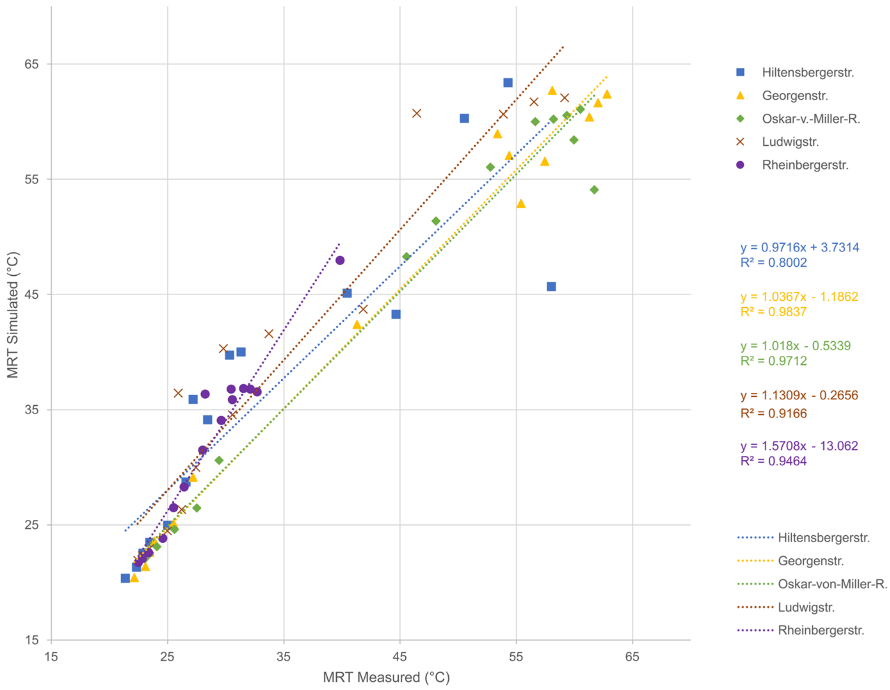


Figure 4.8
Scatter plot of measured and simulated MRT values on August 15th, 2018.

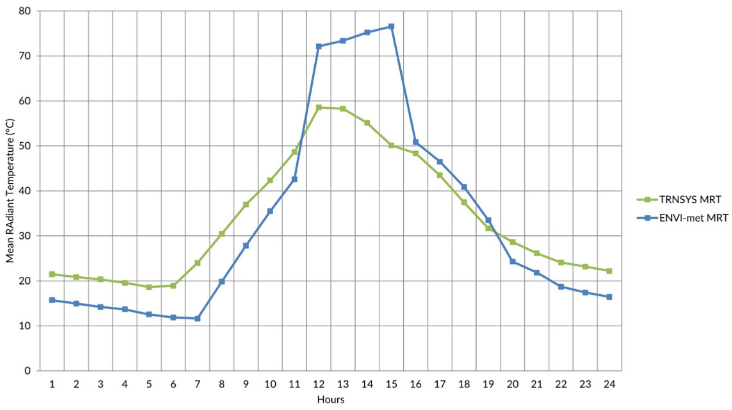


Figure 4.9

Mean Radiant Temperature (24h) at 1.5 meters in the center of the typical urban canyon simulated with ENVI-met and TRNSYS.

4.4 RESULTS

4.4.1 MRT Comparison

For comparing the MRT values from both simulations, the results are mapped for a hot day at 2 AM, 8 AM, 2 PM, and 6 PM. In order to focus on mean radiant temperature, hourly results recorded in the middle of the canyon, from ENVI-met and TRNSYS simulations, are compared for both configurations. Regarding the night time MRT values (7 PM to 6 AM), there is a difference ranging from 5 to 12 K. Differently during the day (with peaks at 12 AM and 1 PM) MRT simulated by ENVI-met shows up to 26 K higher values which confirms a very different treatment of short-wave radiation and it's a contribution to MRT in both models (Figure 4.9). Mean radiant temperature sums direct and reflected short and longwave radiation fluxes. Since during nighttime, short-wave radiations are eliminated, the differences among ENVI-met and TRNSYS simulations' outputs can be related to long-wave radiations which can be translated into the better capacity of transient models to estimate the thermal mass effect of the surfaces.

Figure 4.10, illustrates the maps for different hours of the day. For 2 AM, we see a very uniform distribution of temperatures in both models however the values are higher in the case of TRNSYS. For 8 AM, a visible effect of thermal mass and direct solar radiation on the west wall of the canyon is observed. ENVI-met simulations show lower temperatures (up to 1 K) near the building façade compared to the center of the canyon. This behavior is noticed also in a mirrored trend at 6 PM. Moving to 2 PM, the results of ENVI-met simulations show that short wave radiation has a major influence on mean radiant temperature calculations, resulting in a high difference between sunny and shaded areas (up to 26 K). This phenomenon is also highlighted by the isolated peaks, which are visible on the East and Southside of the canyon (up to 72°C). Differently, TRNSYS simulations show a gradient from West to East ranging from 40°C to 47 °C.

The comparison results of hourly and spatial maps show that the TRNSYS model is suitable to capture night-time radiant temperature gradients and estimating longwave radiation exchanges. It should be noted that for air temperature in the canyon due to the one dimensional ACH of the transient model we cannot see any UHI effect captured by the model which puts into evidence the potential of CFD models to address this phenomenon.

4.4.2 UTCI Comparison

Given the importance of MRT, as one of the most influential parameters on human energy balance and thermal comfort, other authors have focused on this as well. According to Ahmed, Ossen [27], mean radiant temperature should be used as an indicator of outdoor conditions rather than the air temperature. In order to identify the contribution of this parameter on thermal outdoor comfort using different models, UTCI values are calculated and compared. Figures 4.11 show the UTCI values calculated

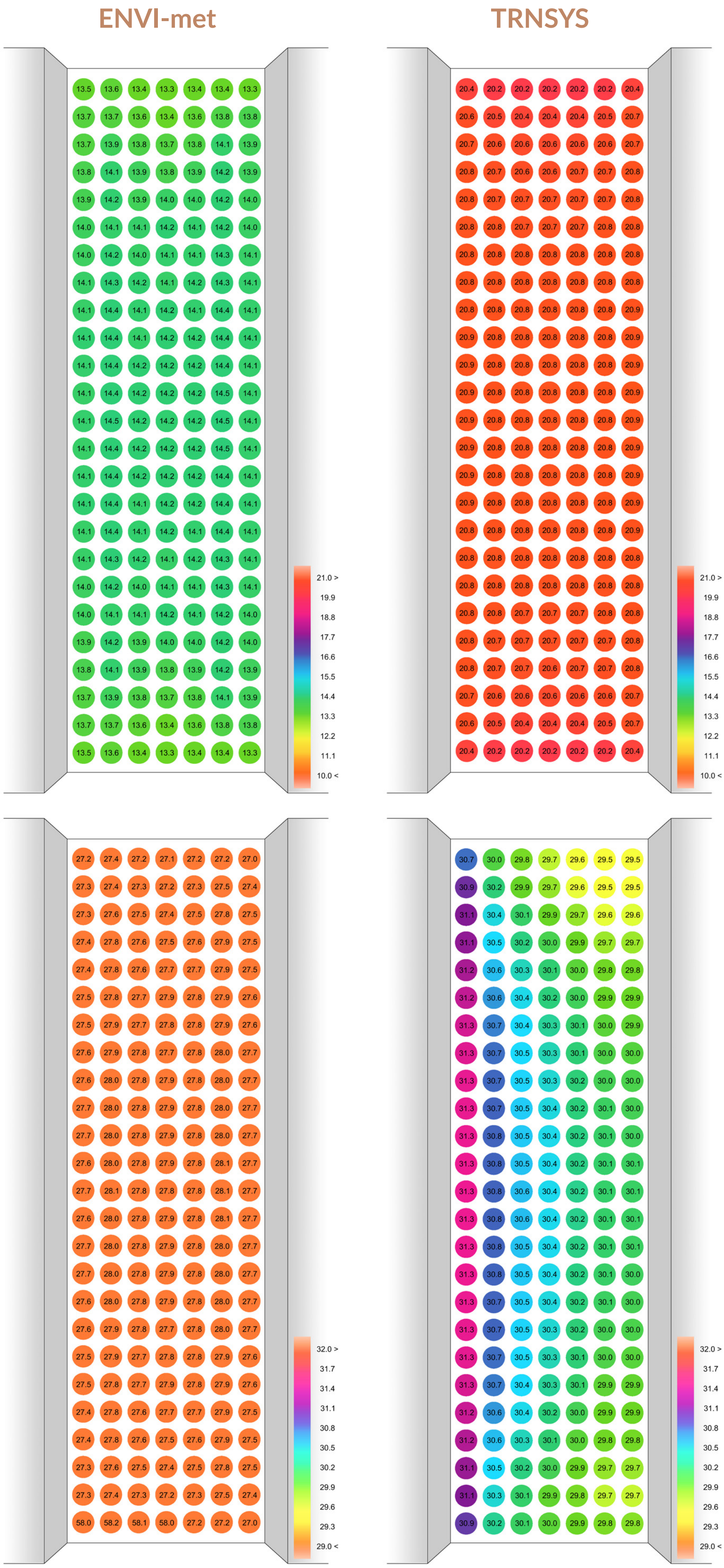


Figure 4.10
Mean Radiant Temperature maps based on TRNSYS (right) and ENVI-met (left) simulations at 2 AM, 8 AM, 2PM, 6 PM at 1.5 meters.

2 AM

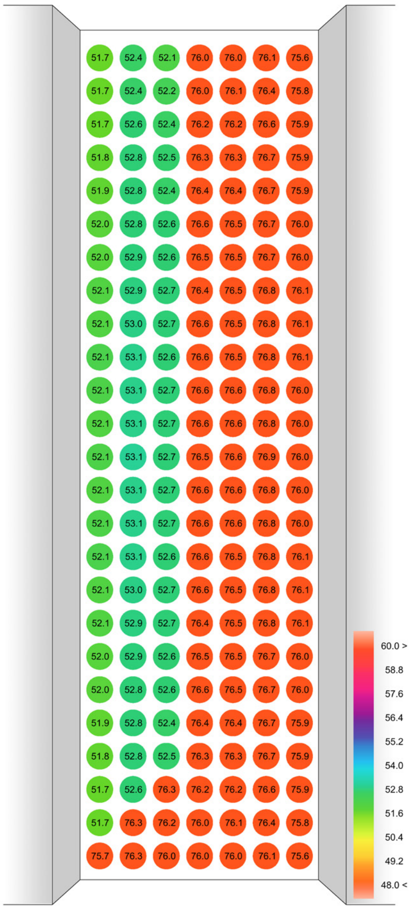
8 AM

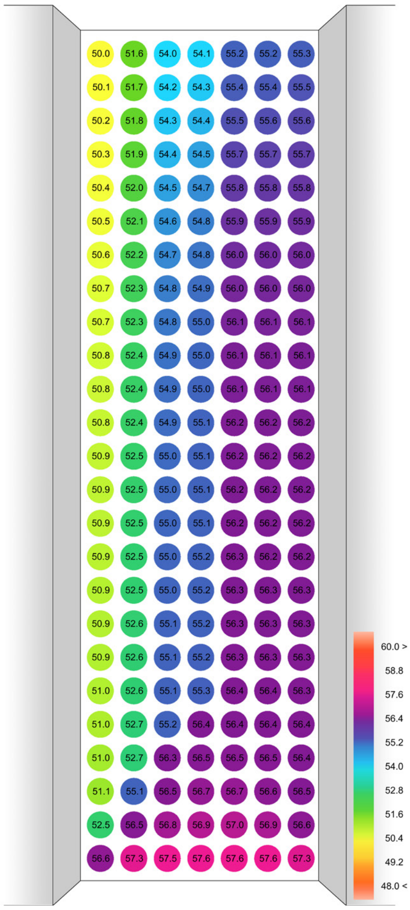
MRT

MIRI

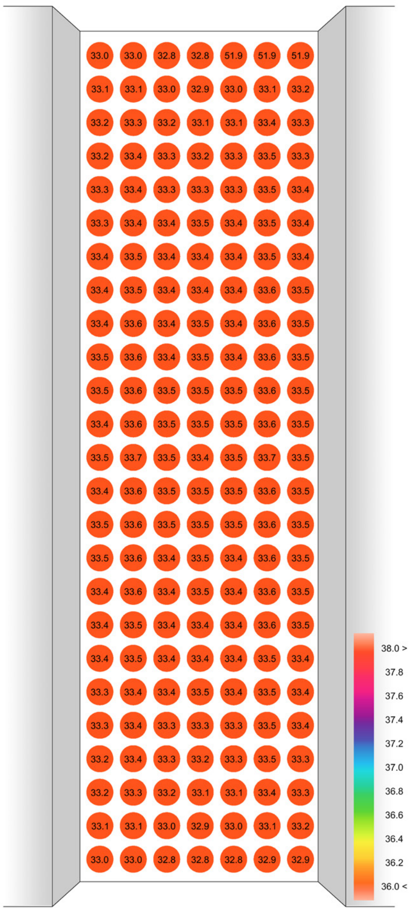
ENVI-met | TRNSYS

2 PM





6 PM



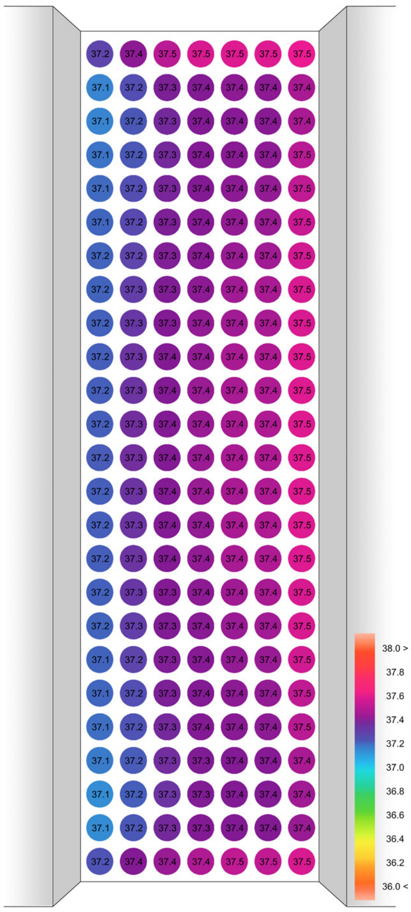
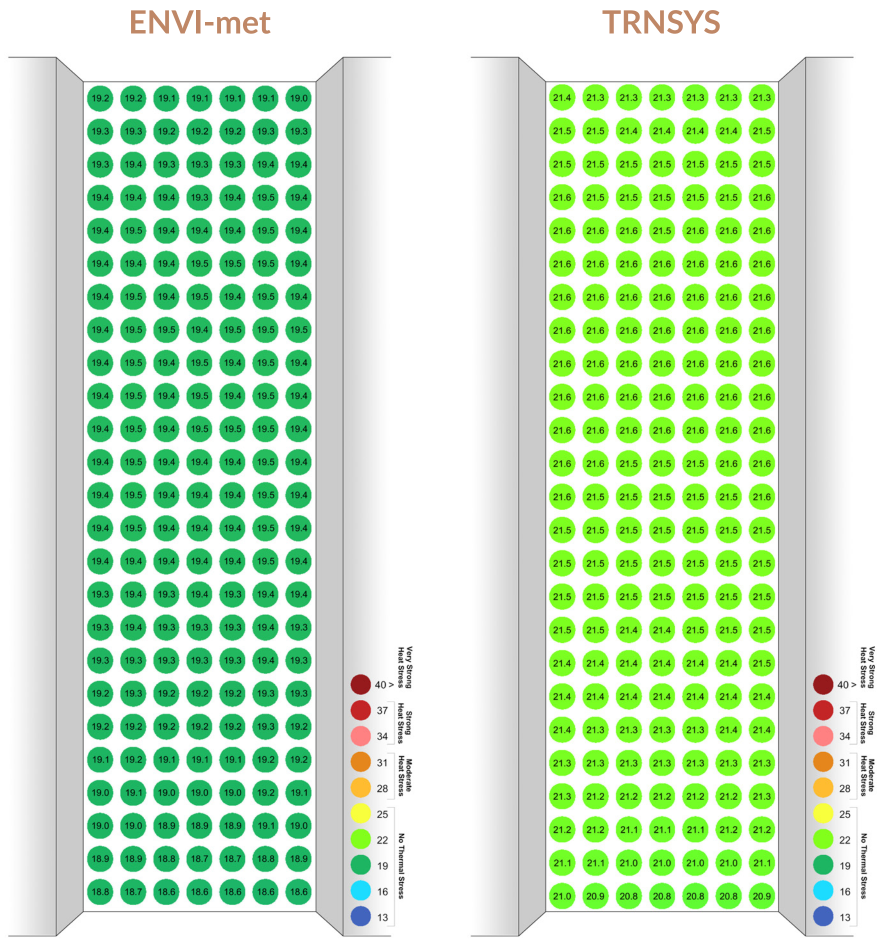
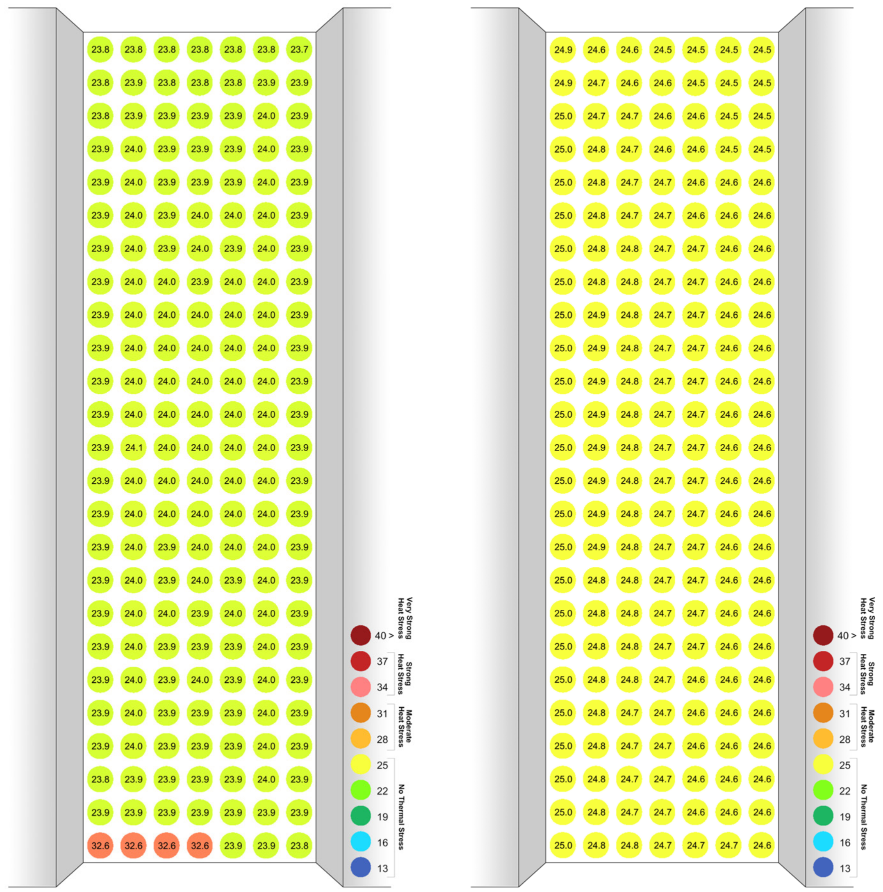


