# ANALYZING THERMAL COMFORT OF TRANSITIONAL SPACES THROUGH CLIMATE RESPONSIVE DESIGN SOLUTIONS

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## ABSTRACT

## ANALYZING THERMAL COMFORT OF TRANSITIONAL SPACES THROUGH CLIMATE-RESPONSIVE DESIGN SOLUTIONS



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Amount of green spaces in the cities has gradually decreased and left its place to rapid construction as a result of the rapid increase in population and urbanization, causing the temperature difference between the city and the rural area to increase, resulting in the formation of Urban Heat Island (UHI) in cities. The necessity to create comfortable areas in dense cities increases the intensity of energy usage, requiring multi-layered studies to mitigate the urban heat island effect by developing climate-responsive design methodologies that are resistant to the impact of changing climatic conditions on the urban form and building envelope. This research aims to assess the efficacy of user comfort-based climate-responsive design techniques in mitigating the urban heat island effect. Within the scope of the study, the performance of mediating transition spaces between indoor and outdoor environments and climate-responsive design solutions on user comfort has been examined holistically, from neighborhood scale to building scale. Thus, as a strategy to reduce the urban heat island effect, it proposes using transitional spaces as a passive cooling strategy with climate-responsive design solutions.



Keywords: Transitional Spaces, Climate-Responsive Design, Urban Heat Island

# ÖZ

## GEÇİŞ MEKANLARININ TERMAL KONFORUNUN İKLİME DUYARLI TASARIM ÇÖZÜMLERİ YOLUYLA ANALİZ EDİLMESİ

Ulu, Ümmühan Nur
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Tez Yöneticisi: Assoc. Prof. İpek Gürsel Dino

Ocak 2023, 143 sayfa

Nüfusun ve kentleşmenin hızla artması sonucunda şehirlerdeki yeşil alan miktarı giderek azalarak ve yerini hızlı yapılaşmaya bırakmış, bunun sonucunda şehir ve kırsal alan arasında sıcaklık farkı artarak, şehirlerde Kentsel Isı Adası oluşumuna neden olmuştur. Yoğun kentlerde, konforlu alanlar yaratılma ihtiyacı enerji kullanım yoğunluğunu artırmakta ve bu durumda, kentsel form ve yapı kabuğu üzerinde değişen iklim koşullarına dayanıklı, iklime duyarlı tasarım yöntemleri oluşturarak kentsel ısı adası etkisinin azaltılması için çok katmanlı çalışmalara duyulan ihtiyacı gittikçe artırmaktadır. Bu çalışma, kentsel ısı adası (KSI) etkisini azaltmak için iklime duyarlı tasarım stratejilerinin performansını, kullanıcı konforunu temel alarak analiz etmeyi amaçlamaktadır. Bu çalışmada, iklime duyarlı tasarım çözümleri kapsamında, iç ve dış mekanı bağlayan geçiş mekanlarının kullanıcı konforü üzerindeki etkisi, mahalle ölçeği ve bina ölçeği olmak üzere bütüncül bir şekilde incelenmiştir. Böylece, kentsel ısı adası etkisinin azaltılmasına yönelik bir strateji olarak, iklime duyarlı tasarım yöntemleri ile geçiş alanlarının, pasif soğutma stratejisi olarak kullanımı değerlendirilmiştir.

