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A Human-Centered Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces

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Abstract: The concept of resilience in urban design and decision-making is principally focused on change instead of resistance over an adaptive process. For cities, this concept in a broader scale means how to withstand unforeseen events that will fundamentally amend the city's wellbeing, rather than being stabilized and protected. The same concept is applicable for outdoor comfort as an adaptive approach to compensate extreme heat waves and health risk conditions. This chapter presents methods, tools, and applications to enhance urban resilience at a micro scale looking for correlations between environmental factors and human behavior in terms of outdoor comfort.

Keywords: microclimate; outdoor comfort; urban modeling; urban data; sensing

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1. Overview

The summer of 2003 is still remembered in Europe for the extreme heat wave that caused 15,000 additional deaths in France, and also for the average temperatures persistently rising above 32 °C in the United Kingdom (UK.) Nearly 3000 deaths were attributed to the heat wave in the UK during this period, with an increase of 42% just in the London city area. Robine, Cheung [1] claimed, in total, higher than 38,000 excess deaths during this period have been declared in seven European countries.

In addition to that, heat waves also cause other significant problems, such as extended periods of heat stress and droughts also cause extensive crop losses, spikes in electricity demand, forest fires, air pollution, and reduced biodiversity in vital land and marine ecosystems [2]. Another notable consequence of heat waves is that they are statistically concentrated in urban areas, and this is not just in line with increased population density, however it is due to urban form, materiality, and urban metabolism as a driver for the urban heat island effect. The character and intensity of urban heat island formation has been profoundly documented though the field of urban climatology since the 1960s: the maximum intensity of the effect has been measured between 2 and 12 °C, which most large cities have already experienced [3,4].

This scenario indicates the necessity to shift to a Human-Centered approach to transform the built environment. To reach this target, it is essential to understand local microclimate at a pedestrian level and to propose design interventions to increase comfort levels and to prefigure how to mitigate extreme climatic conditions. Within this respect, we focus on humans as source of information that are captured by methods including measurements, simulations, and data mining. Within this regard, the public realm is fundamental for promoting the quality of life in cities: especially in cities that often are located in hot or tropical climates, or experience extreme weather conditions, both in summer and winter [5,6]. However, the thermal experience in an urban environment is a complex issue with multiple layers of concern. The environmental stimulus (i.e., the local microclimatic condition) is the most important factor in affecting the thermal sensations and comfort assessments of people; these assessments are both dynamic and subjective [7]. In addition to the climatic aspects of thermal comfort, a variety of physical and social factors that influence perceptions of urban space come into play when people are outdoors. The challenge for designers and urban planners is not only how to collect, process, or interpret such huge arrays of environmental information, but to develop an integrated understanding of dependencies to prefigure vibrant urban environments [8,9].

This scenario could be achieved through different approaches. For example, mapping comfort over time (i.e., physical and physiological characteristics) has been modeled effectively to provide "climatic knowledge". Although people's subjective perceptions and responses to the urban environment are various and not yet well understood, simulation and scenario-testing tools are always of particular importance in an assessment framework because they provide a platform for the integration of knowledge from various perspectives and comparisons of various design scenarios [10]. It has been already addressed that the need for "predicting tools" in the research for how changes in design details influence outdoor thermal comfort is fundamental [11]. In recent years, we are repeatedly confronted to terms such as 'climate resilient', 'climate proofing', and the 'resilient city' putting emphasis on the idea that cities, urban systems, and urban constituencies need to be able to quickly recover from climate related shocks and stresses. If we zoom into the idea of a resilient city, the concept of micro climate becomes more dominant. The idea of compensation from heat stress could be manipulated in the micro scale with a better understanding of human behavior and built environment characteristics in a transient mode of thinking.

1.1. Urban Resilience in Micro Scale

Resilience is a widely used term with diverse definitions for each discipline, although the term could be broadly categorized into: urban ecological resilience; urban hazards and disaster risk reduction; resilience of urban and regional economies; and, the promotion of resilience through urban governance and institutions [12]. Besides, in recent years there have been several attempts to apply the concept of resilience to urban design and urban sustainability. Applying the theory of resilience to urban design could result in design principles, which are quite different from traditional ones [13].

In general terms, resilience is defined as the capability of a system to absorb disturbances and impacts, e.g., extreme weather events, and the ability to self-adapt to changes [14]. Breaking down to the urban context, Leichenko [12] defines urban resilience as the ability of a system to withstand a major shock and maintain or quickly return to normal function. In other words, urban resilience generally refers to the ability of a city or urban system to endure a wide array of stresses, starting from an early focus on urban-based ecosystems to the analysis of urban coupled human–environment systems, to an examination of cities and urban networks as complex adaptive systems [15].

As mentioned above, resilience stands for the ability of system to recover failure, however the recovery may or may not restore the system to the default configuration, but it compensates the situation to an acceptable mode. To make the concept of resilience more clear, imagine a system of urban context with all of its complexities, urban resilience is defined as the ability of a city or urban system to survive by absorbing and reacting to a wide range of stresses, shocks, and pressures.

In order to prepare cities for the potential effects of climate change, the topic of resiliency should be interpreted in larger ranges. Resilience actions could be divided into mitigation and adaptation: in other words, mitigation tries to reduce the impact of climate change, and adaptation aims to decode built and social environments to make the correct adjustment to decrease the negative effects of climate change. Besides the extreme climatic phenomena, many cities, particularly in Central Europe, suffer from the intensification of severe heat that is caused by regional climate change as neither their structures nor their residents are adapted to this meteorological hazard [16].

At present, half of the world's population lives in cities and the predictions show a rise to 80% by 2050. This means major resilience challenges of our era, known as natural hazards and climate change, poverty reduction and social inclusion will be intensified in cities. This topic becomes more crucial since most of the contemporary cities were not necessarily designed with resiliency concepts in mind. Urban form, street patterns, block structures, and building typologies are often produced according to organizational principles rather than resilience to climatic changes, which has only become a major topic in recent years. In order to move to more resilient and sustainable systems, the need for new organizational mechanisms and principles for the existing urban form and structure is urgent. In this context, urban planning faces the huge challenge to develop and apply measures, which may lead to a local reduction of human heat stress under regionally predetermined heat. As these measures have to be focused on citizens, they need a human-biometeorological basis [17]. Within this respect, this chapter reviews methods, tools, and applications on how the microclimate of cities along with urban form and structures can give us directions to generate more resilient systems. We provide a brief overview of strategies and implications at a micro scale to understand the phenomena, possible outlines, borders, and boundaries of the topic backing up with application methods.

1.2. Adapting for Climate Change and Heat Resilience

In recent decades we have gained a valuable understanding of the link between microclimate and urban settlements. Improved outdoor thermal conditions are in direct connection with how people behave and use outdoor spaces, this reaction may be spontaneous, but human body knows how to get adapted to different climate conditions in urban spaces. Having a place with optimum comfort level will enhance the city in a different direction such as: encouragement for cycling and walking, attracting more number of people to comfort zones in the city, and turning this opportunity into business and tourist attractions to shift the area economically profitable [18]. Within this respect, comfortable and enjoyable outdoor spaces could be realized with set of strategies according to the context, such as planting trees with the advantage of evaporative cooling plus a shading effect, or adding manmade canopies with local materials. Being comfortable or feeling like having no thermal stress is dependent on several factors and parameters, and at the same time it differs from each person to another one, but scientifically, if the body reaches thermal equilibrium with the surroundings, then the feeling should be close to the comfort zone. In urbanized regions, the lowest part of the atmosphere is known as urban boundary layer (UBL), which is certainly affected by the nature of building typologies. The UBL is mainly divided into smaller sub layers according to its climatic considerations and fundamentals, and the lower part is where microclimate studies are being done. Figure 1 shows a conceptual sketch of effective parameters on outdoor comfort in urban canopy layer considering directs and diffused solar radiation, wind speed, air temperature, and humidity. This environmental model could be completed with adding subjective measures in terms of expectations, cultural background, metabolic rate, clothing factor, and etc.