Figure 4.11
UTCI maps based on TRNSYS (right) and ENVI-met (left) simulations for 2 AM, 8 AM, 2PM, 6 PM at 1.5 meters.

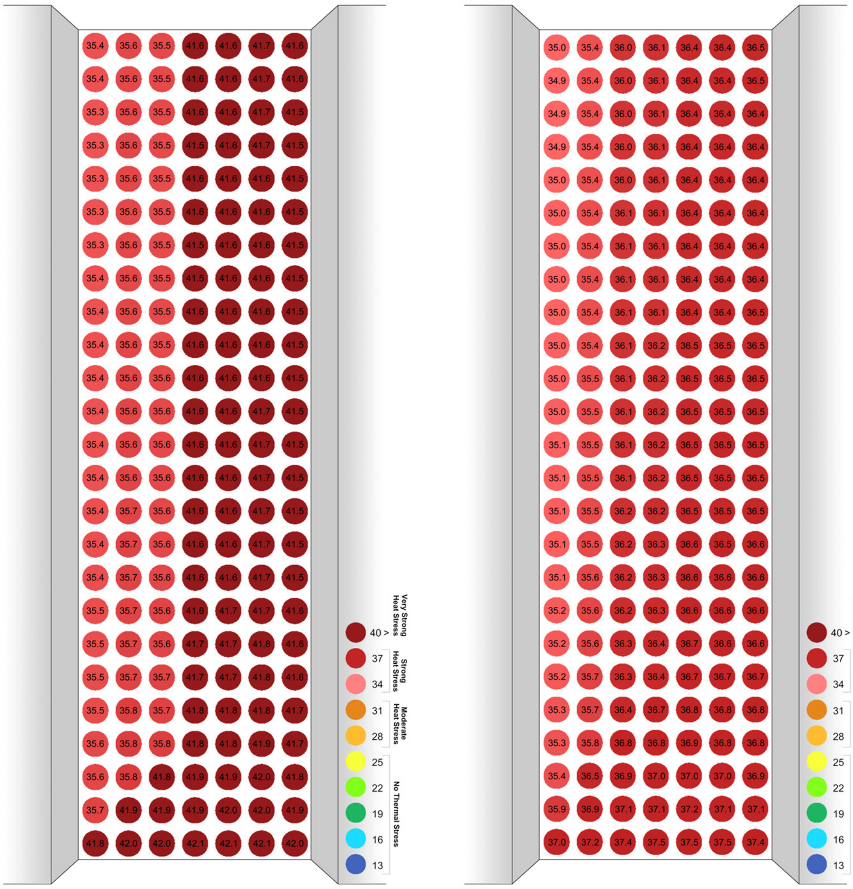


2 AM

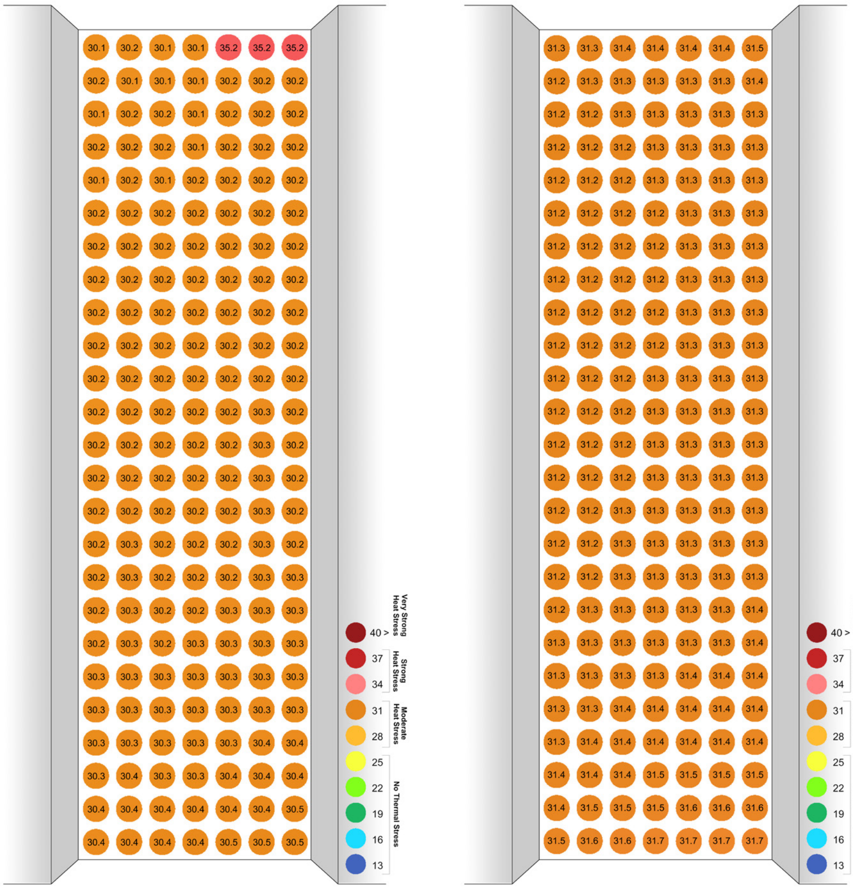


8 AM

ENVI-met   TRNSYS



2 PM



6 PM

from two models separately. The first one only with ENVI-met outputs (Air Temperature, MRT, Humidity and Wind speed), and the second time with MRT values replaced from TRNSYS.

The results show that for 2 AM maps, UTCI values using TRNSYS MRT projects slightly higher (about 2 K) compared to the only ENVI-met results due to the influence of mean radiant temperature. However, we don't see any shift in thermal stress since all the values are in no thermal stress zone and this might not necessarily cause any shift in the perception of the pedestrians. A similar trend can be observed in the case of 8 AM and 6 PM with TRNSYS UTCIs slightly higher (1 K).

For the case of 2 PM, the results show a very different projection compared to other hours of the day where the sensor points are exposed to the direct sun. Looking into the sidewalk on the west side of the canyon shows 5 K difference between the two models for perceived temperatures. Since the numbers are at the borderline of strong and very strong heat stress, the spatial distribution of UTCI for the ENVI-met model shows 40% of the street exposed to very strong heat stress wherein the TRNSYS model, the entire area of the canyon is in strong heat stress threshold. One may argue that any number above 34 °C should be noted as heat stress and the effect on human perception might be similar depending on the exposure time, however, these differences between the two models which is mainly due to the different short-wave radiation models, can give a very different image for cumulative or annual statistics of thermal comfort over a longer period of time. Additionally, since TRNSYS shows a very smooth gradient from shade to the sunny side of the street, it might not be suitable to capture the immediate effects of being exposed to the sun, in other words, the concept of alliesthesia.

4.4.3 Material Behavior Study

For further implementation of the workflow and to have more architectural and urban planning-related results and recommendations, the developed framework is used to examine the effects of different material properties (Table 4.2) on outdoor thermal comfort perception in the same canyon setup in the city of Munich. This section focuses on the thermal performance of the building façade with the question of how and to what extent the radiant fluxes in the canyon can affect perceived temperatures.

Several studies have already delivered insights on the effect of urban canyon material on outdoor comfort. Salata, Golasi [28] prove that the application of high albedo materials on vertical and horizontal faces of a canyon determines deterioration of thermal comfort, especially in summer. This phenomenon could be handled by increasing the sky view factor of high albedo materials to limit the radiation reflection inside the canyon. In contrast, high albedo materials usually improve microclimate during winter. This improvement is directly in connection with the climate because the improvement is not exactly equal to worsening that happens during the summer and most of the time it has less effect on winter.

This specific study on the building material and outdoor comfort also uses the previously described workflow (section 4.2.1) in TRNSYS using typical urban block located in Munich city center having mid-rise density

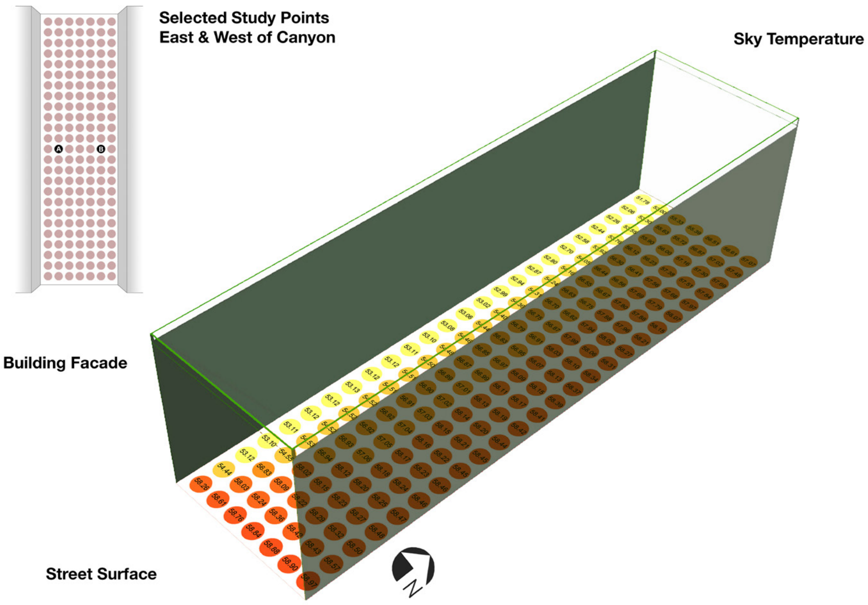


Figure 4.12
3D model of urban canyon and study points.

surrounded by the same height buildings. In order to compare both sides of the canyon, two test points are selected in pedestrian height on the sidewalks. Point 'A' on the east and point 'B' on the west facade (Figure 4.12). To compare the effect of material variation with different wall constructions and solar absorptions, the MRT values are mapped on the street at 2 pm. This can give us a visual understanding of how the radiant temperature is distributed over the canyon and the changing patterns over the day. The results show the highest MRT values for the case with exterior Insulation with 30% solar absorption and the lowest for the brick wall with 68% absorption keeping in mind the hour of the day (Figure 4.13).

As we know without even simulating these cases it would be possible to guess which material might project lower or eventually higher radiant temperatures, however, the aim here is to quantify these effects and set a guideline to understand how much is the effect and the contribution to the

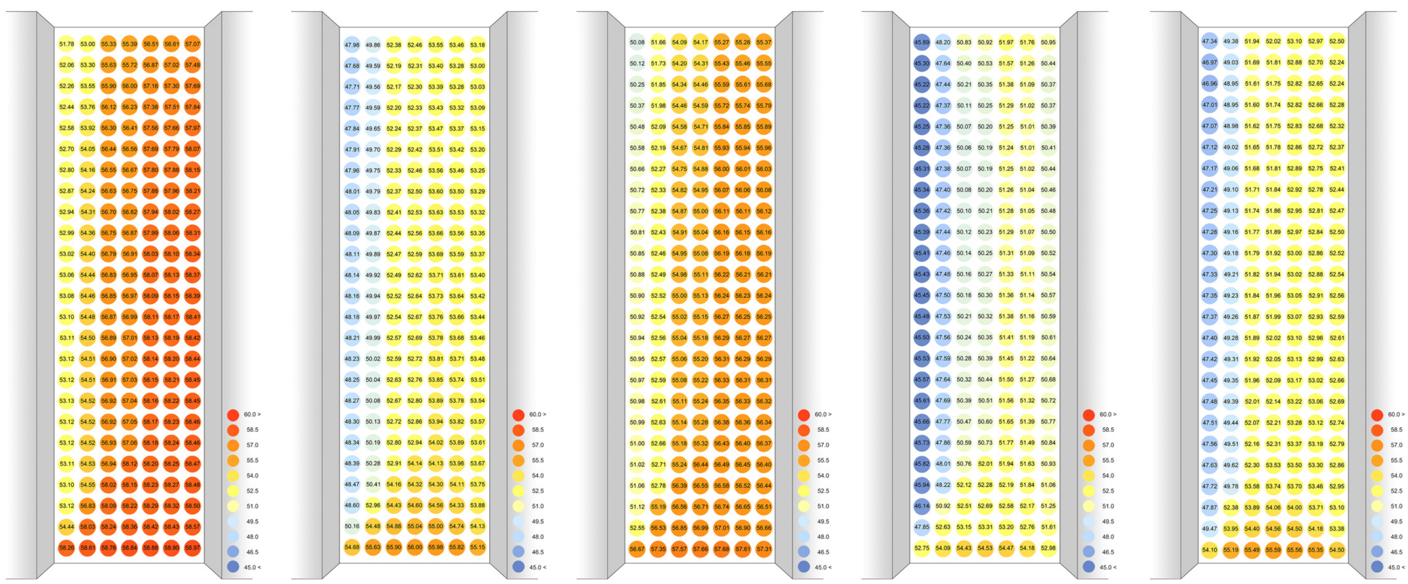


Figure 4.13
Comparison of MRT values for Different facade materials at 2 PM.