Anahtar Kelimeler: Kentsel Isı Adası, İklime Duyarlı Tasarım, Geçiş Mekanları

To my family and Kiwi

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## LIST OF ABBREVIATIONS

ABBREVIATIONS

**AF:** Adaptive Façade

**AIP:** Adaptive Building Initiative

**ATC:** Adaptive Thermal Comfort

**BPS** : Building Performance Simulaiton

**BUHI :** Boundary Level UHI

**CC:** Climate Change

**CFD:** Computational Fluid Dynamics

**$CO_2$:** Carbon Dioxide

**CUHI**: Canopy-level UHI

**GUHI**: Substrate UHI

**HVAC:** Heating, Ventilation and Air Conditioning

**MRT:** Mean Radiant Temperature

**LCZ:** Local Climate Zone

**IPCC:** International Panel on Climate Change

**UTCI:** Universal Thermal Climate Index

**PMV:** Predicted Mean Vote

**PET:** Physiological Equivalent Temperature

**SUHI**: Surface Level UHI

**UHI:** Urban Head Island

## LIST OF SYMBOLS

SYMBOLS

**C** :  convective heat flow,

**ED** :latent heat flow,

**ERe** :sum of heat flows for heating,

**ESw** : heat flow due to sweat evaporation.)

**Esk** : Total rate of evaporative heat loss from skin, W/m,

**Eres:** Rate evaporative heat loss from respiration, W/m2

**f :** 200-term polynomial approximation.

M = metabolic activity,

$\eta$ = mechanical efficiency usually in the range of 0–20%.

**To**: Outdoor Running mean temperature (◦C)

**Top:** Operative temperature (◦C)

r :Node number

**Ta :** Air Temperature

**Tc:** Comfort temperature (◦C)

**Tmrt** = Mean Radiant Temperature

**Va** = Wind Speed

**RH** = Relative Humidity

**W** = physical effort

**R**: Radiant heat transfer, W/m2

u:Average wind velocity

# CHAPTER 1

# INTRODUCTION

INTRODUCTION

## 1.1 Motivation of Research

Since 1950, significant population expansion and urbanization have caused urban regions to have a greater population density than rural areas. Sixty-eight percent of the global population is expected to live in by 2050, up from fifty-five percent today (UN Department of Economic and Social Affairs, 2018). Cities' use of fossil fuels (coal, gas, and oil) is the major contributor to anthropogenic CO2 emissions, which are the primary driver of climate change (Stewart & Mills, 2021). As a demonstration, the built environment is responsible for between 25 and 40 percent of the total greenhouse gas emissions, and between 40 and 90 percent of these emissions are related to operational energy use within buildings (Yi & Peng, 2014). Furthermore, urbanization and the resulting expansion of the built environment and alteration of the terrain cause significantly different average temperatures in urban areas in comparison to suburban areas surrounded city. This situation created temperature difference described as Urban Heat Island by Luke Howard firstly (Parry & Chandler, 1966).

At the urban microclimate scale, UHI have a considerable impact on the temperature conditions surrounding and on the surfaces of buildings, and most notably, on the amount of energy used to cool such buildings (Kolokotroni et al., 2006). The effects of UHI on building energy consumption are significant since the majority of buildings and building energy consumption are in urban settings (X. Li et al., 2019) Besides the impact of building stock on UHI, climate variables (i.e.

air temperature, air relative humidity, wind speed) and the associated local synoptic weather conditions,thermal-optical characteristics of the materials, anthropogenic heat released, and the presence of heat sources in the areas all play a role in the manifestation of the UHI phenomenon (Mohammed et al., 2020). Therefore, there has been increased interest in conscious and resilient attempts at both the urban context and the building scale to mitigate UHI impacts (Mirzabeigi & Razkenari, 2022). Changing the building geometry, planting vegetation, using cool surfaces, and incorporating their effects on wind speed, air temperature, radiation, and humidity can be listed as common strategies focused on this research (Lai et al., 2019). Because the building envelope is strongly influenced by climatic factors and external conditions, it is critical to efficiently manage the building envelope within the context of building energy use (Lim et al., 2022). The construction of shading systems that respond to environmental and human inputs allows the conceptualization of versatile, responsive, and dynamic facades and can control solar radiation that can create thermal and visual stress for building occupants and raise cooling demands (Tabadkani et al., 2020). At this point, Hastings, (1989) summarized the interaction of climatic effects with the building by dividing the ways of interaction of the building with the environment into three groups; Climate-insensitive design, climate-combative design, and climate-responsive design.

Climate-responsive design is based on the concept that the building may operate as an environmental filter, in contrast to combative and climate-insensitive design, which are design approaches in which the connection between the structure and the surrounding environment is severely restricted (Looman, 2017a). This design method prevents undesirable external factors while useful ones are included. An essential point for building design is that the building acts as an intermediary between the interior and exterior environment, especially in climate-responsive design, which stands out with the depletion of resources and the search for sustainable methods (Sala Lizarraga & Picallo-Perez, 2019).