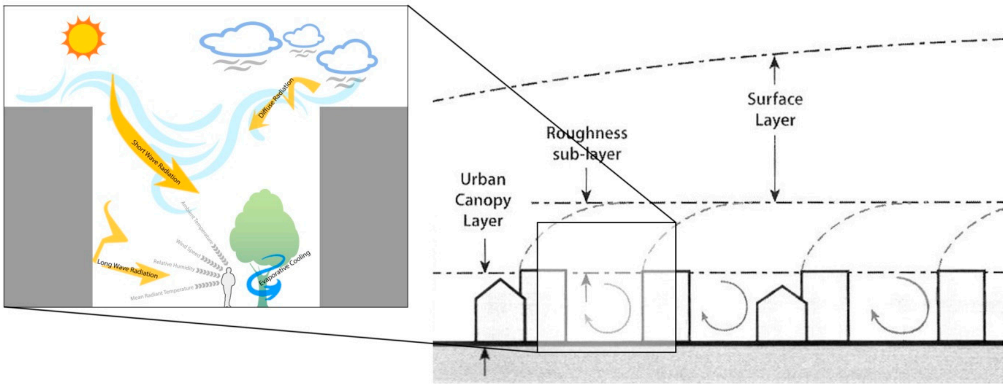

Figure 1. Schematic sketch of the environmental parameters affecting outdoor comfort equation [19].

Looking to the concept of urbanization and densifying cities, in the first glance there are several critics and debates over the concept itself, however if we add the knowledge of climate responsive design to understand limits and borders of building density, both in terms of indoor and outdoor qualities, this challenge will turn into opportunity rather than a problem. Climate change is the incident reality and takes place at the micro scale, but the stronger effects impact at a macro scale. Cities and urban structures are the drivers of change in the world: if we are confronted with the effects of climate change, this occurs abnormally in cities. In order to understand, predict, and mitigate the effect of climate change, it is necessary to both measure and simulate microclimate. In this chapter, first we investigate tools and methods for simulating microclimate and outdoor comfort, following with measurement methods at a high resolution with case studies. The chapter concludes with discussions on further applications and perspectives.

2. Tools & Enablers

2.1. Simulating Microclimate, Coupling TRNSYS & ENVI-Met

One of the common methods to predict the behavior of physical models is to use simulation programs. There are several tools for large-scale analysis; however as in the case of micro climate simulations, each has its own advantages and short comings. One of the most efficient and common methods to overcome with limitations of each simulation program is the coupling approach, which is based on linking inputs and outputs. This method can maximize the accuracy of results for each parameter if the use is aware of the limitations of each tool. This is the first time that this method is applied to simulate outdoor comfort and measure the effect of façade material on the universal thermal climate index [19]. The process could be divided into three parts, the first part of the simulation is done with ENVI-met to calculate relative humidity and wind speed since ENVI-met is accurate in CFD (Computational Fluid Dynamics) modeling [20]. Second part is done with TRNSYS version 17.1 to simulate effect of different surface materials on mean radiant temperature and air temperature inside the canyon. For both of the simulations the same model is implemented with same dimensions and properties. The last step was bringing results from two different simulation environments into one layer and overlapping them to map outcomes. This was done with grasshopper as visual programming interface to read data from both simulations and map outdoor comfort visually, as well as calculating values numerically (Figure 2).

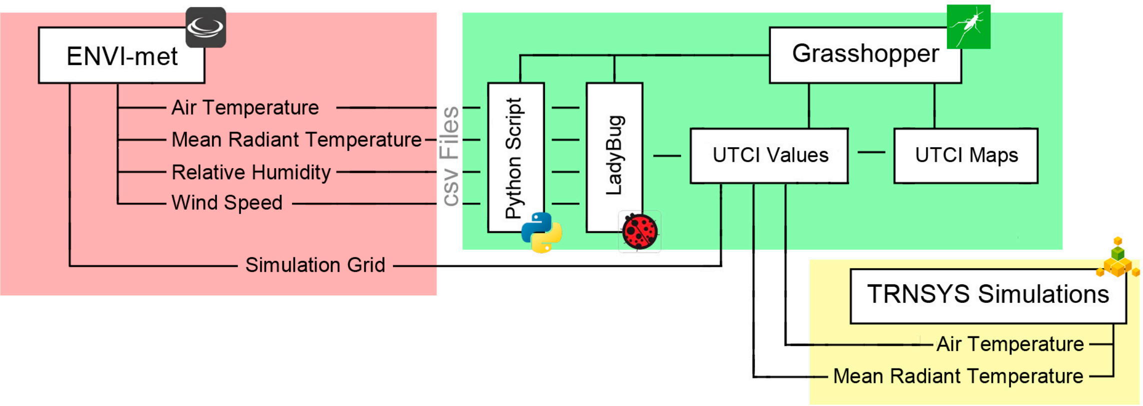

Figure 2. Diagram of Coupling Methodology to simulate outdoor comforts [19].

Material choice is one of the main role playing factors in terms of having less impact on the environment. Selection of material type depends on applied location on the building, for example, high reflective materials can reduce the temperature of urban surfaces, like roofs and pavements, as well as summer time building cooling energy demand. At the same time, high albedo materials absorb less radiation, and this increases Mean Radiant Temperature (MRT) depending on sky view factor in the daytime. Studies find that reflected radiation from high-albedo pavements can increase the temperature of nearby walls and buildings, increasing the cooling load of the surrounding built environment and increasing the heat discomfort of pedestrians. Harmful reflected UV radiation and glare, unintended consequences of reflective pavements, need special consideration for human health [21]. Results and findings through this study reveal that:

1. The solar absorption, surface temperature, and mean radiant temperature have proportionally reverse relationship
2. The effect of different façade materials is significantly smaller than the impact of difference between solar absorption percentages on local mean radiant temperature values
3. Higher solar absorption means higher surface temperature, but lower MRT, and vice versa.
4. For the climate of Munich, the results show that light color walls with less solar absorption are worse than dark color walls in terms of outdoor comfort during hot periods.
5. Materials with higher thermal mass effect and absorption capacities will enhance outdoor comfort conditions by up to 30% over the public pedestrian ground (Figure 3).

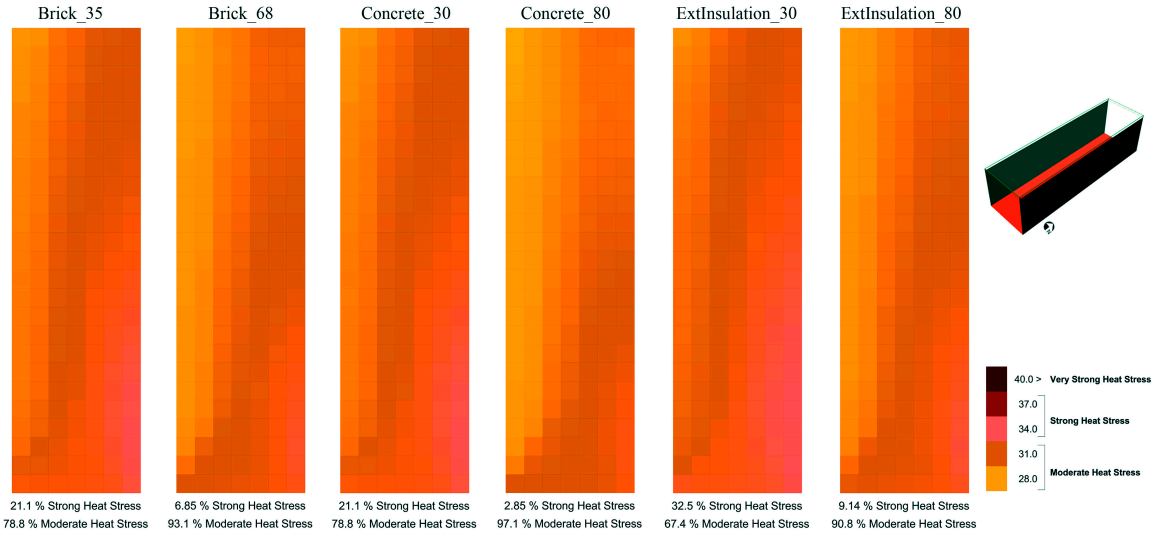

Figure 3. Universal Thermal Climate Index for different facade materials mapped on canyon surface on pedestrian level, 2 pm—12 August [19].

The aim of this research was not just to investigate material variation; however, the developed coupling methodology with different simulation tools gives an opportunity to have a more accurate simulation result depending on the input parameters. The developed method is also being used to compare simulations from TRNSYS and ENVI-met in terms of mean radiant temperature calculation accuracy over the course of the day. See Perini, Chokhachian [22].