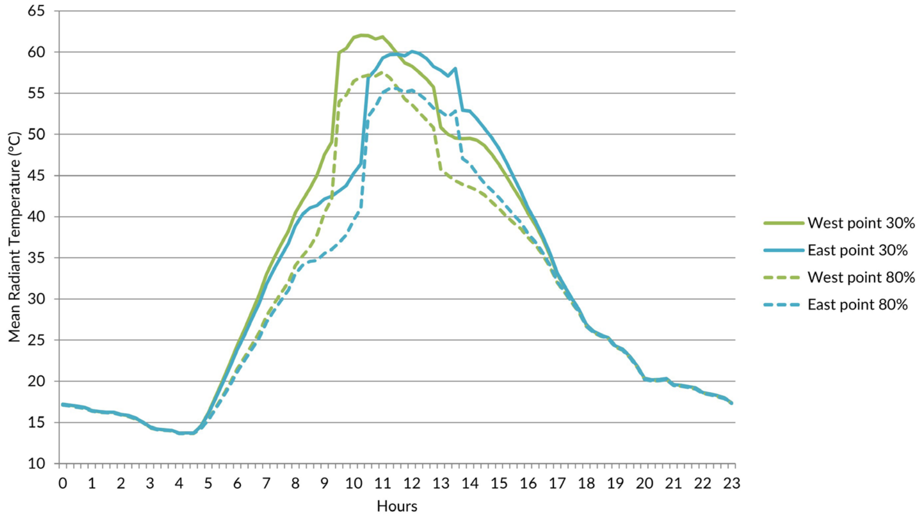
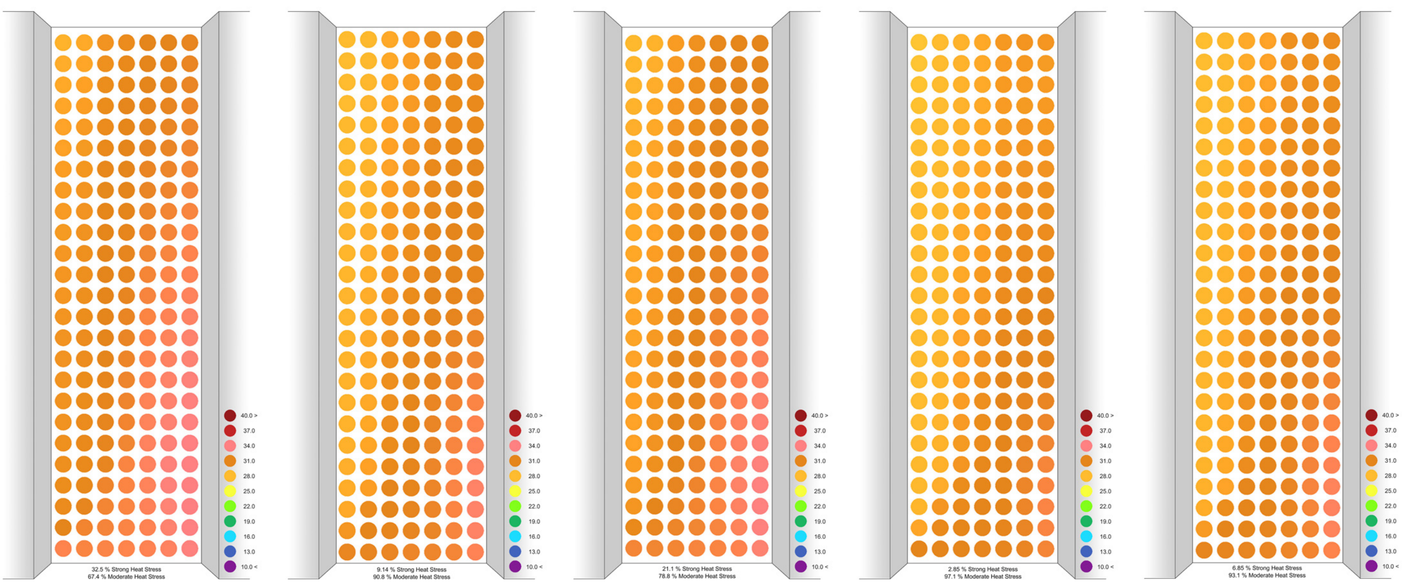


Figure 4.14
Mean radiant temperature for Point A & B for facade with exterior insulation.

final numbers of UTCI for the people walking on the sidewalks. Moreover, over the last years, driven by more stringent building codes and energy-saving measures, adding a layer of insulation on the exterior walls of the buildings as a refurbishment strategy has gained more and more popularity. In this study, as we see the highest MRT values were recorded for the wall construction with the insulation since the thermal mass effect of the material is minor and MRT during the day goes up to 61 °C. In this case, the reflected radiation from the facades can be absorbed by the ground and surrounding surfaces depending on the sky view factor. This could be the main driver for trapping the heat in the canyon during the day and keeping night temperatures relatively high which translates to an intensified nocturnal UHI (Figure 4.14).

The final step is to transform MRT values into UTCI numbers in order to quantify the effects of each material in terms of perceived temperature over the canyon. The maps are produced for a typical hot day at 2 pm. Heat stress probability over the canyon area is calculated using the UTCI metric. In all cases, the UTCI values are between moderate heat stress and strong heat

Figure 4.15
Universal Thermal Climate Index for different facade materials at 2 PM.



stress. Between the alternatives, concrete material with 80 percent of solar absorption has the least heat stress (2.8 percent); in contrast, the façade with exterior insulation and 30 percent solar absorption causes the most heat stress in the canyon with 32% over the street which is 11 times more than the brick wall (Figure 4.15). This comparison helps us to quantify how much the material choice of building skins can have a positive or negative contribution to the immediate surrounding environment, especially on the human thermal comfort. We can highlight from the findings that the effect of different façade materials is significantly smaller than the impact of the difference between solar absorption percentages on local mean radiant temperature values. Additionally, for the climate of Munich, the results show that light color walls with lower solar absorption are worse than dark color walls in terms of outdoor comfort during hot periods.

4.5 CONCLUSIONS

This chapter focused on the identification of a new method for estimating outdoor thermal comfort in urban environments, considering the relevant effects of urban form and materiality on the radiant environment and perceived temperatures. As echoed before, the early stages of urban design could be a promising area for addressing outdoor thermal comfort to have livable public spaces and promote walkability. However, the microclimate of the cities in the design process has thus far attracted minimum attention during the planning phase of cities due to the complexity and time-consuming simulation procedures [29]. This has been changing at a considerable pace where cities like London, are developing guidelines to better evaluate and quantify the impacts of new building design on the microclimate of their surroundings [30]. Additionally, the appearance of new simulation tools and workflows like Eddy3D [31] and Surfer [32] pave the ground to have more instantaneous feedback loops in urban design processes with validated models which can be a great benefit to estimate annual outdoor comfort conditions in urban environments.

As observed before in comparing the MRT values from two different modeling tools, there is a significant deviation, however translating those numbers into the perceived temperatures of UTCI, we can see that the effects are almost neglectable since they don't cause any thermal status shift but this might be different if we look to heat accumulation of subject walking outdoors. In fact, the effects of shaded and exposed areas are much more significant. Some may conclude that for early-stage evaluation or massing studies, a fast and reliable MRT modeling can put into evidence the problematic areas for the periods of the year with heat stress probabilities. However, for winter scenarios, a study on wind patterns would be necessary as well.

It should be mentioned, that the shading effect caused by the buildings is one side of the story as a passive contributor, on the other side we have trees as active modifiers of the radiant environment not only with shading but also including the evaporative cooling potentials and their seasonal behavior. As mentioned before, CFD tools would be the appropriate available solution to model such a domain, however, they won't provide long-term statistics on the microclimatic changes over time. This takes us to use transient tools for informing design not only with the data of a hot day or extreme week but with annual simulations. In this research domain, there is an urgent need to introduce a process-based numerical plant simulation tool to bridge the gap of vegetation modeling which can have the same resolution spatially and temporally with the transient simulation engines.

As discussed before, one of the main limitations of numerical process-based simulation tools like TRNSYS or EnergyPlus for outdoor comfort modeling is the integration of tree models in the simulation process. For this reason and as an essential need to develop such a model, next chapter demonstrates in detail the development and validation of the PANDO tool which bridges the gap for simulating longer periods of thermal comfort unlike the CFD-based tools including tree canopies..

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C H A P T E R F I V E

URBAN FORESTRY AND COMFORT OPPORTUNITIES

Summary

This chapter introduces a numerical process-based simulation tool (PANDO) that enables the user to model individual trees and canopies in the Rhino Grasshopper3D interface. This plugin simulates radiation fluxes and counts for photosynthesis and transpiration by tree canopies. PANDO can estimate root water uptake, drainage, canopy interception, and cooling potential of trees by coupling with outdoor thermal comfort models. The tool enables the user to plan and design urban greenery more efficiently in cities considering the benefits and future paybacks. The chapter continues with the validation and application of the plugin to model and quantify the benefits of urban forestry on annual pedestrian thermal comfort in 270 cities over the world.

5

Partial results of the presented work in this chapter have been published in:

Ata Chokhachian, Marion Hiller (2020): PANDO: Parametric Tool for Simulating Soil-Plant-Atmosphere of Tree Canopies in Grasshopper. SimAUD 2020, Society for Modeling & Simulation International (SCS).

5 URBAN FORESTRY AND COMFORT OPPORTUNITIES

5.1 INTRODUCTION

Trees are one of the critical components for cities to improve livability and health measures. Studies show that healthy and well-planted trees can mitigate the impacts associated with the built environment [1]. Over the last 30 years, the primary purpose of street trees has changed from an aesthetic role of beautification and ornamentation to one that also includes the provision of services such as stormwater reduction, energy conservation, and improved air quality [2, 3]. As an example, a recent report from Britain's Office of National Statistics estimates that trees saved the capital more than 5 billion pounds from 2014 to 2018 through air cooling alone. Additionally, by keeping summer temperatures bearable for outdoor workers, trees prevented productivity losses of almost 11 billion pounds as well [4]. Besides economic benefits, trees improve urban life and the microclimate of cities to a more enjoyable place to live, work, and play, while mitigating the city's environmental impact [5].

There is ample literature proving that trees in urban areas make significant economic, environmental, social, cultural, and spiritual contributions to the well-being of people [6-10]. The most recent review on the human health-related benefits of urban trees by Wolf, Lam [11] provides a comprehensive review of existing literature on the health impacts of urban trees that can inform future research, policy, and nature-based public health interventions. Accordingly, the primary benefits of trees are typically being investigated under three categories of environmental, economic, and social profits listed in Figure 5.1 with impacts on people, society, and the city itself.

Environmental Benefits	Slowing global climate change [12] Energy conservation potential [13] Better storm water management [14] Improved air quality and respiratory Condition reduction [11, 15] Lower summer air temperatures [16] Natural resource and biodiversity conservation [17] Healthy urban communities [18] Reduce exposure to Ultraviolet Radiation [11] Improve in mental health [19]
Economic Benefits	High return of investments [20] Increase property value [21] Community and business district appeal [22]
Social Benefits	Improved health [23] Crime prevention [24] Increase community engagement [25] Lower levels of fear [24]

Figure 5.1
Categorical benefits of urban forestry.

Starting from 2006 projected to 2040, several cities over the world committed to the "milliontrees" initiative. Metropolitans like; Los Angeles, Denver, New York City, Shanghai, London, Ontario, and Pune started planting one million trees aiming at increasing urban forest pointing at reduction of carbon dioxide in the air to reduce the effects of global warming [20]. Moreover, It has been already proven that there is a significant relationship between the amount of green space and trees in the public spaces and how people occupy and choose walking routes in daily commutes [26, 27]. As an example, Larsen, Gilliland [28] investigated the influence of the physical environment on the mode of travel finding that land use mix and presence of street trees were the only significant variables. The study highlights that the likelihood of walking or biking to school was positively associated with both increased land use mix and a greater number of street trees. Although land-use mix and population density should also be considered with regard to increasing rates of non-motorized travel, the study recommends that planting trees may be the most efficient and cost-effective environmental intervention to encourage walking to school.

Despite the amount of investment in tree planting, some may question the need for additional investigation on the benefits and future paybacks of such a service. Plus, there is a necessity for further empirical research in order to efficiently guide the design and planning of urban green space, and specifically to investigate the importance of the distribution and type of greening. Accounting for these effects requires proper modeling of vegetation, including vegetation physiology and phenology to estimate latent energy fluxes and the interactions between soil, vegetation, and atmosphere. Bowler, Buyung-Ali [29] suggests that the current research body does not determine exactly how urban greenery should be employed in terms of abundance, type, and distribution and therefore a suitable modeling tool is needed to provide solid quantitative assessments of the effectiveness of tree canopies in terms of heat mitigation for pedestrian outdoor comfort in urban environments. Such a tool can guide the process of effective tree planting in cities.

At the other end of the complexity spectrum, there are a number of models and tools, mainly based on computational fluid dynamics, that are able to resolve at a micro-scale the influences of vegetation on microclimate and outdoor thermal comfort [31-34]. However, their complexity and computational intensity put them out of reach for less specialized users, plus they lack providing annual simulation results which are fundamental for informing the urban planning design process.

Nice, Coutts [30] argues that there is a need for an approach that fits in between the two levels of complexity, a new innovative method to balance detail, accuracy, and complexity with efficiency and usability, while also being able to consider a wide variety of vegetation types and arrangements. To fill this gap, PANDO is developed based on MAESPA [35, 36], a process-based model, simulating fluxes of energy, water, and carbon at the tree and canopy scales. It is expected that the findings of this chapter would be useful for developing approaches for future planning and management of the urban tree canopies under different climates and urban configurations.

5.2 SOIL-PLANT-ATMOSPHERE MODEL

Numerical Process-based Simulation Models (PBMs) are one of the useful methods to incorporate the fundamental physical and eco-physiological processes (e.g., photosynthesis and transpiration) to estimate fluxes of energy, water, and carbon in the ecosystem, as a function of climate, soil, and plant characteristics. Also, they can be used as an effective tool to identify interactions between environmental drivers, plant and canopy structure, leaf physiology, and soil water availability and their combined effects on water use and carbon uptake [37].

There are different approaches to model trees in terms of complexity and scale. The two-dimensional multi-layer models (AMBETI) [38] are limited since they consider the interception of light from only a single direction which ends up underestimating the transpiration and photosynthesis rates [39]. Therefore, three-dimensional tree-scale models are more accurate and appropriate to simulate the radiation transfer and soil-plant atmosphere [40]. One model that uses voxels to make the required trade-off between computation time and precision is MAESPA [35]. The model is a coupling of a) the tree-scale light interception and ecophysiology model MAESTRA [36, 41], and b) the soil and ecosystem water and energy balance SPA [42]. MAESPA occupies a very interesting niche in the PBM complexity continuum, between the complex, detailed 3-D models [31] and the less-detailed multilayer models [43]. Thus, MAESPA is a suitable candidate for addressing the effects of climate change upon horizontally heterogeneous tree canopies.

5.2.1 MAESPA Model Evolution

MAESPA (https://maespa.github.io/bibliography.html) has a long development history, dates back to the work of John Norman and Paul Jarvis in the 1970s and 80s which later further developed by Wang [44] know as MAESTRO. In 2004 Medlyn [41] revised the model, with the purposes of modularizing the code to make the program easier to understand and modify. She also incorporated standard formulations of leaf gas exchange and called the model MAESTRA. In 2008, Duursma and Medlyn [35] developed an individual tree-based model named MAESPA largely based on combining the MAESTRA and SPA [45] ecosystem models. The collective model includes a hydraulically-based model of stomatal conductance, root water uptake routines, drainage, infiltration, runoff, and canopy interception, as well as detailed radiation interception and leaf physiology routines from the MAESTRA model. In 2018, Vezy, Christina [46] modified the MAESPA model to add calculation of foliage surface water evaporation at the voxel scale, computation of an average within-canopy air temperature, and vapor pressure, and use of iterative calculations of soil and leaf temperatures to close ecosystem-level energy balances. In the modified version, each tree in the canopy is described individually and can have different sets of physiological and structural parameters; for instance, according to each tree species, age, and size. MAESPA simulates the foliage light absorption, photosynthesis, soil evaporation, transpiration, and balances of water and energy. The coupling with SPA model allows a precise computation of soil water balance and plant hydraulics, so that stomatal conductance can respond to leaf water potential.

5.2.2 MAESPA Radiation Model

In MAESPA, the foliage energy balance is computed at the voxel scale for each tree. Each voxel contains a given amount of leaf area within a tree, which has a set of homogeneous properties such as leaf inclination angle distribution, optical properties, and photosynthetic parameters controllable over different layers on the tree height (Figure 5.2).

The net radiation of each voxel is computed from the light interception sub-modules in three spectral domains which are: Photosynthetically Active Radiation (PAR), Near Infrared (NIR), and the thermal domains illustrated in Figure 5.3 taking into account the dynamic leaf area over the year with hourly resolution. The light interception submodule takes into account the 3D representation of the stand, in which each tree is located according to its x,y,z coordinates, and characterized by its height, crown length, radius, shape, and total leaf area [46].

The initial radiation routines are described in detail by Wang and Jarvis [36]. The canopy consists of individual tree crowns, which are described

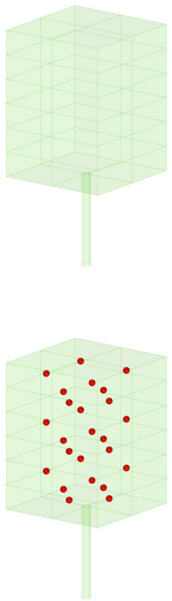


Figure 5.2
3D representation of tree geometry in MAESPA showing the voxels and sensors points.