Climate–responsive design principles and UHI mitigation strategies promote the creation of thermal buffer zones, which provide passive cooling, natural ventilation, cross ventilation, breezeways, shading, and versatile interaction. As an example of these spaces, transitional spaces such as atriums and courtyards are integrated into buildings with architectural designs from ancient times(Taleghani et al., 2014).The courtyard concept is widely used in the traditional architecture of countries in hot, dry areas extending from Iran in the East to regions along the western coast of the Atlantic Ocean, as well as in the design of rural and urban dwellings (Fathy, 1986).  Similarly, In North Africa, single-story atriums collect cold night air and provide shade during the day, while in temperate regions such as Rome, atriums are used as passive sun collectors and wind shelters (Li, 2007).

In the same way as before, today, passive design strategies to mitigate UHI impact have recently gained popularity among professionals working in the construction industry, including architects, interior designers, and civil engineers. Transitional spaces, defined as the ‘in between’ architectural spaces where indoor and outdoor climates are modified without mechanical control systems, provide a passive cooling strategy for highrise buildings (Taib et al., 2014). In addition to the atrium and courtyard spaces, which have been used as climate-responsive design solutions since the past, sky courts and balconies incorporated in buildings to create thermally comfortable and socializing areas are also used in contemporary architecture in the highrise building typology (Taib et al., 2014). This study focus on evaluation of transitional spaces as a passive UHI mitigation strategy through climate-responsive design strategies based on façade and building form design.