2.2. Microclimate Measurements

One of the main consequences of increasing urbanization in dense metropolitan contexts is the issue of microclimate and its relevance for people due to heat and cold stress peak points. Extreme cases occur in tropical climates, where people are constantly exposed to heat stress. This part evaluates—as a case study—the heat tolerance of people in extreme outdoor conditions, to propose a transient model for outdoor comfort based on field measurements. Moreover, predicting the period and the environmental conditions that a person needs to compensate heat stress, basing on his/her thermal background and physiological state. The surveys are done within the "Urban microclimate" workshop that was organized by the Technical university of Munich in collaboration with the Chinese university of Hong Kong in June 2017. During the one-week workshop, students did measurements by mobile micro-meteorological sensors that were selected for the measuring of relevant environmental parameters to investigate thermal comfort, including Wind Speed, Air Temperature, Humidity, Globe Temperature and Solar Radiation to calculate the universal thermal comfort Index (UTCI) [23]. A thermal comfort questionnaire was also used for collecting data about subjective perceptions and thermal sensations.

The measurement backpack was carried walking through outdoor spaces collecting data for all of the selected routes. The routes were pre-selected so that the measurements could be completed within 1 h (Figure 4). Another factor was the skin temperature of people, which was measured with an infrared thermal camera, which was adapted to the cell phone's camera. There is also possibility to measure skin temperature by normal cell phone cameras [24]. Photos were taken for every survey stop.

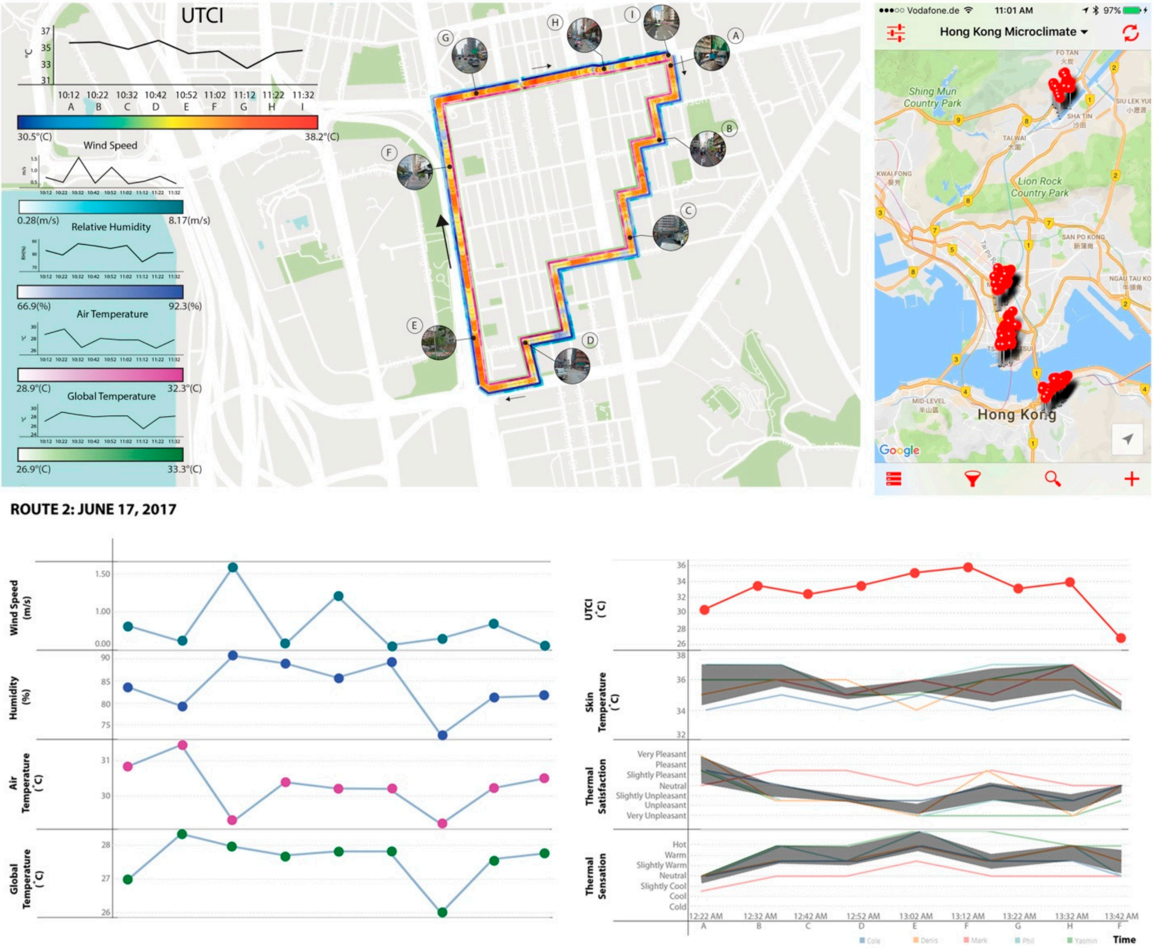

Figure 4. (**Top left**) Universal Thermal Climate Index (UTCI) map over the routes; (**Top right**) measurement locations; (**Bottom**) survey responds for the selected routes.

Data visualization done by using Rhinoceros, Grasshopper, and the plug-in LadyBug [25], allowed for importing maps for each route and a series of scripts in Python code were developed in order to combine data from CSV (Comma Separated Values) files. Overlaying all collected data (wind speed, relative humidity, air temperature, global temperature and UTCI) with the actual routes on a two-dimensional (2d) view was the most complicated task, once a sequence of parameters had to be taken into account, such as: changeable speeds during the walk that had to be adjusted in a linear path; variables that interfere in the data collection and a process of understanding the situation, cause and effect of those; and, divergences between data and reasons for this occurrence. In parallel, the measured data was also compared to the survey data (skin temperature, thermal satisfaction and thermal sensation) through chart visualization in order to create a general view from the analyzed parameters and how they are inter-related. Those charts were produced in Tableau (Figure 4). In order to present the average of all the responses, all extreme answers were taken out of the analysis.

The results and findings from data analysis reveal that the skin temperature becomes stabilized at 34–36 degrees Celsius after 20 min. Paradoxically, in the case of sudden rising of the air temperature, the temperature of skin remains lower. From the graphs it can be deduced, that the face temperature is proportional to the relative humidity values and inversely proportional to the velocity of the wind. Moreover, the extremely high humidity, which caused discomfort to all of the participants and intensified the feeling of heat, even though the temperature did not present drastic changes. This feeling of discomfort was higher in areas near to high buildings and completely paved floors, which could be a consequence of blocked wind flow and more intensively reflected heat waves. The developed method is currently implemented for different locations in the city of Munich over diverse times of the year, with varying outdoor comfort conditions.

2.3. Data Mining

Since the 1990s, publications such as The Global City [26], or Manuel Castells' concept of a space of flows [27], research on global cities have abounded in several fields of urban studies. Urban space can be regarded as an agglomeration of multiple distinct networks in a mutual influence of network dynamics, providing specificity for each urban point of interest [28]. In that regard, cities are dynamic and highly mutable entities. City creation and living in cities is in constant flux [29], change of urban structure being closely linked to social circumstances, such as property and social structure, but also shared values. From then, the challenge seemed to be explaining the relative stability of urban environments.

In the previous decade, we have learned valuable aspects of human mobility, mainly from large-scale data that has been mined from mobile phone networks. Individuals' visit patterns are highly predictable, presenting unique and slow exploration habits [30]. Large-scale urban sensing data, such as mobile phone traces, are emerging as an important data source for urban modeling [31]. These data sources offer the unique opportunity to understand and characterize the use of public realm, as the centre of human social activity and as an indicator for quality of life. Models of human mobility have a wide range of applications: the correlation between individual mobility and microclimatic conditions in dense urban environments could reveal essential evidences on how people perceive urban space and on how the quality of urban space could be improved.

Outdoor comfort conditions affect the way people occupy and use public spaces in all seasons and weather conditions. The evaluation of such behaviors demands innovative computational methodologies and tools. Nowadays, there is a preponderance of research data that is available to social scientists—especially the manifold data of social life that is generated by human activities in cities and urban areas: public transport, everyday interactions and demographics, education, public health, crime, environment, and etc. As a result, the challenge facing social scientists is not only the question of how to collect, process, and interpret such huge arrays of information; it lies in how to manage this data in an interdisciplinary setting, through the exchange of expertise between disparate disciplines in order to develop an integrated understanding of socio-technical environments and interactions. Recent advancements in technologies and tools—such as big data and fast computation power—are opening up a completely new platform for allowing us the ability to push into the micro-scale to monitor behaviors in high resolution. In light of this, the necessity for developing tools that allow us to shift through different layers of data gathering, data visualization, and data mapping is growing in importance (Figure 5).