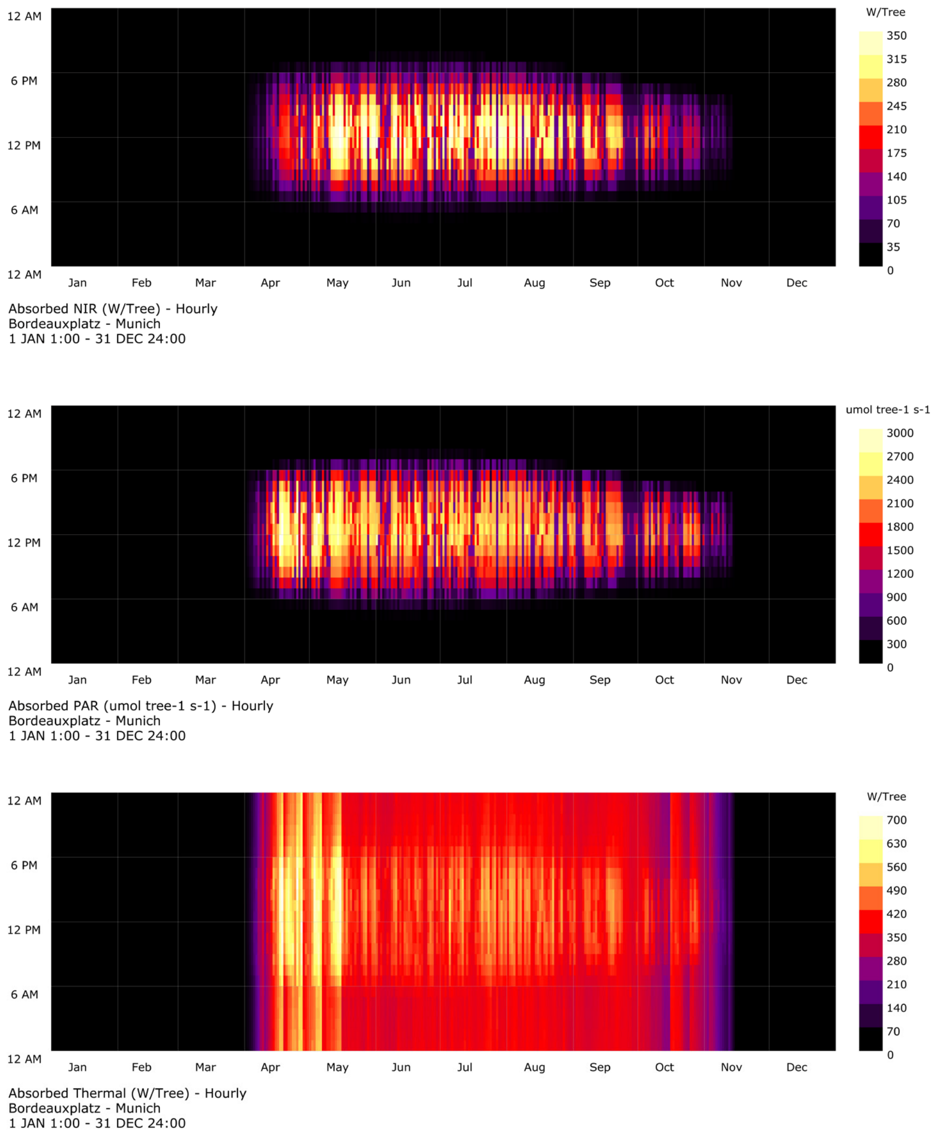


Figure 5.3
Annual radiation spectrum (NIR, PAR and Thermal) with dynamic Leaf Area Index.

by a basic shape, length, height, and width. Radiation calculations can be performed for the entire canopy or only for a set of target crowns specified by the user. The points in the voxels are used to calculate radiation domains based on shading within the crown and by neighboring trees, the location of the sun, and whether radiation is direct or diffuse. The scattering of radiation is approximated following the method described in detail by Norman [47]. Leaf area within crowns is assumed to be distributed randomly or to follow a beta distribution in horizontal and/or vertical directions [48]. At each grid point, the leaf area is separated into sunlit and shaded leaf areas [49], and the coupled stomatal conductance and photosynthesis model is run separately for each fraction.

5.3 PANDO DEVELOPMENT

PANDO is a parametric tool scripted in python for Grasshopper3D, a visual programming interface that runs within the Rhinoceros CAD application. The Tool comes with input and output components that prepare the input files directly from Rhinoceros for MAESPA and import the results back for visualization. The workflow consists of components to generate tree geometries, weather data, water balance, and simulation setup (Figure 5.4). After running the simulation, PANDO reads the results back to visualize a wide range of hourly or daily outputs including absorbed, transmitted and reflected radiation fluxes; transpiration; sensible heat fluxes; leaf photosynthesis rates; water potential; CO2 concentration, and Leaf temperatures all in a single tree or canopy scales. There is also an optional input for extracting total PAR, scattered PAR, diffuse transmission, sunlit area, and direct beam fraction for sensor points under the tree to quantify annual dynamic variations on a grid resolution. Figure 5.5 shows on each point the fraction of exposure to direct sun on 9th of August at 2 PM.

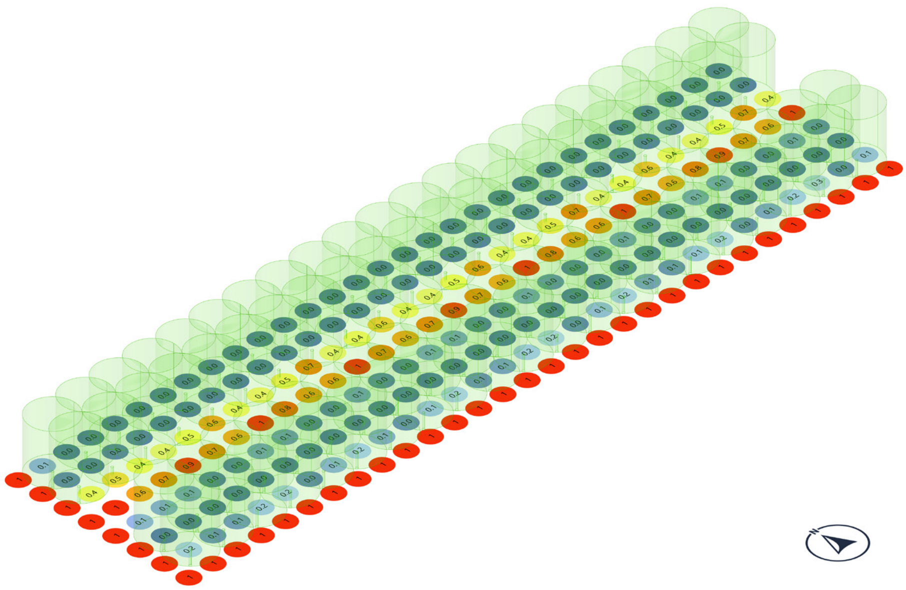


Figure 5.5
Sunlit fraction mapped on each grid point between 0 and 1.
1 = fully exposed, 0 = fully blocked by the tree

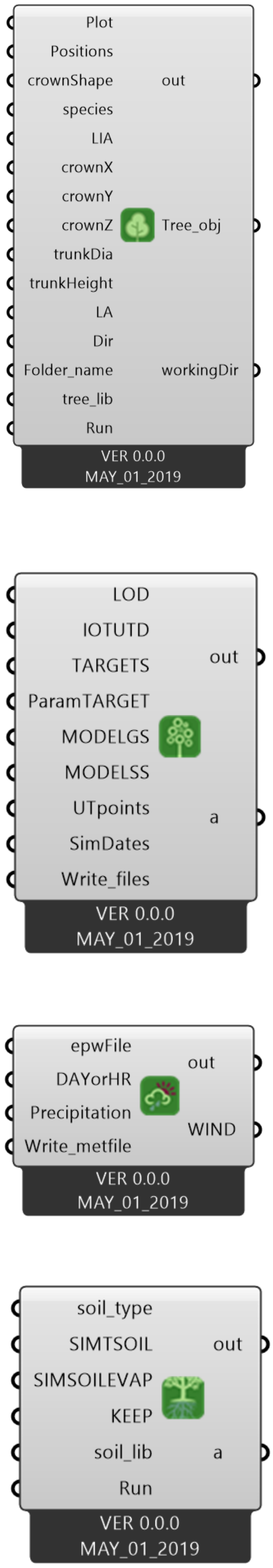


Figure 5.4
Grasshopper components of PANDO.

5.3.1 Geometry and Structure Settings

In PANDO the user can customize the tree canopy with the tree geometry component in terms of shape, size, species, and leaf area parameters. Each of these settings can be assigned separately for each tree geometry or uniform for the entire canopy. The component transforms the geometric inputs from the CAD environment into data files including the location coordinates, crown and trunk size, and leaf area parameters. In the tree structure settings, the user can choose between different predefined shapes including conical, half ellipsoidal, paraboloid, full ellipsoid, cylinder, and box for the crown shape (Figure 5.6). For the leaf angle distribution which is an input for the radiative transfer calculations, the options are uniform for the entire canopy or a ratio of horizontal and vertical distribution.

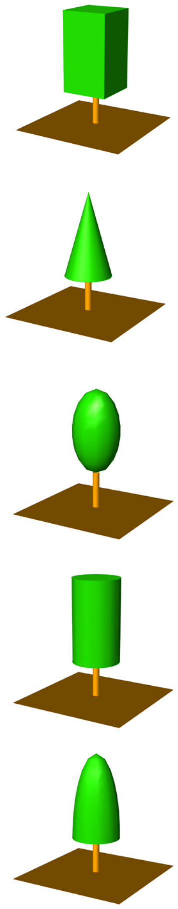


Figure 5.6
Optional tree geometries for canopies.

5.3.2 Weather Data

This file contains meteorological observations that drive MAESPA including location information, atmospheric pressure, temperature, radiation, and humidity. PANDO converts the commonly used TMY file formats into meteorological files readable by MAESPA. The input file can be in hourly or daily time steps. The precipitation rates can also be separately included for accurate estimation of soil water content.

5.3.3 Phenology Model

One of the main challenges of modeling tree canopies is to estimate the seasonal behavior of trees. This was crucial since one of the main objectives of this study was set to simulate and estimate the benefits of urban greenery in annual cycles. Thanks to MAESPA's phenology model [50] the user can define the flushing date and the number of days from the flush date to the end of the first flush, end of the second flush, the start of leaf senescence, and end of leaf senescence to create a dynamic leaf area index for the canopy.

Since finding these numbers might not be straightforward, the developed component generates these numbers based on the input weather file using average daily temperatures to estimate the flushing date and start of leaf senescence automatically. Using the provided inputs, the model will generate an annual variation of leaf area which is used by MAESPA to estimate the radiation, evaporation, transpiration, and photosynthesis fluxes. Figure 5.7 shows dynamic annual Leaf Area Index (LAI) modeled for Bordeauxplatz in Munich.

Figure 5.7
Annual Leaf Area Index (LAI) variations based on the phenology model.

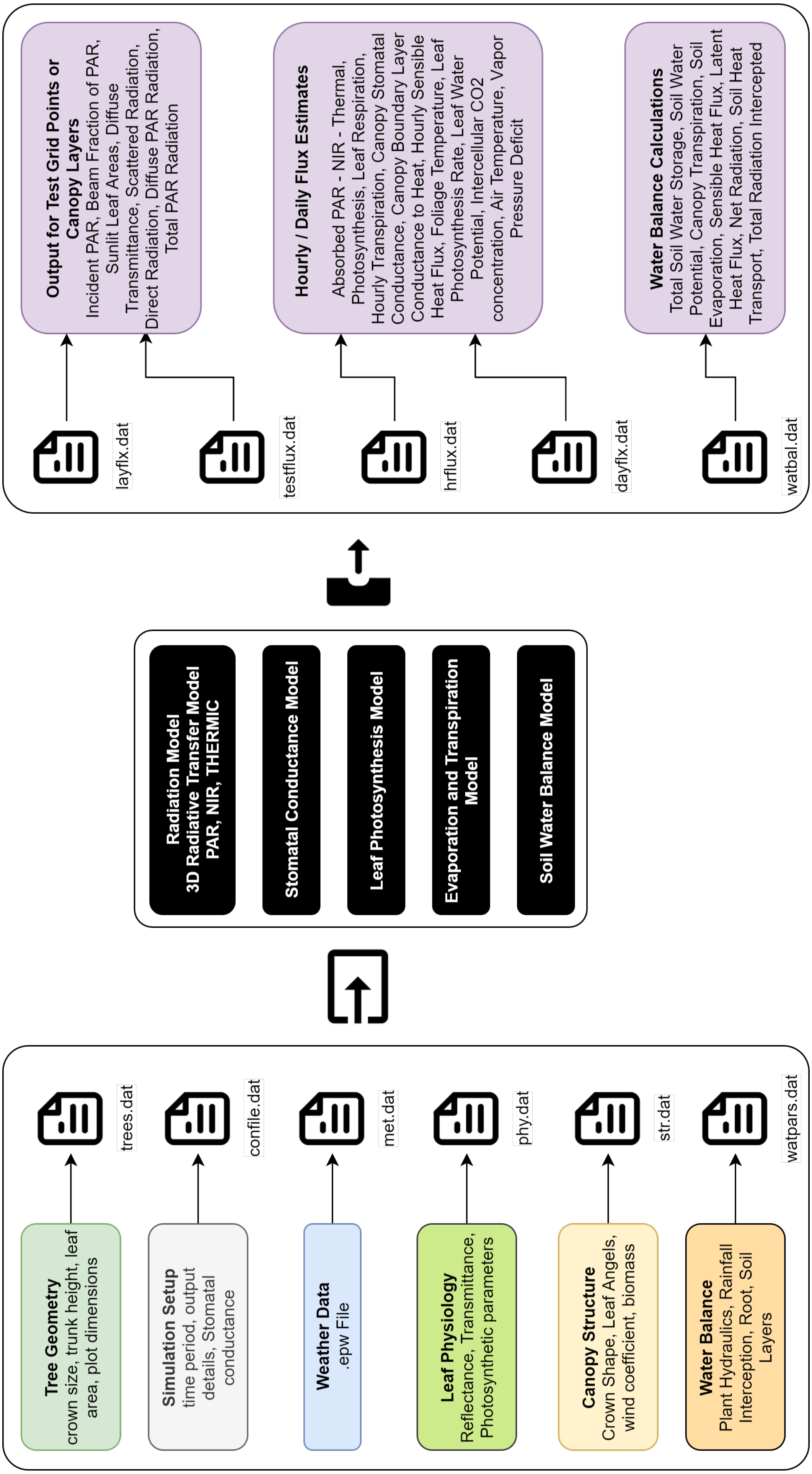


Figure 5.8
The workflow of input and output files in PANDO.

5.3.4 PANDO Tree Templates

The parametrization of the MAESPA model for a non-expert user can be fairly complicated. To foster this problem, PANDO comes with tree and soil templates in JSON file format. The user can import the templates from the library based on the desired plant species. The plant template files include information about leaf physiology, leaf transmittance and reflectance, stomatal conductance, Quantum yield of electron transport, and day respiration rates. The user can also modify and update the parameters and generate custom templates as well.

Figure 5.8 illustrates the overall workflow of the tool including the brief definition of the input parameters and files, different sub-models of simulation, and the list of the outputs in detail.

5.4. MODELING THE RADIANT ENVIRONMENT

Mean Radiant Temperature (MRT) is one of the main components to estimate the thermal impact of the built and natural environment on pedestrian thermal comfort [51]. MRT modeling integrates exposure to shortwave and longwave radiation in a three-dimensional environment assuming that the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure [52]. To calculate MRT the process is divided into shortwave fluxes (direct, diffuse, and reflected solar radiation) and long-wave radiation (urban surfaces, trees, and sky). The modeling process for each component is explained below in detail.