Figure 5. Pedestrian activity in the Greater Boston area gathered from GPS-tracking apps.

Within this framework, our research group is investigating the relationship between environmental conditions in dense urban areas and how people use urban spaces—especially looking at individual pedestrian mobility.

The quality of urban spaces is fundamental to make cities livable. In the last decades, many studies at different scales have developed methodologies to evaluate comfort conditions in public spaces, as this aspect is essential for making cities more walkable. Moreover, pedestrian activity can be considered as significant for health.

In this context, our research group—in cooperation with the Senseable Cities Lab at MIT—develops a methodology for evaluating quality through a data set that collects millions of anonymous pedestrian trajectories that are collected from Smartphone applications. The anonymous human trace data was collected from activity-oriented mobile phone application. This anonymized data, which includes about 1 million trips of over 60,000 anonymous users from May 2014–May 2015, estimates human walking activities.

The data reveals patterns of how people use public spaces for walking in a high spatiotemporal resolution (Figure 6). Presence is used as an indicator for walkability by relating it to additional layers—such as density, canyon size, proximity to recreational areas, etc.—to provide an accurate model of the urban morphology. In an upcoming phase, the results will be validated by microclimatic simulations of outdoor comfort conditions using the UTCI model.

The aim of this methodology is to use walking data for sensing presence, quantified and applied to determine the impact of the urban morphology and its effects on climate at a micro-scale on people's activity. The gathered information reveals how people flows react to highly fluctuating microclimatic conditions and how pedestrians respond to the variability of the urban environment.

The proposed multidisciplinary project is based on more integrated approaches that follow a transactional paradigm and make use of big data sources. The aim is to construct city maps with alternative perspectives that are modeled as multiplex networks with geo-spatial and temporal information to analyze structure and dynamics of movement, communication, and discourse in time and space.

Figure 6. Most frequent pedestrian trajectories in the Boston city center for the month of June 2014.

As "technology will democratize expertise, making it available to many more recipients than could ever by curated by 1:1 professional relationships [. . .] As knowledge work begins the same transfiguration in the world of computation that manufacturing experienced with machine automation, the bespoke relationships curated by architects with clients will be circumvented by widely accessible knowledge systems" [32].

Together, these approaches will impact multiple aspects of human life, including health and wellness, infrastructure, and quality of life in cities. Furthermore, the study will provide a new layer of scientific relevance in developing a dynamic comfort model for increasing quality through design to create more healthy cities: a renewed challenge for architects, designers, and urban planners.

3. Applications

The following chapter presents two case studies that adopt different methods in contributing to delineate strategies of how to implement measuring and simulation into the design process of public space considering outdoor comfort measures.

3.1. The Viktualienmarkt in Munich

Design is a fundamental strategy for creating resilient cities. A significant shift can be assured by the contribution of simulation tools that are essential for prefiguring scenarios within the negotiation that occurs during the design process.

The *Viktualienmarkt* in Munich is one of the most attracting places of the city (Figure 7). For centuries it has been used as a marketplace; nowadays, besides its original function, it is known for being one of the most frequented public places.

Figure 7. The Viktualienmarkt in Munich (Image by Giulia Volpicelli).

The aim of this design proposal is the combination of a design proposal with simulation tools to predict its effects, in terms of environmental quality. Following methodological steps have supported the design process:

Meso-climate analysis: In the first phase, we have analyzed climate data of four years (2012–2015) in a hourly interval from the nearby LMU (Ludwig Maximilian University) weather station in Munich, selecting the most representative days for each season in terms of Air Temperature, Relative Humidity, Wind speed, and Wind direction that are considered typical in relation to the season's averages. This selection was done basing on the occurring frequency during each season during the four years period. 18 July 2015 was chosen as a representative extreme hot summer day due to high air temperatures combined with low relative humidity and typical wind direction, registered in the four years period; 28 January 2014 was chosen as a typical cold winter day. Those datasets were used to create a simulation model of the *Viktualienmarkt* with the ENVI-met software [33]. The model has an hourly timeframe resolution over a grid of 4 m. The model, which includes the place has an area of 280 m by 280 m, provides air temperature, mean radiant temperature, water vapor pressure, relative humidity, and wind speed in a height of 10 m as a result.

Outdoor comfort mapping: The simulation model has generated the input information to map outdoor comfort using the Universal Thermal Climate Index [34]. This index was chosen as it has shown to be the most suitable system to represent outdoor conditions basing on the equivalent temperature and is used by meteorologists across the globe [35]. The model accounts for clothing using correlations that are derived from observations of human adaptive behavior in the outdoors. All of the ther personal factors such as age, height, and weight are averaged over the population. The UTCI mapping was processed with Grasshopper and is expressed as an equivalent temperature (ET). The building geometry file has been provided by the *Referat für Stadtplanung und Bauordnung* (data were processes by SynerGIS web office).

The simulations aim to obtain a detailed mapping of the UTCI values. The used UTCI scale has been applied to all of the results in order to obtain a spatially distributed mapping of comfort levels. The simulations evaluated the main microclimate parameters in cells with a resolution of 4 m × 4 m for a total surface of 7.84 ha. The area is composed for 37.6% by buildings, 11% by road asphalt, and 51.4% by pavement and has no soil surface. Each simulation starts at 7 a.m. but considers values starting from noon and ran for 24 h for each simulated day. Cloud coverage was considered as non-occurring.

After all of the factors were plugged into the UTCI model, several high resolution maps of UTCI were generated on an hourly basis for the four previously mentioned typical days for the present status.

Winter days have shown a slight cold stress of over 90% of the market's surface between noon and 4 pm. This means that comfort conditions are acceptable, even when air temperatures are just above 0 °C. The extreme cold day—28 January 28 (air temp. max 3.7 °C, min 0, RH max 100 min 68 avg 85) has slightly worse comfort conditions due to the increase of the relative humidity (Figure 8).

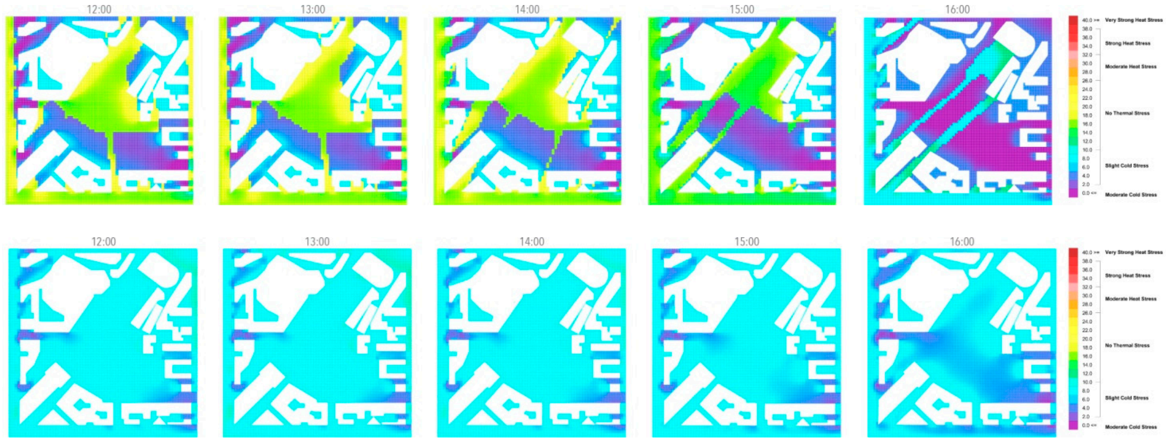

Figure 8. Simulation results—winter days, respectively 28th January (**top**) and 2nd March (**bottom**).

Spring days have no thermal stress conditions during the entire observed time period. The marketplace guarantees optimal comfort conditions (Figure 9).