5.4.1 Solar Radiation

To accurately represent the contribution of direct and diffused short-wave solar radiation in the MRT model, these values are simulated. For the direct radiation component, analysis nodes were used as an input for radiance to raytrace these components using Daysim's hourly irradiation method in the Rhino Grasshopper3D environment. Daysim uses solar radiation data input from a weather station, which is typically reported as global horizontal radiation that is split into direct normal irradiance and diffuse horizontal irradiance. The output is hourly radiation for each analysis node. For the longwave domain, sensors are used as input for Radiance to send spherical rays out from each sensor to all surrounding surfaces. This means that the sensor is attempting to detect the first surface each ray hits. Using this method the view factors are computed based on the number of rays that hit each surface. Having the surface temperatures and the view factors, the longwave radiation is estimated by equations 1 and 2. Consequently, the MRT component is then calculated for each hour of the year based on the Stefan-Boltzman law using equations 3 to 5 [53-55].

$$E_i = \varepsilon_i \sigma T_i^4 \qquad (1)$$

$$mrt_{diff} = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(E_i + a_k \frac{D_i}{\varepsilon_p}\right)F_i\right]^{0.25} \qquad (2)$$

$$mrt_{dir} = \left[f_p a_k \frac{I}{\varepsilon_p \sigma} \right]^{0.25} \quad (3)$$

$$f_p = 0.308 \cos \left[\gamma \left(1 - \frac{\gamma^2}{48402} \right) \right] \quad (4)$$

$$mrt_{lw} = \left[\sum_{i=1}^{n} e_i T_i F_i \right]^{0.25} \quad (5)$$

Where: E_i = Long-wave radiation, T_i = Surface temperatures (i = 1 to n), ε_i = Surface emissivity, F_i = View factors, D_i = Diffuse short-wave radiation, ε_p = Emission coefficient of the human body (standard value 0.97), a_k = Absorption coefficient of the irradiated body surface area of short-wave radiation (standard value 0.7), σ = Stefan–Boltzmann constant (5.67×10^{-8} W/m^2K^4), I = Radiation intensity of the sun on a surface perpendicular to the incident radiation direction, f_p = Surface projection factor, γ = Sun elevation angle in degrees.

For trees, the radiation intercepts differently compared to solid objects in the urban environment. They prevent incident shortwave and longwave radiation arising from the context reaching pedestrians and nearby surfaces. As incident radiation reaches the tree canopy, a certain amount is blocked until the radiation passes through. The ratio of intercepted energy is calculated using equation from Park, Lee [56]:

$$Tree\ intercepted\ fraction = 1 - exp\left(-K_{bs} \Omega LAD \frac{w}{x} \right) \quad (6)$$

Where K_{bs} is the extinction coefficient of the leaves (assumed 0.5 for this study) and Ω is the clumping factor ranging from 0 (clumping leaves) to 1 (random distribution) to generate differences in the probability of radiation being intercepted [57], and w, x is the distance between tree and crown size respectively. The tree canopy is simplified as a box, and the dynamic leaf area density (LAD, m2 /m3) and clumping factor of each tree layer are defined as having values of 1. Assuming a spherical leaf angle distribution, the extinction coefficient is set at 0.5 [58].

5.4.2 Sky Temperature

Sky temperature is also one of the main drivers to accurately estimate the radiant temperatures, especially at night. Kasten and Czeplak [59], in 1980, developed a cloudy sky emissivity model based on a Cloudiness Factor (CF). This factor ranges between 0 and 1, from a clear to a completely overcast sky. This model was developed after 10 years of measurements of sky heat flux, from 1964 to 1973. Their study is based on hourly data of solar and terrestrial radiation, aiming at calculating the cloudiness effects. If weather data do not include the cloudiness factor of the sky, it can be determined according to the following equation:

$$CF = \left(1.4286 \frac{G_{dif}}{G_{Glob,H}} - 0.3 \right) \quad (7)$$

Where G_{dif} is the horizontal diffuse radiation and $G_{Glob,H}$ is the total horizontal radiation. For this study the effective sky temperature is determined by Martin and Berdahl [60]:

$$T_{sky} = T_{amb}\left[\varepsilon_{sky} + 0.8\left(1 - \varepsilon_{sky}\right)CF\right]^{0.25} \quad [K] \qquad (8)$$

Sky emissivity is also calculated based on dew point temperature by the equation of Duffie, Beckman [61]:

$$\varepsilon_{sky} = 0.7122 + 0.0056 \times T_{dew} + 0.000073 \times T_{dew}^{2} \times 0.00884 \qquad (9)$$

5.4.3 Surface Temperature of Ground

To estimation of the long-wave radiation flux density emitted by the solid surfaces like ground, the surface temperatures are calculated based on equations from Matzarakis, Rutz [51]:

$$E = \varepsilon.\sigma.T_s^4 + (1 - \varepsilon).A \qquad (10)$$

$$T_s = T_a + \frac{Q + B}{(6.2 + 4.26\,.\,v_{wind}).\left(1 + \frac{1}{B_0}\right)} \qquad (11)$$

Where Q is net all-wave radiation flux density, the soil flux with the condition of B=-0.19Q if Q>0 and B=-0.32Q if Q<0, V_{wind} is wind velocity, and the Bowen ratio as B_0 for heat transfer.

The final step after having all the surface temperatures and radiation fluxes is to calculate the mean radiant temperature for each node with the following equation:

$$T_{mrt} = \left[mrt_{lw}^4 + mrt_{diff}^4 + mrt_{dir}^4\right]^{0.25} \qquad (12)$$

Following the explained methodology, for the longwave fluxes, the surface temperatures are estimated based on air temperature, wind velocity, net all-wave radiation, and Bowen ratio from the sky and the ground. The average leaf temperature is simulated using the PANDO model over the tree profile on an hourly basis taking into account the seasonal variations of the LAD. Figure 5.9 shows a daily variation of radiation fluxes and surface temperatures for a typical hot day in the city of Munich. The leaf temperatures are slightly higher during the day compared to nighttime since they're averaged over the canopy profile for each hour.

Having radiant fluxes from the adjacent surfaces, based on the view factors from the body position, the MRT component is calculated for each hour of the year. In the next step, using the annual hourly MRT values with local wind speed, air temperature, and humidity, the perceived temperatures

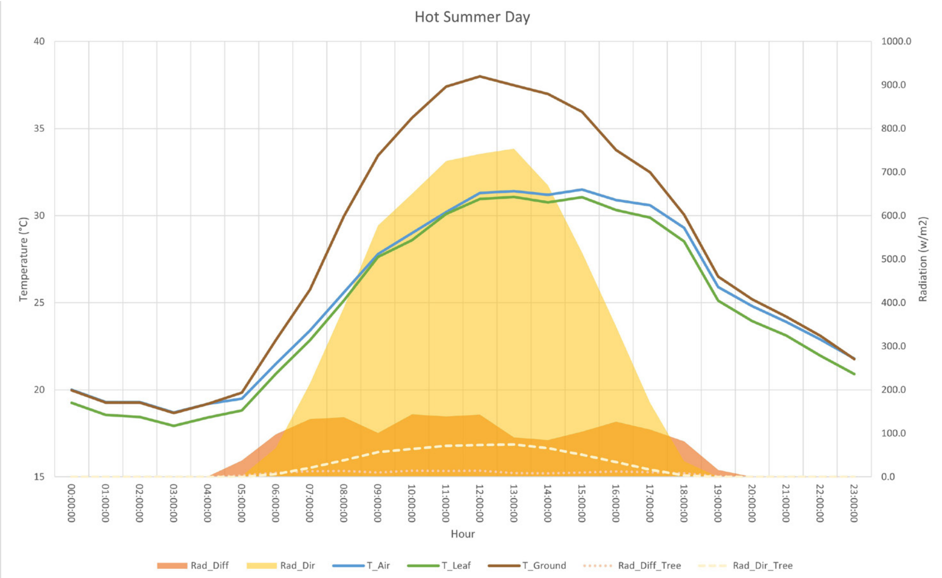


Figure 5.9

Hourly variations of radiation fluxes, air, leaf and ground temperature for a hot summer day in Munich.

are estimated for a person with two scenarios of being fully exposed to the sun and standing under the tree. The UTCI results for the case of Munich show significant improvement by decreasing the strong heat stress from 16.9 % to 3.9 % over the year due to the shading effect and cooling potential of the leaves caused by lower surface temperatures. Also, a considerable improvement (8 %) is notable in the comfort band of UTCI ranging between 9 to 26 °C (Figure 5.10).

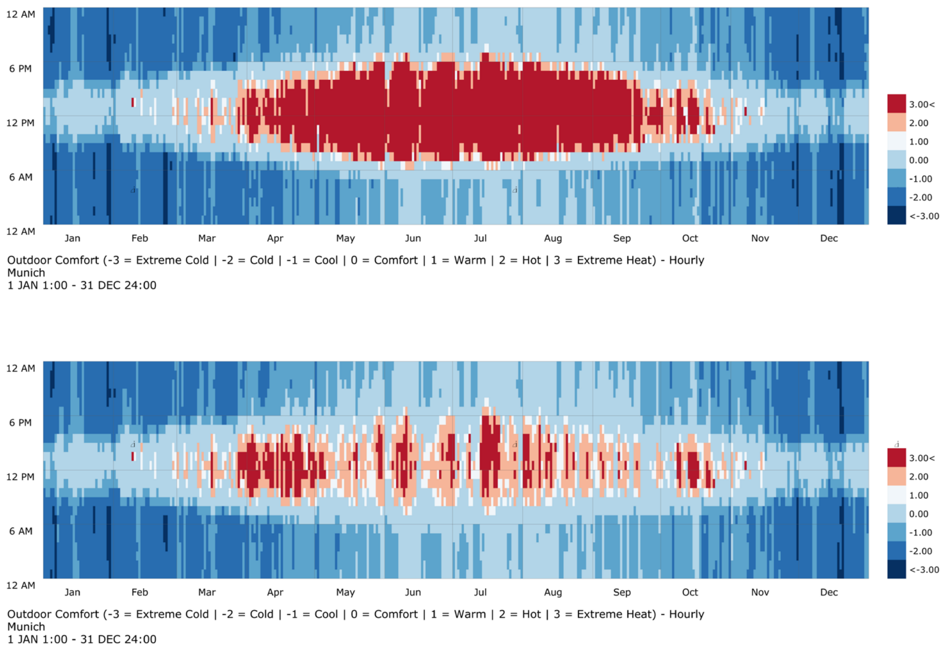


Figure 5.10

Comparison of the annual perceived temperatures (UTCI) exposed (top) and under the tree (bottom).

5.5 MODEL VALIDATION

Radiation is one of the main drivers for simulating reliable energy balance in process-based models. For this reason, this thesis has conducted two separate validation experiments. The first one was used to confront the Photosynthetically Active Radiation (PAR) values with in-situ measurements and the second one was designed to validate the estimated MRT values for two measurements points of an exposed and shaded by trees.

5.5.1 PAR Validation

The simulated PAR values of PANDO are confronted with on-site measurements obtained from previously published research by Rahman, Moser [62]. The experiment was done in the city of Munich in Bordeauxplatz as an open green square with an avenue canyon running from North to South. The site has four rows of T. cordata trees of the approximately same age. Two rows each were planted on the two sides of a pedestrian walkway on each side of the square. Table 5.1 summarizes the morphological parameters of the trees in Bordeauxplatz used for parametrization of the PANDO simulation model [63].

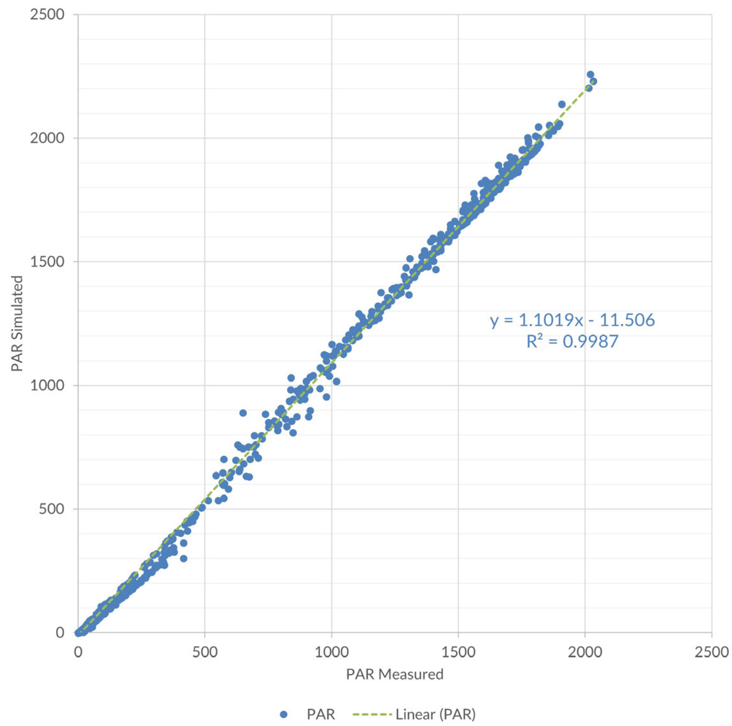


Figure 5.11
Confronting measure and simulated PAR values from August 5th to 15th.

Table 5.1: PANDO parametrization for tree geometries.

Parameter	Unit	Value
Age	Years	40±20
Crown Projection Area (CPA)	m^2	62.2±0.4
Crown radius	m	4.46±0.03
Crown surface	m^2	670±24
Crown volume	m^3	290±26
Diameter at Breast Height (DBH)	cm	28.7±0.76
Height	m	14.9±0.29
Leaf Area Index (LIA)	m^2 / m^2	2.3±0.28

The measured PAR values were collected using a PQS1 sensor (Kipp & Zonen, Delft, The Netherlands) installed on top of a 3.3 m street lamp post by a 3.5 m cross arm, 2 m outward from the lamp to avoid the influence of lamp and shade of the nearby trees and buildings. The data were recorded continuously at a 15-min resolution from August 6th to October 13th, 2015. Figure 5.11 shows the confrontation of measured and simulated PAR values with 15 minutes intervals from 5th to 15th of August 2015. The results show a high correlation between simulated and measure Photosynthetically Active Radiation with a squared correlation coefficient of 0.99 over the study period.

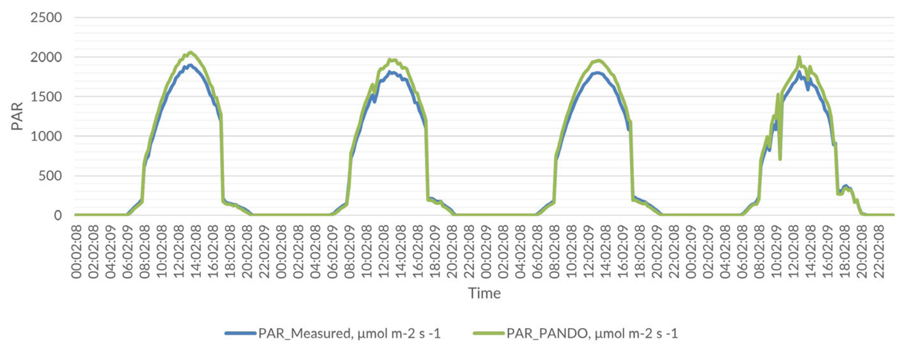


Figure 5.12
Line graph of measured and simulated PAR between 5th to 8th of August (15 minutes interval).

Comparing the hourly values in Figure 5.12 shows that the simulation model overestimated the daily peaks up to 230 µmol/m2/s around the noon. The PANDO weather file input should normally have direct and diffused radiation fluxes separately, however, the measurements only had the global radiation. This input is separated by the radiation model into direct and diffused automatically and this simplification could be the reason for overestimation of the output PAR values.

5.5.2 MRT Validation

The second validation experiment was designed to approve the simulated MRT values as one of the main influential variables on human perceived temperature. The experiment took place on August 9th, 2019 in Bordeauxplatz, Munich. For outdoor comfort data collection, the experiment setup with sensors and data loggers explained in section 3.3.1 was used. Two sets of static stations were located in selected points of the plaza with different microclimatic conditions. The first point was fully exposed to the sun and neighboring building and the second one was under the tree canopies. Figure 5.13 pinpoint the exact location of each measurement point. The experiment period was 13 hours from 6 AM to 7 PM.

For a day with similar weather conditions, a simulation model was set using PANDO workflow to estimate the MRT values for both scenarios. Figure 5.14 illustrates the correlation graph between the measures and simulated MRT for the selected points of interest. The values for the exposed point show a high correlation with R^2 of 0.95, however, for the other point under the trees, the correlation tends to be slightly lower with an R^2 of 0.78. The reason for this could the immediate variations of solar radiation under the trees because of their porosity and movement of the leaves. But generally, the hourly differences were always between 1 to 4 K under the trees.