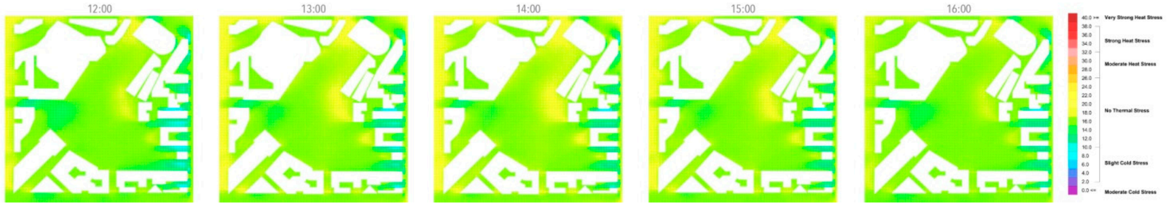

Figure 9. Simulation results—UTCI mapping for a typical spring day: 2nd April.

Summer days show moderate heat stress over at least 35% of the surface, while more than 50% undergoes to strong heat stress.

Looking at hot summer days, the percentage of strong heat stress goes up to 60% at 12 a.m., while very strong heat stress rises up to 35% at 3 p.m. corresponding to equivalent temperatures of 40 °C (Figure 10).

Basing on the outlined analysis, the mitigation strategies were selected primarily to reduce heat stress in summer, for both average and hot days, since comfort conditions in winter and off-season can be considered acceptable, or even very good. As a first step, the existing tree coverage, composed by 74 chestnut trees, has been increased by 73%: 34% of it consists of deciduous trees added in the area facing northeast, and 39% of evergreen trees in the southern part of the place (Figure 11).

Figure 10. Simulation results—UTCI mapping for 30th July (**above**) and 18th July (**below**).

Figure 11. The Viktualienmarkt: current status and proposed interventions.

Furthermore, for an additional heat stress reduction, we proposed to introduce a water surface along the marketplace: the water basin has a surface of 790 m^2, which corresponds to 2.7% of the place's surface. Both of the measures can be easily implemented and modeled in the ENVI-met model.

The water surface area was located at the southern border of the place in correspondence of the existing most congested road. This choice was done when considering the prevailing wind direction during summer (east, occasionally south-east) and the main access to natural ventilation, to increase the effect of evaporative cooling during hot days. Besides the aesthetic and microclimatic reasons, historical maps and pictures supported this location also: for centuries, Munich has been characterized by the presence of several water channels that were used for powering mills and for transporting goods. They were essential for Munich's development from the 14th century. During the 20th century, almost all of the channels were closed to facilitate car circulation and to improve hygienic conditions, by strongly reshaping the appearance and the environmental qualities of the city center [36].

The proposed river is considered a segment of a wider system, a circle, which includes Munich's entire city center, which is, at present, mainly a pedestrian area (Figure 12). This intervention could contribute in promoting advantageous conditions for walking and biking, aiming at creating a more livable and walkable city: a healthy city that is built for people.

Figure 12. Munich's city center: plan of the proposed water channels system.

The comparison of the simulations' results show evident improvements in terms of heat stress reduction, especially during hot days. The UTCI score difference between 18 July 2015 and the design proposal—that was simulated with the same climatic conditions—is about 8 K equivalent temperature difference in peak (Figure 13). Besides the significant heat stress reduction, the proposed design solution, which combines additional vegetation to the presence of an urban river, will provide several benefits in terms of acoustic comfort and air pollution that were not yet analyzed.

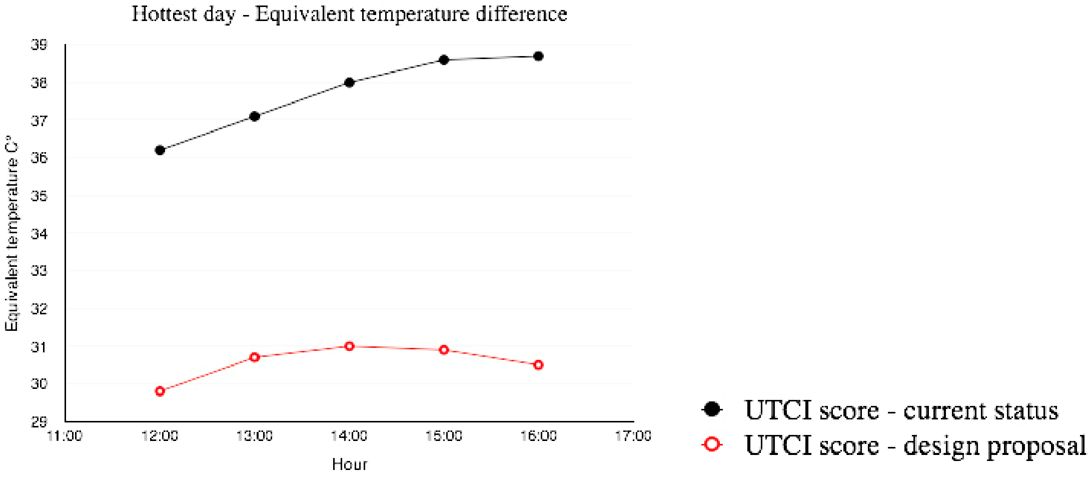

Figure 13. Equivalent temperature difference for the hottest day in an exemplary point of the place.

In conclusion, the design proposal contributes in combining a new image for the city with increased microclimatic conditions, especially during hot days and continuing heat waves. Through the reduction of peaks, the market could become not only a more comfortable place, but also a 'cold spot' that assures more attractiveness in general, and more specifically, a place to recover and to compensate extreme heat stress during hot summer days. In Munich's climate, air-conditioners are rarely used in residential buildings where overheating phenomena occur frequently: the combination of a large presence of thermal mass, a dense urban environment, and a low temperature shift during summer nights is therefore often fatal for elderly and sick people. This research project finds and validates significant associations between design proposals and their effects on outdoor comfort improvement, and opens new opportunities to understand the more challenging aspects of the urban environment and its impact on individuals' health contributing to create more healthy and resilient cities.

3.2. The Elytra Filament Pavilion Survey

Following the hypothesis that microclimate highly influences the use of outdoor spaces, this case study aims to outline the impact of a canopy structure on outdoor comfort conditions. Through the prediction of human comfort in outdoor spaces, the rules of relating people flows and microclimatic conditions are put into evidence.

In the case of Elytra Filament pavilion (An experimental pavilion comprises of a modular robotically constructed canopy commissioned by the Victoria & Albert Museum in London, a collaborative work between the ICD Stuttgart, the ITKE and Transsolar climate engineering) (Figure 14), new ways were explored to combine real time on site measurements and simulations, in order to estimate the microclimate effects of the canopy and to seek correlations between people's movement and thermal comfort. The aim of the present research phase is to integrate the graphical correlation (Figure 15) between comfort levels (assessed by the UTCI—Universal thermal climate index) and movement patterns, with a statistical approach considering spatiotemporal patterns of mobility in relation to thermal comfort.

Figure 14. The Elytra Filament Pavilion in the Victoria & Albert Museum in London (Photo by Daniele Santucci).

The Elytra Filament Pavilion has been adopted as a case study for the first step of undertaking evaluation of the outlined relation and methodology. Since the beginning of the installation, the project has considered the opportunity to sense movement, relating it to microclimatic conditions, at a resolution that corresponds to the human scale.

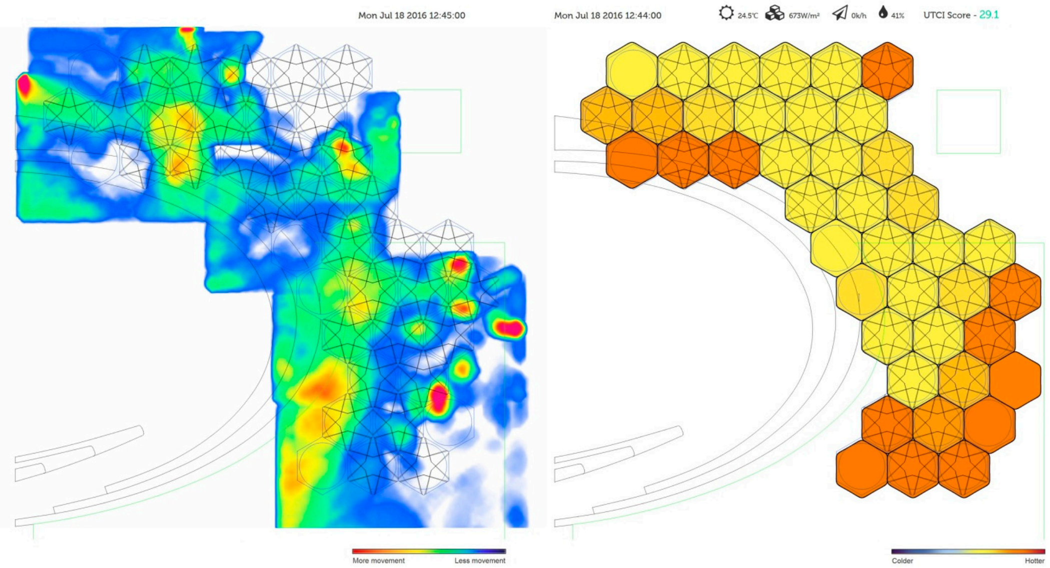

Figure 15. Graphic correlation between movement intensity (**left**) and outdoor comfort (**right**).