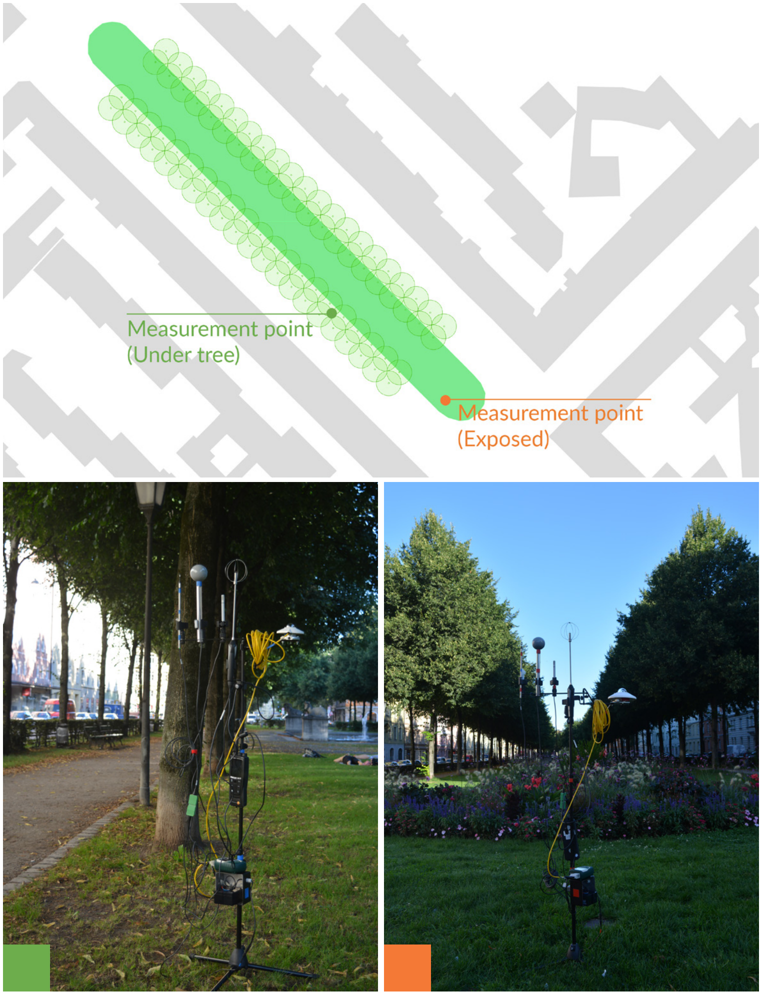


Figure 5.13
Measurement points for two scenarios of exposed and shaded by trees in Bordeauxplatz, Munich.

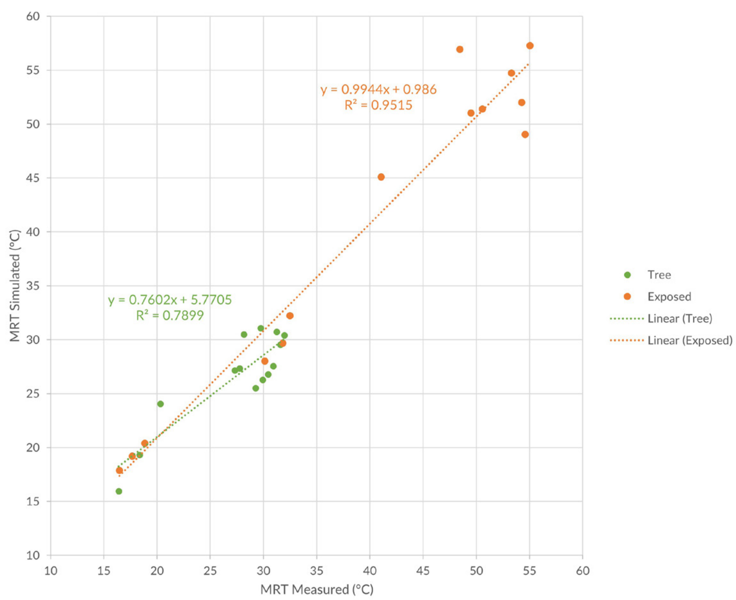


Figure 5.14
Scatter plot correlation graph for two measurement points.

In concrete terms, the correlation results show the reliability of the PANDO tool in estimating the shading and cooling effects from tree canopies on the surrounding radiant environment and mean radiant temperatures.

As mentioned before, one of the main aims of this approach is to demonstrate where and to what extend trees can improve outdoor thermal comfort and give pedestrian comfort opportunities. For that reason, the explained workflow is upscaled over the world map to see the potential of urban forestry benefits in a bigger picture.

5.6 WORLD MAP OF COMFORT OPPORTUNITIES

Heat stress in urban areas is the physiological heat load enforced by the outdoor environment on the human body which correspondingly reacts via different physiological responses, such as sweating, to maintain its core temperature within certain boundaries. Studies to quantify and map heat stress have a long history in the urban climate research field. The distribution patterns of heat stress using the comfort index in the world, was first time introduced by Terjung [64] in 1968 where he mapped for each month the psychological sensation of the average person in terms of temperature and humidity (Figure 5.15). In his study, he categorized the effective temperatures, modified by wind chill, and applying an arbitrary correction for solar radiation by decreasing wind chill by 200 kcal/m^{2}hr^1 for every hour of bright sunshine.

Five years later, Landsberg [65] criticized the work of Terjung pointing out that the results neither have the merit of generality as the preceding ones nor do they represent the detailed data ensemble, which can only be reflected through the use of simultaneous values of meteorological elements, and summarized from discrete hourly observations. He published the map of effective temperatures and clothing chart based on climatic criteria as an attempt for bioclimatic classification and he provided charts for people working outdoors.

Since then, several studies with different models and metrics have tried to create a bigger picture of global bioclimatic patterns. Those maps and datasets are relevant and applicable for public health applications ranging

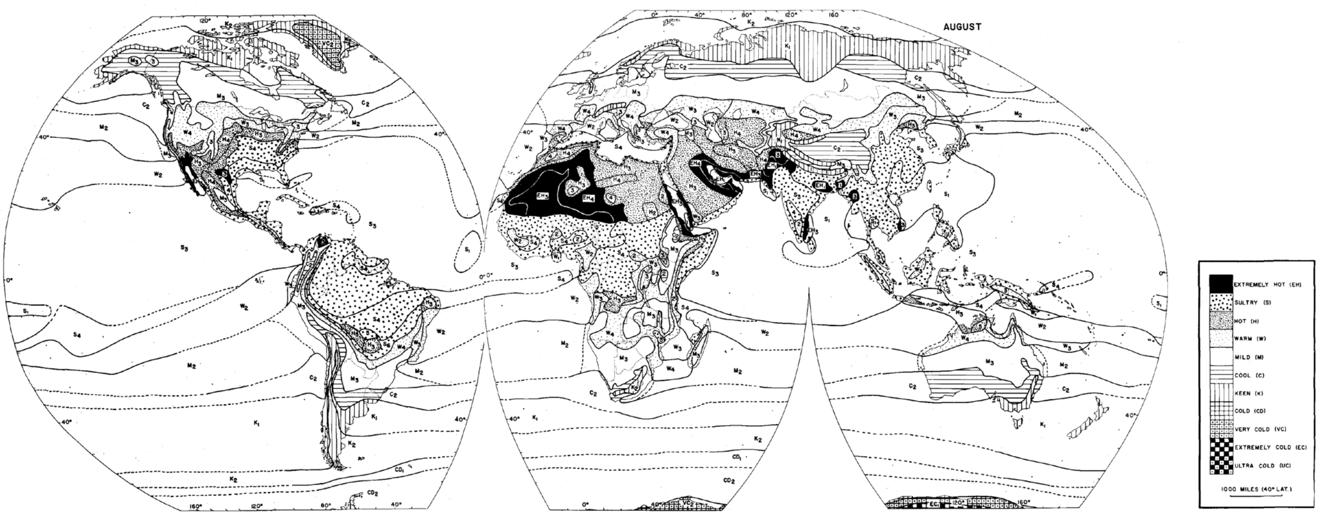


Figure 5.15
Comfort Index map for August, from Terjung [64].

from epidemiology, with the identification of health impacts (i.e. mortality) in relationship to thermally hazardous events, to tourism. As an example, a study on using global maps for prediction of wildfire and heat stress (UTCI) to improve evidence-based decision making, proposes a new spatial layers that can make suggestions on how these maps could be used in the context of a Multi-Hazard Early Warning System. This could be beneficial for disaster risk reduction and emergency response management in cities to identify hot spots [66,67].

Furthermore, a study done by Di Napoli, Pappenberger [68], using 38 years of meteorological reanalysis data, projected UTCI maps to assess the thermal bioclimate of Europe for the summer season. Their findings demonstrate that there was an increase in heat stress up to 1 °C during recent decades and it correlates with mortality data from 17 European countries. The study revealed that the relationship between UTCI and death counts depends on the bioclimate of the country, and death counts increase in conditions of moderate and strong heat stress which translates to UTCI between 26 and 32 °C. These UTCI ranges are also used in this chapter to filter the number of hours over the year with the risk of heat stress for each city as a threshold. The reduction percentages of heat stress can quantify the potential of urban forestry to mitigate local heat stress for the pedestrians in different cities and climates.

Another study at the intersection of health and heat stress in cities, done by the same researchers, demonstrates the verification of heat stress thresholds for urban health. The study proves the detrimental effect of prolonged high heat stress (at day and nighttime) and suggests the daily minimum and maximum heat stress levels equal to or above corresponding UTCI 95th percentiles (15° ± 2°C and 34.5° ± 1.5°C, respectively) for 3 consecutive days correlate to periods of excess mortality. They conclude that this threshold can be used as a health-meaningful metric for a potential heat-health prediction system in urban areas [69]. Since this metric gives a better picture in terms of the frequency of heat stress events, it is applied in this study as well. Figure 5.16 shows a comparison graph of two cities, Munich and Paris for the month of August. The red line shows UTCI values

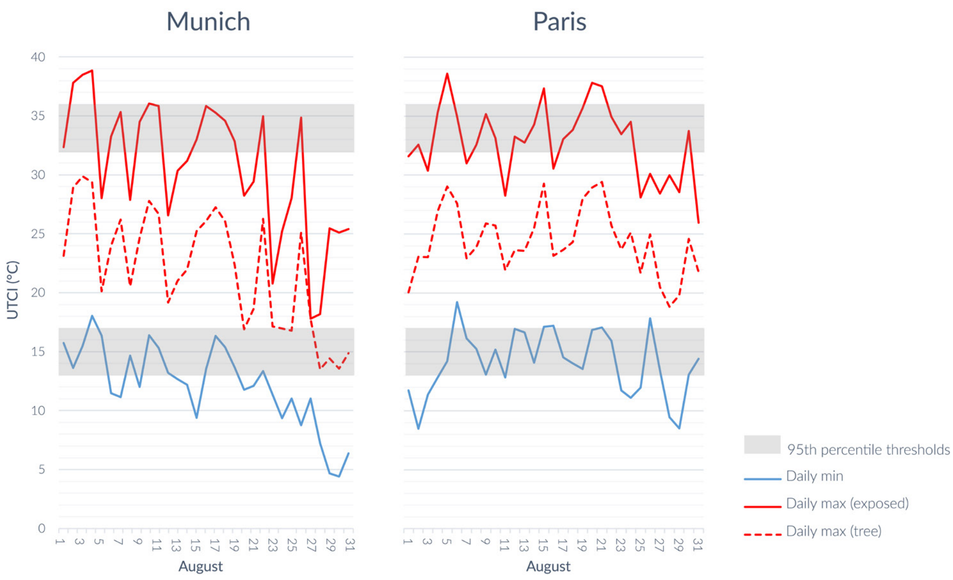


Figure 5.16
Time series of daily minimum and maximum UTCI values in August.

for an exposed person and the numbers go over the 95th percentile for more than 3 consecutive days which means there is one heat stress risk for Munich but for the case of Paris, this happens 3 times in August. The dash lines show the case for a person walking or sitting under the tree and the idea is to quantify how many times the heat stress risk can be avoided by the shading and cooling effect of trees. This doesn't mean that people will constantly walk under a tree canopy however, it is more useful to identify in which cities there is more potential for tree planting as a mitigation strategy to create a cold spot for people to recover from heat stress. Additionally, the UTCI 95th percentile metric besides the one with heat stress reduction percentages would be useful to see the benefits of urban forestry in a bigger picture and connect it to urban health.

Following the concept of understanding climate change from a global analysis of city analogs, the dataset published by Bastin, Clark [71], projects the future climate of the cities for 2050 expressing that 77% of future cities are very likely to experience a climate that is closer to that of another existing city than to its own current climate. Using the same cluster of cities and implementing the developed and validated workflow for modeling the tree canopies, this study projects annual perceived temperatures using UTCI index for two scenarios of a person fully exposed and shaded under the tree canopy to see the improvement potential in different cities, since trees are one of the effective components of urban planning to enhance livability and health.

To project the comfort potential of urban forestry, the workflow is applied on 270 cities modeling UTCI for both scenarios. There are generally two methodologies that are usually adopted to derive predictions for heat stress levels: one is based on the number of events that daily temperatures go beyond a certain threshold, and the other is based on the analysis of the probability distribution over the year between certain hours. This study employs both metrics (heat stress percentages and UTCI 95th percentile) and the results included the daytime period between 6 to 18 when the most public outdoor activities are happening. The projected maps could be beneficial to find the spots with a high risk of heat stress exposure and estimate how much trees can save us from the heat exposure (Figure 5.17). As a comparison reference, Figure 5.18 illustrates the global potential tree cover that has the possibility for restoration or plantation by 2050 retrieved

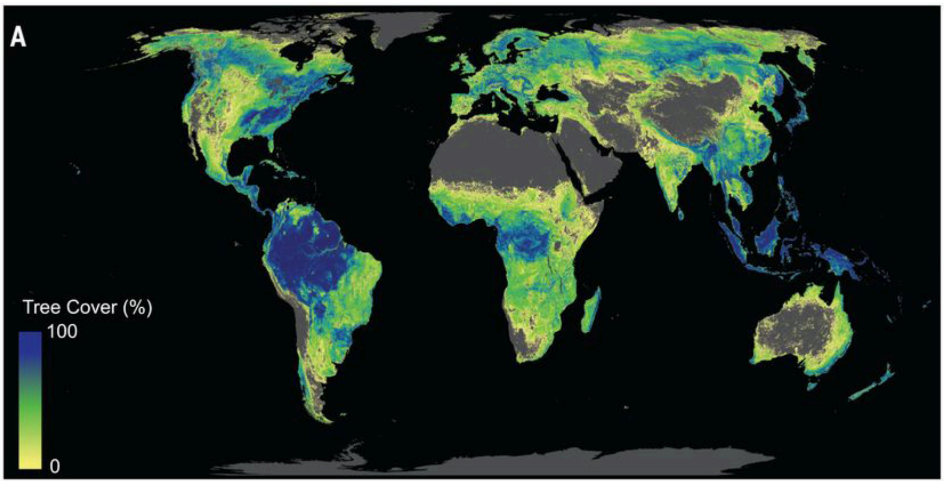


Figure 5.18

The global potential tree cover representing an area of 4.4 billion ha of canopy cover distributed across the world [68].