The study aims at developing a statistical approach on top of the graphical evaluation in order to open new possibilities to analyze much bigger data sets with higher resolution to apply the methodology on the urban scale. The study bases itself on the combination of sensing and simulation.

The Microclimate, the variation of urban microclimate in a specific context in relation to recorded weather data available from weather stations is obtained through simulation. Since outdoor comfort models require precise microclimate data to determine conditions with a high resolution.

People flows in public spaces can be captured and mapped through GPS tracing devices. In Europe, the issue of privacy is extremely relevant and accessing this data is difficult. New technologies that are based on video content analytics enable quick image processing. Its main components are a camera sensor and a software module that only analyses shapes without interferences with security and privacy reasons.

In order to access the thermal comfort conditions, we have used the UTCI: an index that is commonly used to evaluate thermal comfort in outdoor conditions in a height of 10 m above ground level (Figure 16). UTCI values were calculated for every canopy element in order to better understand the microclimatic conditions that the structure determines [37].

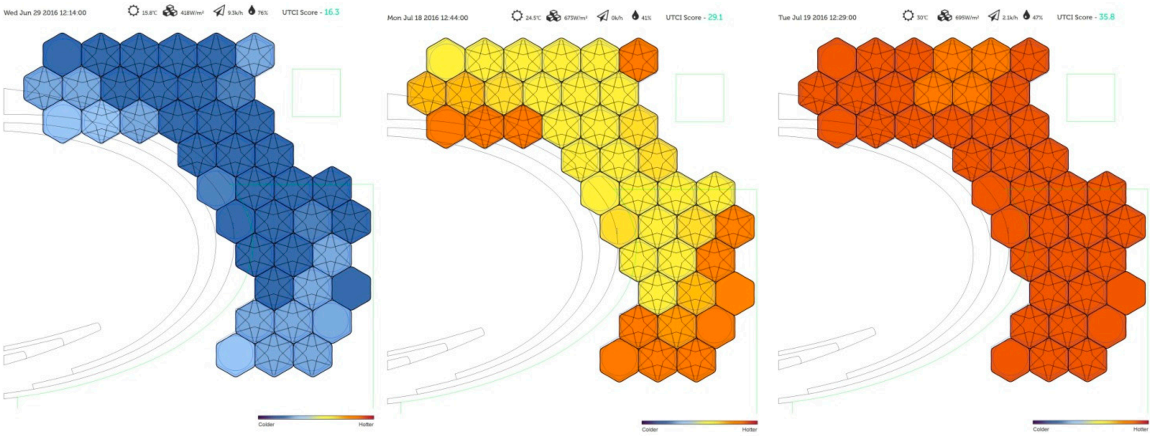

Figure 16. Thermal comfort mapping—Example of three different frames.

For the water vapor pressure value, we used the standard atmosphere value of 01.325 kPa. Air temperature, wind speed, and relative humidity were retrieved from a nearby weather station in five-minute intervals. The process of estimating the mean radiant temperature required a few more steps. We conducted a radiation simulation using Honeybee and Daysim [38] for a five minute interval between May and November (the time frame of the pavilion exhibition). As a following step, we calculated the relative radiation values based on the global horizontal radiation values from the weather file that was used for the simulation. Therefore, for instance, if the global horizontal radiation value in the weather file was 800 Wh/m^2 for a certain time, and the simulated radiation for a test point was 400 Wh/m^2, the radiation percentage was 50%.

As a following step, we retrieved the global horizontal radiation from the same meteorological station, and for the corresponding time, multiplied the actual global horizontal radiation with the radiation percentage. This method offered a simplified model for estimating local radiation values, although further research should be conducted to measure the reliability of this method. Once we calculated the radiation values, then we estimated the mean radiant temperature using the Human Bio-Meteorological Chart [39]. At this stage, the UTCI values for all of the test points were calculated and stored in a database.

Several limitations involving the museums regulations led to seeking solutions that would be as transparent as possible for the occupants and will not store any personal information. The use of infrared cameras, thermal imaging, or Wi-Fi tracking was abandoned and instead we have adopted the Modcam (Modcam (2016-04-09). Retrieved 2016 from http://modcam.io/), a device developed by a Swedish start-up that tracks occupancy patterns. The device has a built in camera and by analyzing the pixel difference between frames, movement patterns emerge.

For the pavilion, we have used 11 Modcam devices integrated seamlessly in the canopy and have been collecting data from May 2016 for a period of several months in 15-min intervals. Both occupancy and thermal comfort information have been stored in databases for further analysis and post processing of the results. In addition, a web application has been developed that offers a visual representation of the results and an interface to choose and move between different times (Figure 17).

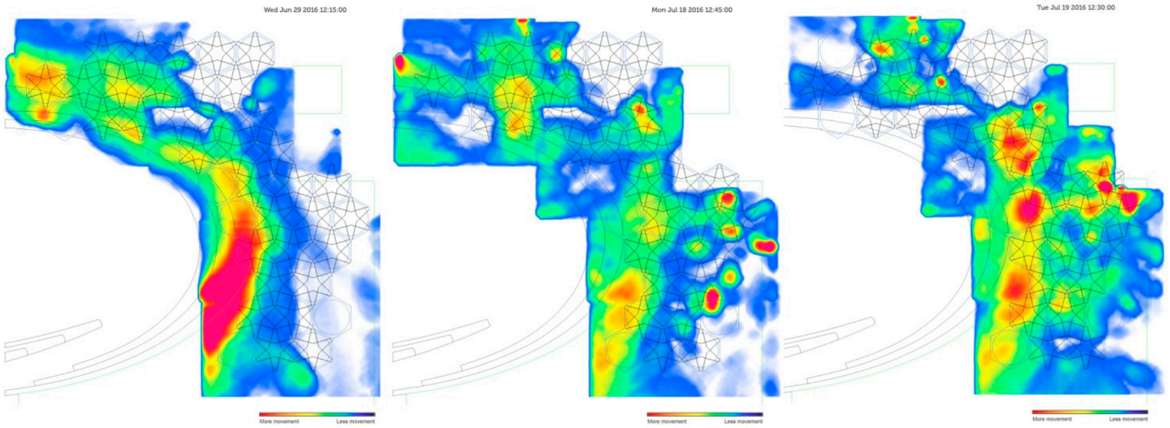

Figure 17. Mobility frequency—example of three different frames.

In the symbiotic relation between the built environment and people's flows in space, urban microclimatic conditions are confronted with the recorded data of people movements to evaluate their influence on human mobility. The relation between digital information and its physical manifestation is therefore linked with the environmental conditions that are obtained by simulations and measurements of microclimate in the selected area.

The relevant time interval for the analysis is related to the museum opening hours, and, therefore, to people's presence in the courtyard where the pavilion is located. It results in a useful timeframe from 12 a.m. to 5:45 p.m.

The data evaluation was carried out using two different methods: a tabular, a graphical, and a statistical method.

In the tabular analysis, the single values composing the UTCI are confronted using day average resulting from the recorded data. The UTCI-Score, the equivalent temperature (ET), and the daily average movement frequency are included. This approach is intended to lead to a general objective overview for understanding the local dependencies and influences that are related to the single parameters and context of the Elytra filament pavilion and its environment.

Following, a more detailed observation was done based on the graphical observation. With the information gathered from the tabular evaluation the single frames of a specific day are defined. The graphical analysis allows a more detailed spatiotemporal distribution of information and through the more effective visual representation.

The following evaluation consists of two steps: first, the evaluation of local weather data and its influence on the UTCI-Score; second, the movement frequency is related to the UTCI-score. The data recordings that were used start from June 2016 and end in July 2016.

Outdoor comfort evaluation: The climatic factors (solar radiation, air temperature, relative humidity and wind velocity) determine the level of the UTCI-Score and have relevant dependencies one to each other. The equivalent temperature is used as an indicator to determine comfort conditions and is correlated to the moving frequency.

Movement frequency: Figure 18 generates an abstract overview of the moving behavior of the museum visitors. It represents the frequency during the observation period (7 June to 31 July 2016). The violet curve represents the movement intensity during opening hours based on the Modcam values. It corresponds to the average of all 15-min frames composing one day.

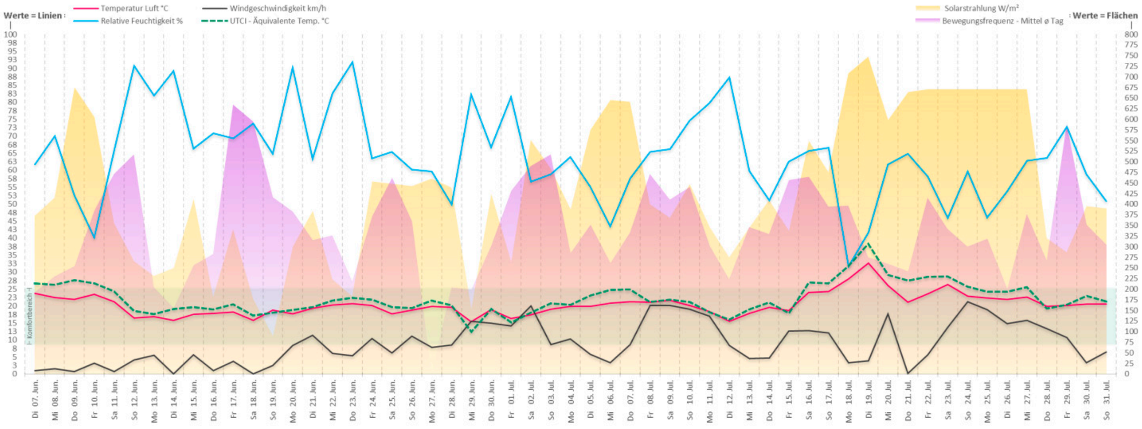

Figure 18. Tabular evaluation—all factors.

Low movement intensities are in a range of 100–150, regular frequencies around 300–400, and high frequencies are up to 600. These values have not a specific unit as the Modcam technology measures movement frequency e.g., how much movement is recorded in each of the 10 by 10 cm pixel. This does not indicate the amount of people moving, but the moving intensity at a certain point. The represented data is therefore a sum of recorded movements. Nevertheless, the data corresponds precisely to people's presence as it is increases during museum opening hours and shows peaks during weekends or bank holidays, independently from the UTCI-Score. Also, the different opening time on Fridays (10 a.m. to 9:30 p.m.) is precisely represented.

The graphs shown in Figures 18 and 19 were used as temporal overview over the entire observation period. The results do not show any strong correlations between UTCI Score and moving frequency, but they validate the assumption on the amount movement and—consequently—of people's presence. The graphical evaluation was used to carry out a more detailed analysis of the dependencies, in particular to determine more precisely stay time, paths, and positions under the pavilion.

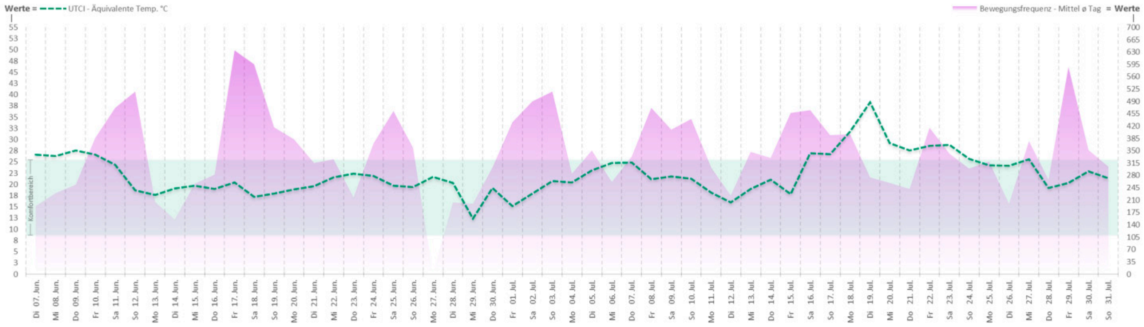

Figure 19. Tabular evaluation—UTCI and mobility frequency.

The graphical analysis bases on the observation, overlay, and evaluation of the maps created and shown on the website (elytra-pavilion.com) as a visualization of the recorded data.

To filter the consistent amount of frames, six representative days were selected corresponding to the three following criteria: A high UTCI Score, An average UTCI Score, and A low UTCI score. The days correspond to a hot sunny day, a cloudy dry day, and to a cold, rainy day. Due to this differentiation the frequency, the activity and the behavior is evaluated relating to the UTCI score. For each reference day a visualization of all movement patterns was done indicating peaks in movement frequency that allows for reading clear characteristics and tendencies. To each image, a corresponding picture of the UTCI is associated.

Figure 20 visualizes the data for 29th June and 1st July, as these two days have very similar climatic conditions. 29th June has an average UTCI-Score of 12.4 °C-ET and 1st July 15.2 °C-ET. Both days are far below the average value of 21.8 °C-ET of the entire survey period and are in the range of 'no thermal stress' close to the 'slight cold stress' range. Air temperature and solar radiation show low values, whereas relative humidity is higher than average. For those days, the mobility patterns are quite similar, although the frequency is higher on the second day; on 29th June, a Wednesday, movement frequency is very low, whereas, 1st July, a Friday, shows higher movement frequency. What is clear for both days is that the concentration of movement is located around the pond, on the oval segment next to the pavilion. Beyond this, no particular points show stronger occupancy that could correspond to a longer stay. This phenomenon can be related to the fact that most of people just pass by the pavilion to cross the courtyard. Due to the bad weather conditions, the structure has been used just as a rain protection while crossing the courtyard, in particular, because people only used the stone path on the floor and avoided the open roof elements that do not provide any protection from rain. The main difference for both of the days is the amount of movement in the transit area.

The evaluation shows that in the UTCI range between 12–15 °C-ET, the pavilion does not contribute to any specific comfort characteristic as it protects partially from rain but does not provide any protection from wind and side rain. In addition to that, the courtyard does not attract people during rainy cold days.

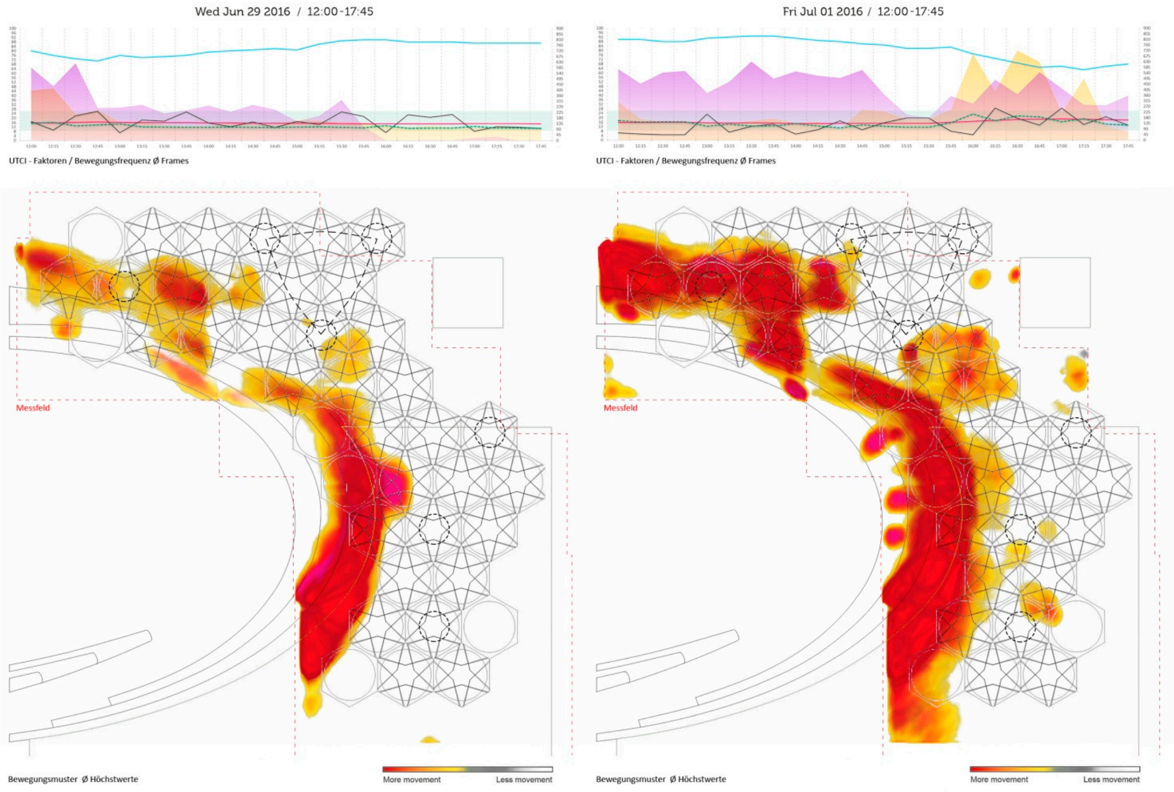

Figure 20. Graphical evaluation of cold and humid days.