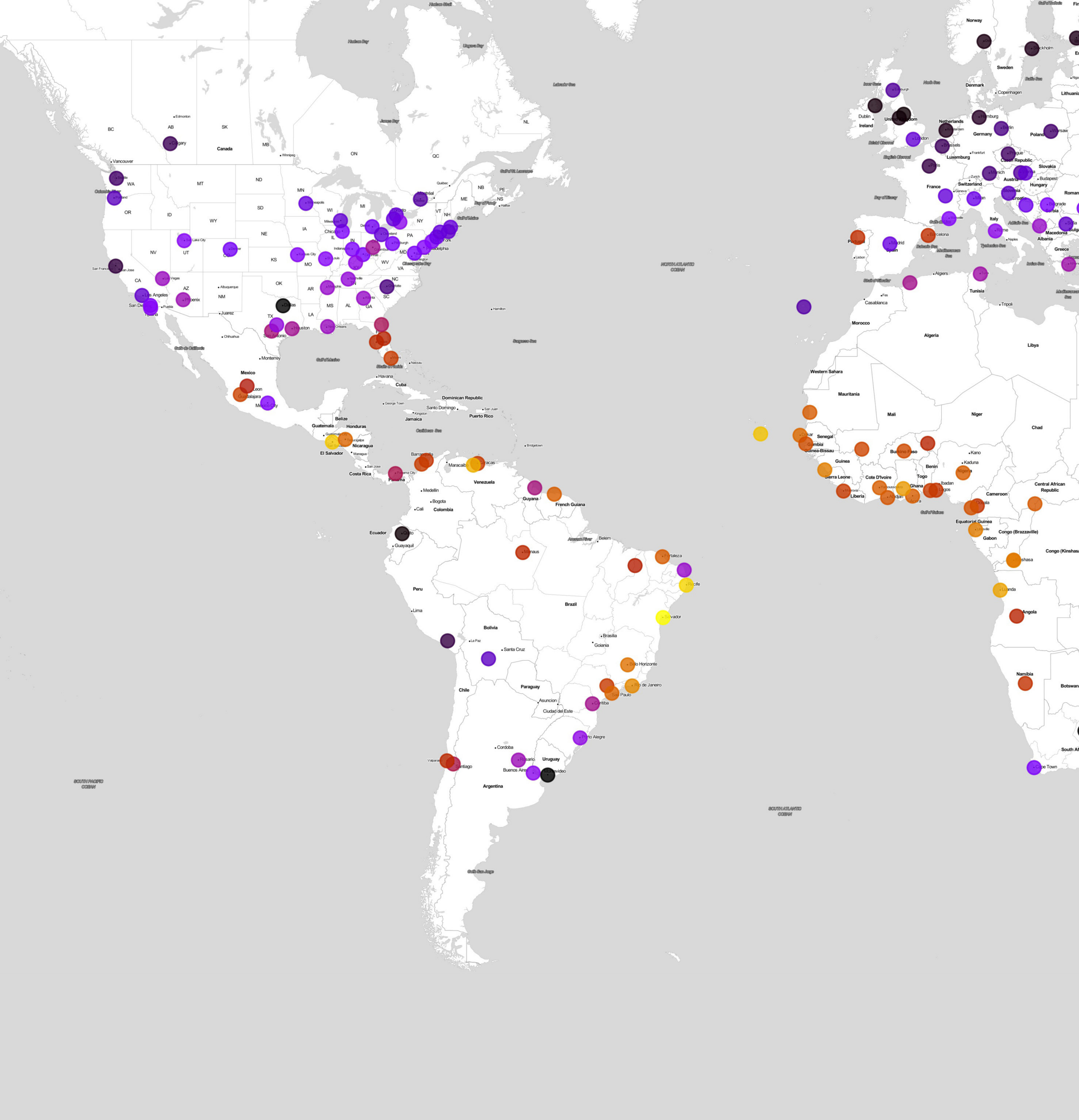
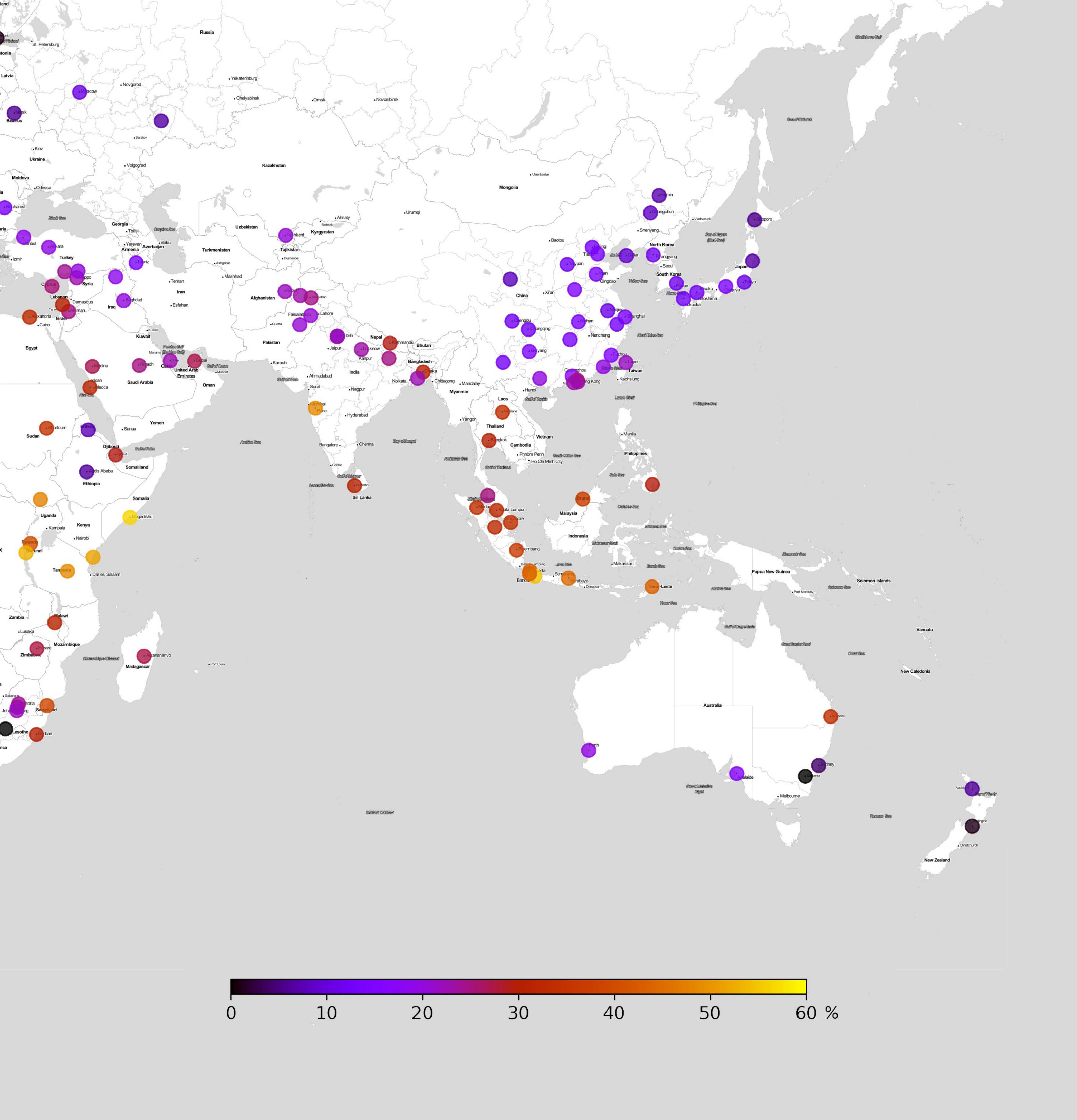


Figure 5.17
Percentage of time over the year that trees save pedestrians from heat stress.



0
10
20
30
40
50
60 %

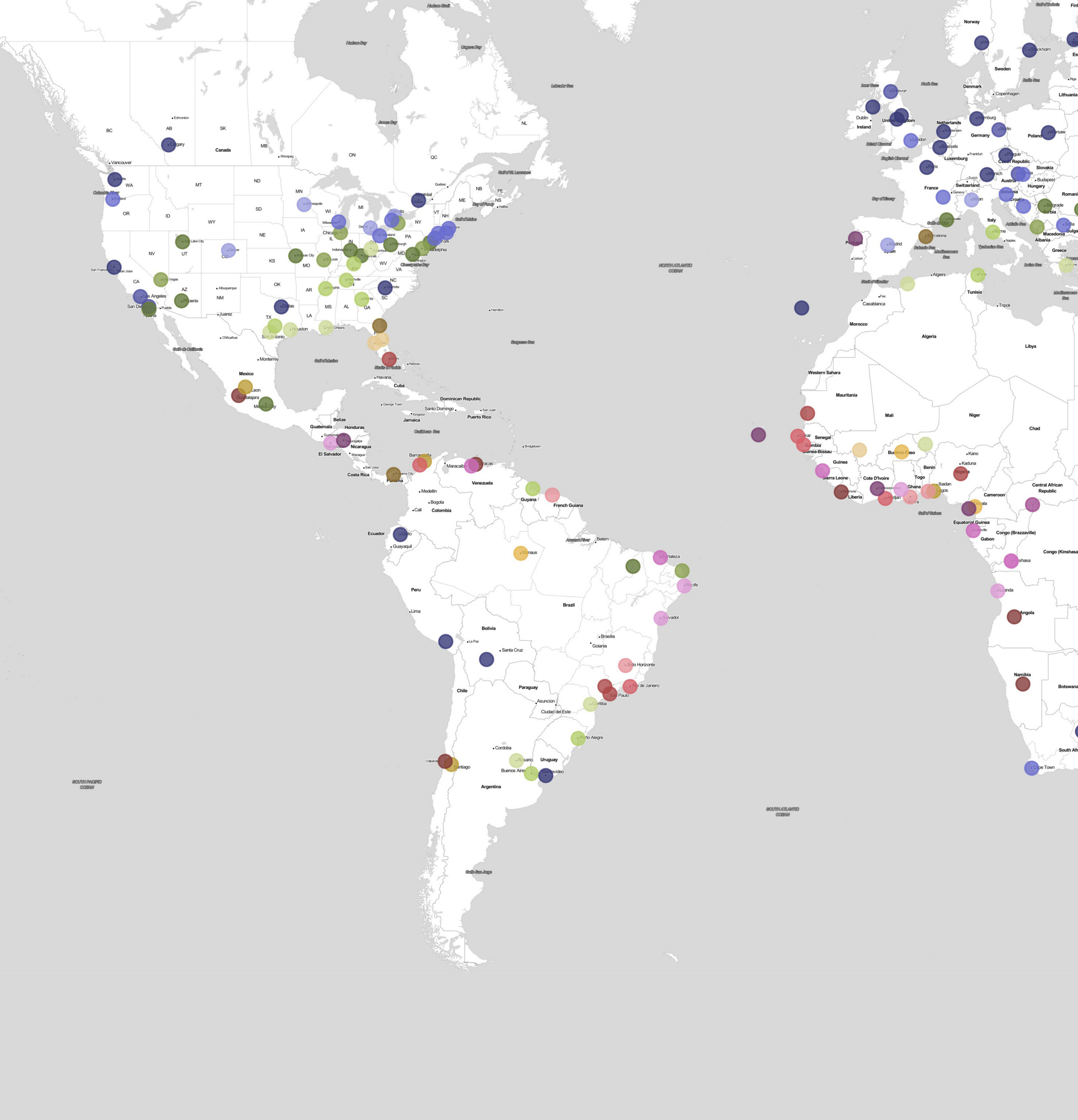
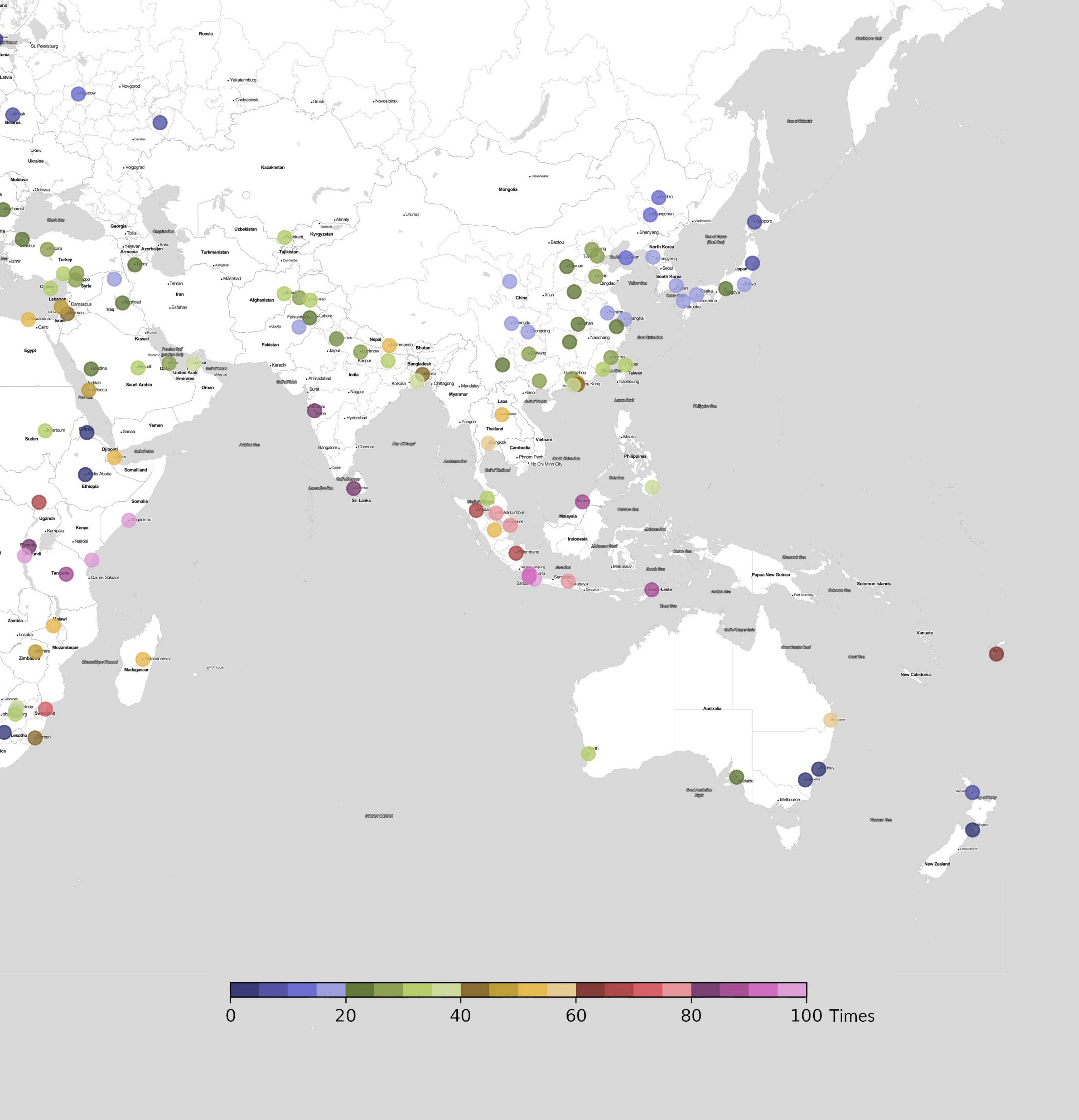


Figure 5.19
Delta of UTCI 95th percentile between exposed and under the tree


0
20
40
60
80
100 Times

from Bastin, Finegold [72]. Overlapping these two maps show that in mid and lower latitudes there is more potential to use trees to mitigate heat stress plus there is more potential for tree cover restoration in that areas as well. In High latitudes, this potential varies between 10-20 percent over the year compared to 40-60 percent heat stress reduction in lower latitudes due to a higher amount of radiation over the year.

The heat stress reduction map has a similar pattern with radiation distribution over the globe and this emphasizes the fact that radiant environment (MRT) plays the main role in comfort assessment. Since the heat stress reduction percentages cannot project the frequencies of such events the second metric (UTCI 95th percentile) is more helpful to capture the benefits of urban forestry in connection to urban health and reoccurrence of heatwave events.

Figure 5.19, illustrates the frequency of heat stress events and we see a slightly different pattern compared to the previous projection. The potential of decreasing the heat stress frequencies for northern Europe goes up to 20 times per year compared to southern Europe where numbers are almost double. From both of the maps, we can see that southern Europe has more potential for heat mitigation by urban forestry and this overlaps with findings of other researchers where that region generally experiences higher heat stress than northern Europe, and summer thermal stress is usually higher in July/August than in June [66].

The cities located in lower altitudes show more potential for heat stress mitigation using trees. Referring back to the strong contribution of radiant temperatures and direct exposure to sun on actual UTCI values, one may conclude that providing shade can already improve significantly exposure to heat stress, however, the cooling effect of trees brings advantage on top not only concerning the individual heat stress but also improving the microclimate of the neighborhoods and immediate surroundings.

Another additional layer for these maps would be to include people's daily behavior patterns in using outdoor space. For example, taking into account the actual time over the day that people spend time outsides rather than having a fixed schedule of 6 to 18. Like in climates where over the noon temperatures are unbearable, most of the outdoor activities happen after sunset. Having such a database can improve the results of urban forestry potential significantly.

5.7 DISCUSSIONS

Heatwaves represent a threat to human health and excess mortality is one of the associated negative effects. Therefore, a health-based definition and method for the frequency of these events are substantial. The developed workflow in this chapter can be readily used to quantify the mitigation solutions, either by planting trees or providing shade to inform and identify the long-term benefits of each intervention through the design process. For instance, the workflow can be used to compute and map only MRT in the presence or absence of direct solar radiation (shade). It has been demonstrated that the MRT is a better predictor of heat-related mortality than the air temperature in Stockholm County, Sweden [73].

Also, the method can be applied to the forecasts of the different radiation components to generate forecast maps of predicted MRT or UTCI at the global scale.

As a limitation of this approach, it should be noted that the workflow does not account for urban effects at the global scale, such as the thermal emission from building walls and the local shading which has been shown to influence human biometeorological comfort in a street canyon in Chapter 4. It should be also recalled from equation 5 that in MRT calculations for an unobstructed person, the view factors are set equal to 0.5. This has been chosen considering radiation fluxes as coming from two directions, the ground, and the sky. In urban settings, however, the two-direction approach has been shown to underestimate MRT at low sun elevations as a standing person receives most of the radiation from the sides [54].

Since MRT is an aggregate measure, meaning it incorporates multiple radiation components that can compensate biases, however, future model developments should focus more on sky models especially for nighttime comfort estimation to reduce radiation-related uncertainties. Also, future studies could further assess the model against observed UTCI in different locations and different spatial scales considering local trees and their distribution.

5.8 CONCLUSIONS

This chapter presented the development, validation, and application scenarios of parametric tools for modeling tree canopies in Grasshopper3D. The developed method can create spatiotemporal information layers that identify hotspots of heat stress risk. The results show that incorporating more vegetation cover into urban areas can effectively mitigate extreme urban temperatures at local to micro scales.