Representative hot days, Monday 18th July and Tuesday 19th July, are the selected reference days for high UTCI values. They differ completely from the others as they have an average UTCI Score of, respectively, 31.8 °C-ET and 38.4 °C-ET. They are far above the average of 21.8 °C-ET. 18th July is in a range between 'strong heat stress' and 'very strong heat stress', July 19th between 'strong heat stress' and 'very strong heat stress'. The air temperature is 6 K below the UTCI ET, air humidity is low (32% and 42%), and solar radiation is in average 700 W/m^2 and 750 W/m^2. Wind velocity is very low.

The movement frequencies are related to the same time interval for both of the days, whereas on Monday 18th July, the value is higher than on Tuesday, which had been the hotter day. This phenomenon could be referred to the higher temperatures and to the consequent tendency of reducing movement due to the 'very strong heat stress'. Figure 21 shows completely different patterns when compared to Figure 20. There are no visible "paths", instead clear places where the movement frequency is higher. This means that people tended to occupy specific places for longer intervals that coincide with the shadow areas of the pavilion. Extremely relevant information that arises is the fact that people prefer to stay on the lawn or under the trees.

Combining the movement patterns with micro climate analysis was the primary aim of this research project. Furthermore, by looking at the intersection of people, place, and technology, this study provides answers to the original question: can microclimatic conditions shape behavior?

To answer this it is crucial to regard both subjective and objective parameters. As thermal comfort in an outdoor environment is a complex issue with multiple layers of concern, at the present stage, our study is limited to an objective observation, excluding subjective factors.

Due to data availability, the survey is limited to the summer period, is referred only to museum visitors and was carried out on considering only a specific sector of the V&A Museum's courtyard: these constraints were given by the project itself.

The analyzed data find its correlation in a model that overlays data on two different temporal scales and with two layers of concern: a wider scale that gives general information about weather condition and people's presence, and a more detailed scale that focuses on typical days with specific climatic conditions and visualizes movement in a higher resolution. Looking to the larger scale, air temperature seems to be the most influencing factor for the level of UTCI; e.g., poor comfort conditions correspond to a reduced presence of people.

Shifting to a higher resolution, there is not a strong recognizable dependency between UTCI and mobility patterns. That raises the question of if this is the right index to evaluate comfort. When comparing movement frequency to the single climatic factors, solar radiation and humidity emerge as the most influencing factors, and not the ET itself. Thinking of a development of the present project, an adaptive comfort model could be more appropriate to detect dependencies.

In general, humidity seems to be a factor that strongly affects comfort: both as an indicator for rainy days, as well as a source of evaporative cooling during hot days. Also, solar radiation is clearly determining people's presence—in sunny days it is consistently higher—because it influences the mobility patterns: during sunny hot days people rather choose shaded places and those close to vegetation. Both the lawn pavement sectors, as well as the areas around the trees, show higher movement frequency.

As a result, it seems clear that canopies have to provide proper shade and rain protection and must allow enough wind flows during hot days. Furthermore, they should integrate devices (also plants or trees) that can provide evaporative cooling or more in general cooling effects and higher wind velocities. A determinant factor is represented by the pavement material that should be considered as an element of the canopy as it influences T_{MR} and path finding.

Finally, when considering the typology of the Elytra filament pavilion—an open structure in a museum courtyard—the results show a clear tendency: under good weather conditions, outdoor comfort acquires more relevance on mobility patterns.

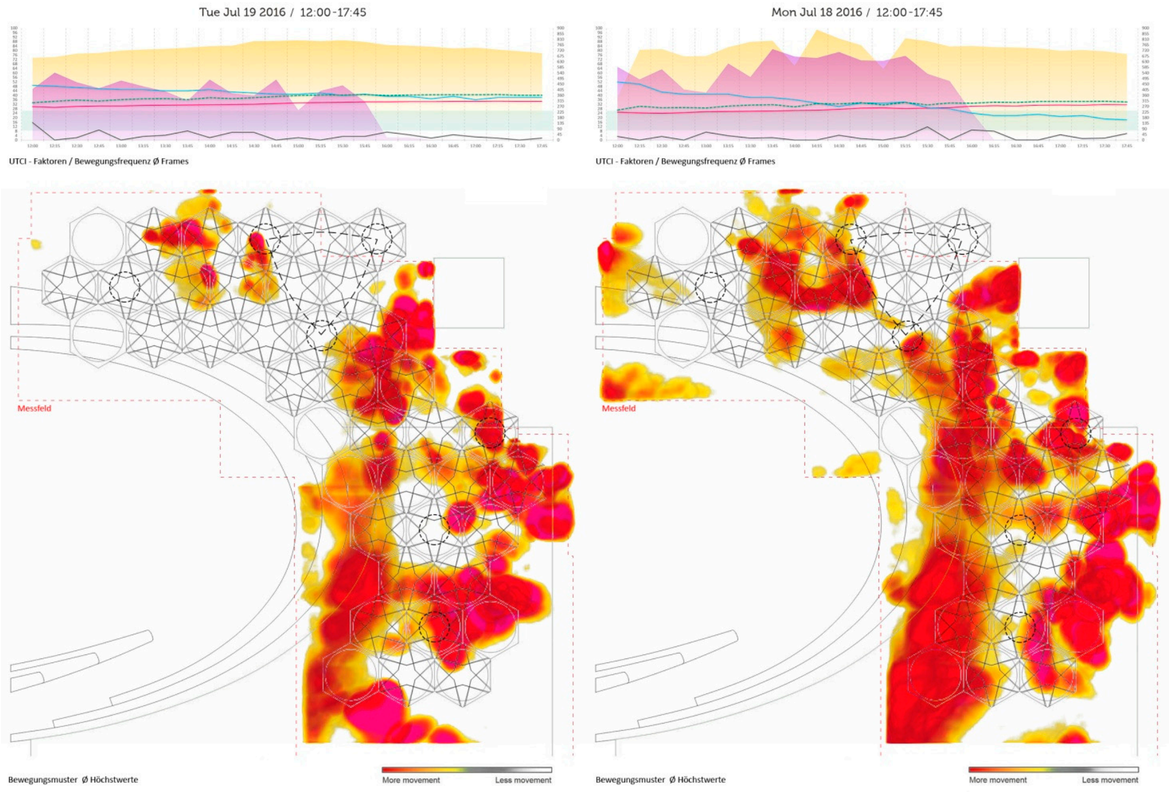

Figure 21. Graphical evaluation of hot, sunny days.

4. Conclusions

The outlined human centered approach provides a vision for the cities of the future, which aims to create a vibrant and healthy environment for people, which is able to mitigate thermal stress and is also prepared to recover from more frequent and more extreme climatic phenomena.

The idea of approaching the problem from human centered perspective gives the opportunity to study the phenomena in higher resolution in terms of human interactions with climatic conditions and urban structures. Furthermore this approach works as a bottom-up system, placing the human at the center of responsiveness considering needs, impacts and influences to start addressing solutions. At this point, it is not likely to quantify self-standing location-based recommendations, but the proposed methods could be applied in different contexts with diverse climate conditions and subjective votes, which obviously will drive into different assumptions and recommendations.

As a support, the presented tools are capable to explore and map invisible parameters, and drivers to prefigure through design and validation qualities of the urban environment considering the public realm at the center of social life. However, there is still room to focus and explore more on data mining concepts merging human behavior and microclimate conditions, since nowadays the availability of data is not the concern anymore, it is more about methods and techniques to map diverse layers of data as a key for predicting urban phenomena.

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