Currently, there is no sufficiently detailed PBM application to model trees in urban environments to output annual statistics on their effects on outdoor thermal comfort. The developed tool can be used as a standalone program to simulate the behavior of tree canopies or can be coupled with a building and/or urban simulation program to model urban canyons including vegetation. Furthermore, it has the potential to be used with the daylight modeling workflows to properly estimate the effect of tree canopies on daylight availability and energy consumption thanks to the phenology model that gives dynamic leaf area estimations. As demonstrated in this chapter, the application scenarios of the tool can go from modeling a standalone tree or single row of tree canopy in a street canyon to project a map of urban forestry potential on a global scale that can inform decision-making processes.

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C H A P T E R S I X

CONCLUSIONS

Summary

This chapter summarizes the key findings of the thesis and links them to the hypothesis and research questions from the introduction chapter. The chapter concludes with an outlook for the future of the research on microclimate and outdoor comfort.

6

6 CONCLUSIONS

6.1 FEASIBILITY OF CONTRIBUTION

As Lisa Heschong frames in “Thermal delight in architecture”, the creation of microclimates is not about implementing a norm in a closed and controlled space, but rather, creating thermal comfort depends on the situations and needs of the people involved. This needs a logical measure of comfort and adequate tools to quantify such effects in a spatiotemporal domain. In concrete terms, this thesis developed a multi-scalar computational model and sensing techniques, that can quantify microclimate at pedestrian level with a high resolution, to measure comfort conditions and predict the impact of climatic phenomena on people´s wellbeing and health in the climate change era.

Furthermore, engaging comfort sensing techniques, this framework allows putting into evidence the relation between environmental qualities of the built environment and people’s individual active mode mobility as climate knowledge to mitigate and design more livable urban environments in the future. Therefore, developing computational and sensory tools for quantifying outdoor thermal comfort and using them for decision-making processes is justifiable to be applied in urban planning.

In Chapter 3, following the argument that the sensory data on a human scale can help to understand the dependencies of microclimate on human thermal perception and urban morphology, an experimental method is introduced with developing a toolkit that records environmental, physiological, and psychological data that can be used to map and understand the interactions between the human in terms of comfort perception and the built environments. One of the main efforts was to update the main toolkit with the aim of gathering different measures such as UTCI, AQ, SVF, TSV, and physiology. The offered plug-and-play approach for the sensory devices makes it possible to upgrade and include more measures in the workflow for future studies or projects. The experiment has been further deployed in several cities as; Hong Kong, Singapore, Munich, Genoa, Sevilla, Barcelona, Malaga, Rome, Copenhagen, Boston, and Amman, both as a participatory approach to make people more conscious of their intermediate surroundings and also providing information on decision-making levels. The results of those experiments are not included in this thesis due to the inclusion of third parties in the experiments but the full list of published results can be found at the end of this thesis.

In Chapter 4, a modeling approach was explored in a comparative study on radiant environment simulation from two different models and the results revealed that the CFD based tool, ENVI-met fails to predict the storage effects of the materials which end up not considering the thermal mass effect over the night for a reasonable MRT estimation. A further study has been done to evaluate the contribution and effectiveness of storages effect on actual perceived temperatures which demonstrates that the choice of material is highly dependent on the time of the day that the designer aims for. Also, the findings confirm the strong contribution of shortwave radiation on radiant temperatures which can be treated very differently in simulation programs and measurements as well. Moreover, the transient model compared to ENVI-met, despite giving annual statistics of UTCI, fails to estimate the cooling and shading effects from trees and vegetation canopies.

In order to overcome the limitations of modeling annual outdoor comfort with trees and their seasonal patterns, Chapter 5 introduced a numerical process-based simulation tool to model tree canopies to estimate root water uptake, drainage, canopy interception, and cooling potential of trees by coupling with outdoor thermal comfort models. The radiation and PAR model of the tool has been validated with a reasonable agreement between measured and simulated values which points out the feasibility of model development and application. Afterward, the workflow was used to estimate the potential of urban forestry in providing comfort opportunities in 270 cities over the globe. The outcomes show a very diverse distribution of the potential overlapped with tree growth potential as well as putting into evidence the paybacks and feasibilities of such an investment.

6.2 JUSTIFIABLE EFFORT

Following the argument that collecting data on a human scale can give a better understanding of human physiology and perception in outdoor space, the developed experimental workflow in Chapter 3, could be already used as a post-occupancy evaluation method for outdoors to evaluate the effects of transient environments on people's perception and thermal comfort. Additionally, the methods could be used as an educational tool to show and demonstrate to the students how the microclimate can be modified and shaped by the natural and built environments increasing the awareness not only on the technical side of the experiment but also on thermophysiological and human-related measures.

Additionally, the tree canopy model from Chapter 5 has the potential to be integrated with other urban modeling interfaces like UMI or daylight and energy workflows to include the seasonal behavior of trees on indoor daylight and thermal comfort analysis. In terms of modeling efforts, the interface, template files, and temperature-dependent phenology model reduces the work significantly to simulate such a model with annual results not only for the tree itself but also including the root parameters and water potential. This approach makes it also feasible to use the tool in early design phases coupled with generative workflows in initial design steps to wisely evaluate the future paybacks of such investments and also plan them more related to the climate, water resources, and morphology of the specific site or development.

6.3 RELEVANCE

This thesis had provided several practical and use-case scenarios for the utilized sensing methodology. As an example the study in Singapore using a detailed physiological measurement combined with environmental sensing revealed a significant impact on pedestrians' physiological reactions moving between conditioned indoor spaces and outdoors. Furthermore, the developed plugin for Rhino Grasshopper3D has been integrated into TRNSYS as part of the canyon model to predict perceived temperatures in early design phases. Therefore, improved modeling and sensing methodologies can provide relevant outdoor comfort-related insights in a high spatial and temporal resolution, which can help to evaluate sustainable design strategies over the design process or built cases.

In Chapter 5, the findings highlight the importance of the UTCI metric as a bioclimatic index that not only captures the thermal bioclimatic variability of the globe, but it is also able to relate such variability with the effects on human health and wellbeing. Continent-wide maps of heat stress and bioclimatic diagrams of capital cities provide information on which a health policy can be formulated and used by stakeholders to interpret the influence of different bioclimatic conditions on health. This can be reflected in the fact that well-designed pedestrian pathways with trees can encourage outdoor recreational, social, cultural, and sporting activities in streets and public urban space with greatly enhancing the city's livability and vitality.

Figure 6.1 summarizes the developed methods in this thesis, first for understanding the relationships and the effects of built and natural environments on the microclimate of cities and perceived temperatures. Second, using the PANDO workflow, to inform the design decision-making process with annual outdoor comfort analysis and urban forestry potential in cities.

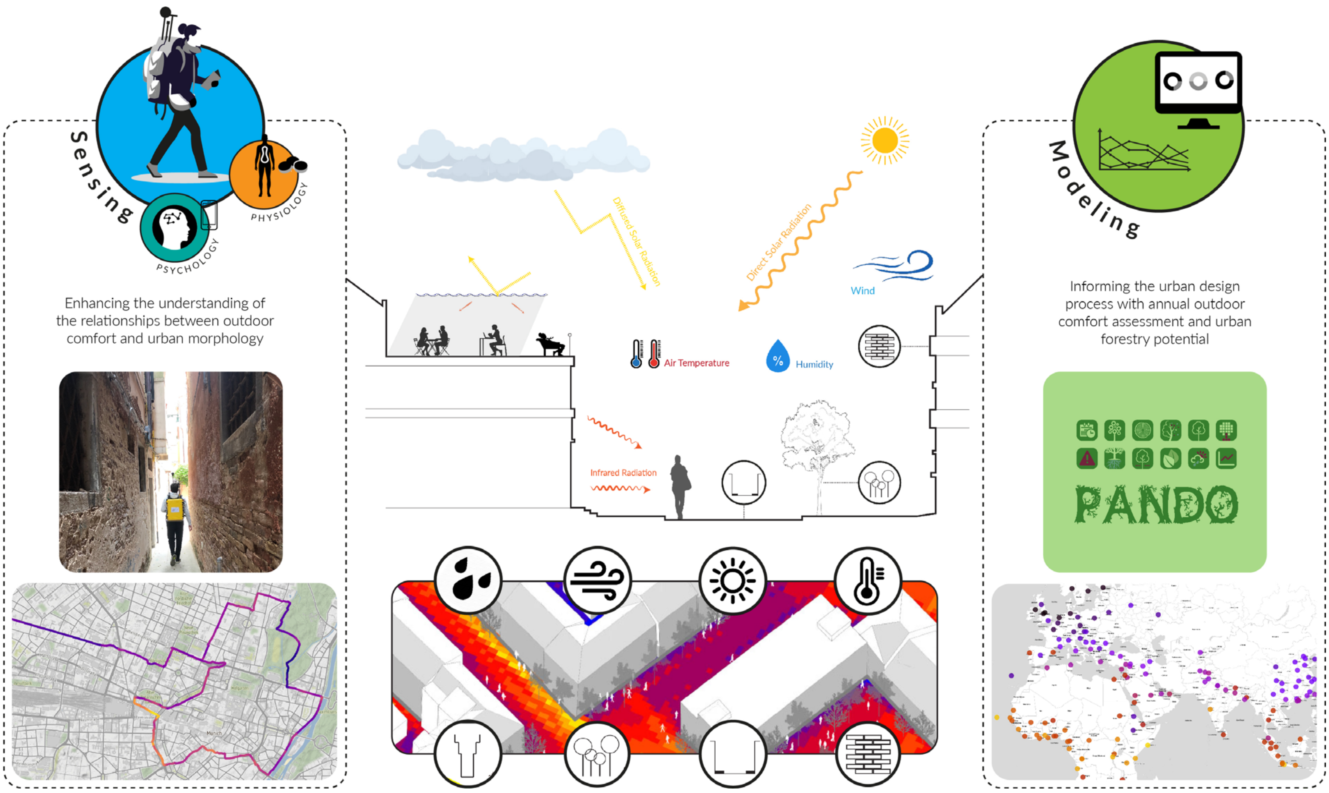

Figure 6.1
Graphical summery of the thesis.

6.4 OUTLOOK

Although this thesis has presented several advances and methodologies in the domain of pedestrian outdoor comfort, however, further work is necessary to foster wider use of the models in design and planning processes.

For the monitoring experiment, the efforts of data processing could be noticeably decreased by using a built-in python script independent from the Grasshopper environment aiming for real-time result feedback. Additionally, the data could be stored in a database format with a more structured layout to make it easier to integrate additional sources of information from the built environment or signals from human behavior and neurobiological sensors. This can facilitate a deeper understanding of the underlying biological and psychological processes by which urban planning and design influence brain circuits, human behavior, and health. The concept of generating microclimatic knowledge could be also deployed as an app to give people suggestions on cold spots in summer and hot spots in winter within their neighborhood. Or suggest the biking routes depending on the heat stress exposure of the path in certain hours of the day and not only based on distance and trip time.

For the developed vegetation model, validation studies for different tree species with different climate zones are necessary. Also, the integration of rainfall data as an input in .met files and including soil and root properties would be beneficial to correctly predict the evapotranspiration potentials for different tree species.

LIST OF PUBLICATIONS WRITTEN IN THE CONTEXT OF THIS THESIS

A) Book Chapters

1. **Ata Chokhachian*,** Santucci, Daniele and Thomas Auer (2020): Informal Microclimates: Study on Self-Built Settlements and Human Comfort in Amman. In Informality through Sustainability: Urban Informality Now, Routledge.
2. Santucci, Daniele*, **Ata Chokhachian,** and Thomas Auer (2020): Temporary Appropriation of Public Spaces: The Influence of Outdoor Comfort. In Temporary Appropriation in Cities, pages 117-126. Springer, Cham.
3. Katia Perini*, **Ata Chokhachian*** and Thomas Auer (2018): Green Streets to Enhance Outdoor Comfort. Nature Based Strategies for Urban and Building Sustainability, edited by Gabriel Pérez, Katia Perini: chapter 3.3: pages 119-129; Butterworth-Heinemann is an imprint of Elsevier., ISBN: 978-0-12-812150-4, DOI:10.1016/B978-0-12-812150-4.00011-2.

B) Refereed Journal Papers

1. **Ata Chokhachian*,** Katia Perini, S. Giulini, Thomas Auer: Urban Performance and Density (2019): Generative Study on Interdependencies of Urban Form and Environmental Measures. Sustainable Cities and Society; 53:101952., DOI:10.1016/j.scs.2019.101952.
2. Ahmad Saleem Nouman*, **Ata Chokhachian*,** Daniele Santucci, Thomas Auer (2019): Prototyping of Environmental Kit for Georeferenced Transient Outdoor Comfort Assessment. International Journal of Geo-Information; 8(2):76., DOI:10.3390/ijgi8020076.
3. **Ata Chokhachian*,** Kevin Ka-Lun Lau, Katia Perini, Thomas Auer (2018): Sensing Transient Outdoor Comfort: A Georeferenced Method to Monitor and Map Microclimate. Journal of Building Engineering; 20., DOI:10.1016/j.jobe.2018.07.003.
4. **Ata Chokhachian*,** Daniele Santucci, Thomas Auer (2017): A Human-Centered Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces. Buildings; 7(4)., DOI:10.3390/buildings7040113.
5. Katia Perini*, **Ata Chokhachian*,** Sen Dong, Thomas Auer (2017): Modeling and simulating urban outdoor comfort: Coupling ENVI-Met and TRNSYS by grasshopper. Energy and Buildings; 152., DOI:10.1016/j.enbuild.2017.07.061.

C) Refereed Conference Proceedings

1. **Ata Chokhachian*,** Marion Hiller (2020): PANDO: Parametric Tool for Simulating Soil-Plant-Atmosphere of Tree Canopies in Grasshopper. SimAUD 2020, Society for Modeling & Simulation International (SCS).
2. Daniele Santucci*, **Ata Chokhachian,** Kevin Lau, hannah pallubinsky, Stefano Schiavon, Thomas Auer (2019): Evaluation of psychological and physiological response to transient comfort conditions in Singapore. COMFORT AT THE EXTREMES: ENERGY, ECONOMY AND CLIMATE.
3. Philipp Molter*, Jakob Fellner, Kasimir Forth, **Ata Chokhachian** (2019): Adaptive Bricks: Potentials of Evaporative Cooling in Brick Building Envelopes to Enhance Urban Microclimate. POWERSKIN CONFERENCE, Munich.
4. **Ata Chokhachian*,** Daniele Santucci, Philipp Vohlidka, Thomas Auer (2017): Framework for defining a transient outdoor comfort model in dense urban spaces, Processes & Findings. 7th International Conference Architecture and Urbanism - Contemporary research, Prague.
5. **Ata Chokhachian*,** Katia Perini, Saverio Giulini, Thomas Auer (2017): Mathematical Generative Approach on Performance Based Urban Form Design. International Conference on Urban Comfort and Environmental Quality (URBANCEQ), Genoa, Italy.
6. Daniele Santucci*, **Ata Chokhachian,** Thomas Auer (2017): Impact Of Environmental Quality In Outdoor Spaces: Dependency Study Between Outdoor Comfort And People's Presence. S.ARCH 2017 I Sustainable Architecture.
7. **Ata Chokhachian*,** Katia Perini, Mark Sen Dong, Thomas Auer (2017): How Material Performance of Building Façade Affect Urban Microclimate. PowerSkin2017, Munich, Germany.

D) Monographs

1. **Ata Chokhachian*** (2020): Beyond the Colorful Mesh in TRANSFORMING BUILT ENVIRONMENTS, Addressing Resource Awareness in Architectural Design Pedagogy, pages 124-129; TUM Press., ISBN: 978-3-941370-83-8.
2. **Ata Chokhachian*** (2019): Climatewalks to Evaluate Outdoor Comfort. Regenerative Design in Digital Practice. A Handbook for the Built Environment, pages 149-154; Eurac Research., ISBN: 978-3-9504607-2-8.

* = Corresponding author

LIST OF ABBREVIATIONS

ACH: Air Change Rate

CAD: Computer-Aided Design

CFD: Computational Fluid Dynamics

ET: Effective Temperature

EUI: Energy Use Intensity

GPS: Global Positioning System

HDOP: Horizontal Dilution of Precision

InFraReD : Intelligent Framework for Resilient Design

LCZ: Local Climate Zone

LST: Land Surface Temperature

MRT: Mean Radiant Temperature

OSM: Open Street Map

OTC: Outdoor Thermal Comfort

PET: Physiological Equivalent Temperature

SVF: Sky View Factor

TPV: Thermal Pleasure Vote

Tskin: Skin Temperature

TSV: Thermal Sensation Vote

UHI: Urban Heat Island

UMI: Urban Modelling Interface

UWG: Urban Weather Generator

UTCI: Universal Thermal Climate Index

WHO: World Health Organization