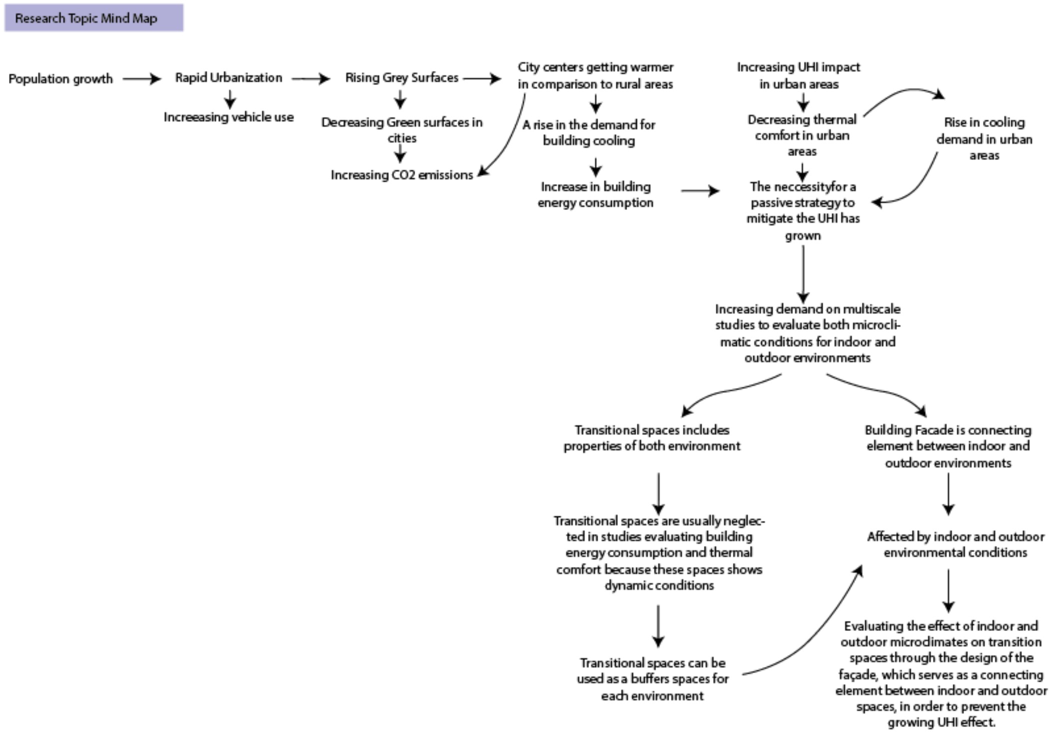



Figure 1.1. Thesis research topic mind map

## 1.2 Aim and Objectives

This study aims to investigate the evaluation of transition spaces in terms of thermal comfort and cooling strategy through climate-responsive design solutions as a passive technique to mitigate the growing heat island effect in cities. In this context, microclimatic data will be used to simulate and assess scenarios resulting from using climate-responsive design principles on building skin, form and surrounding area. By determining the user's thermal comfort indoors and outdoors at various scales, from the building to the neighborhood, the impact of these design solutions on UHI will be investigated, and their impact on occupant and pedestrian thermal comfort will be examined through indoor, outdoor and transitional zone thermal comfort analysis. Building form, material selection, facade design, and orientation were all addressed specifically for Ankara, Turkey, and adapted to the scenarios.

As a consequence of this, the following goals were intended to be accomplished with the help of this research:

- The impact of climatic-responsive design solutions (vegetation, kinetic façade, porosity, thermal buffer) on thermal comfort
- To analyze the effects of the vegetation in outdoor microclimate and thermal comfort
- Examining the effect of transition spaces, which act as a bridge between indoor and outdoor and accommodate both environmental conditions, on increasing user comfort as a passive cooling strategy
- Multi-scale analysis of the impact of climate-responsive design solutions on UHI from building scale to micro-urban scale

By combining different comfort analysis indices in these analyzes, evaluating the impact of climate-responsive design solutions and transition spaces on occupant comfort with the multi-scale simulation method comparatively.

## 1.3 Research Questions

As mentioned before, the purpose of this research is to address the following question:

- Is it possible to employ transition spaces in office buildings as a passive cooling strategy in order to increase user comfort through the implementation of climate-sensitive design solutions?

It is essential to find answers to the subsidiary questions that are stated below in order to provide a response to this inquiry.

1- 1- Is it possible to use climate-responsive design solutions as a cooling strategy by using transition spaces?
2- How does the use of climate-responsive design solutions at the neighborhood scale impact the level of user comfort experienced outdoors?
3- How do Preventive and Spatial climate-responsive design solutions affect user comfort in indoor, outdoor and transition areas?
4- How does the singular and combined use of preventive and spatial solutions affect user comfort?
5- Which climate-responsive design scenario is most effective in providing user comfort?
6- Which climate-responsive design scenario exhibits the lowest performance?

## 1.4 Thesis Structure

This thesis consists of six chapters in order to achieve the research's goals and objectives. The thesis's content and arrangement are described in the introductioon chapter. Moreover, thesis motivation, objectives and objectives, and brief thesis methodology are included in this chapter. Chapter 2 and Chapter 3 are the literature review and research methodology, which aim to establish the basis for the fundamental research by understanding the current knowledge and research status of thermal comfort in transitional spaces and climate-responsive architecture. While the main concept of chapter two is UHI and transitional spaces, the primary concept of chapter three is climate-responsive architecture and façade design. The phenomena of urban heat islands and the phenomenon of climate change are both defined at the beginning of the second chapter. The second section discusses transitional spaces, thermal comfort for transitional zones, and indoor and outdoor microclimates. Chapter 3 introduces the concept of climate-responsive architecture, including its relationship to façade design and climate-responsive design solutions, with the final section explaining climate-responsive façade design and its impact on transitional spaces. Chapter 4 evaluates climate-responsive design solutions which aim to create comfortable spaces using transitional spaces with the EnergyPlus building performance simulation tool integrated with Honeybee occupant comfort analysis tool and simulation parameters and process explained. Chapter 5 represents analysis results thoroughly discussed and presented per each scenario, respectively, neighborhood scale outdoor thermal comfort analysis, thermal comfort in transitional spaces, and building indoor thermal comfort results. Lastly, conclusion section includes discussion and explanation of research in accordance with aims and objectives and results.

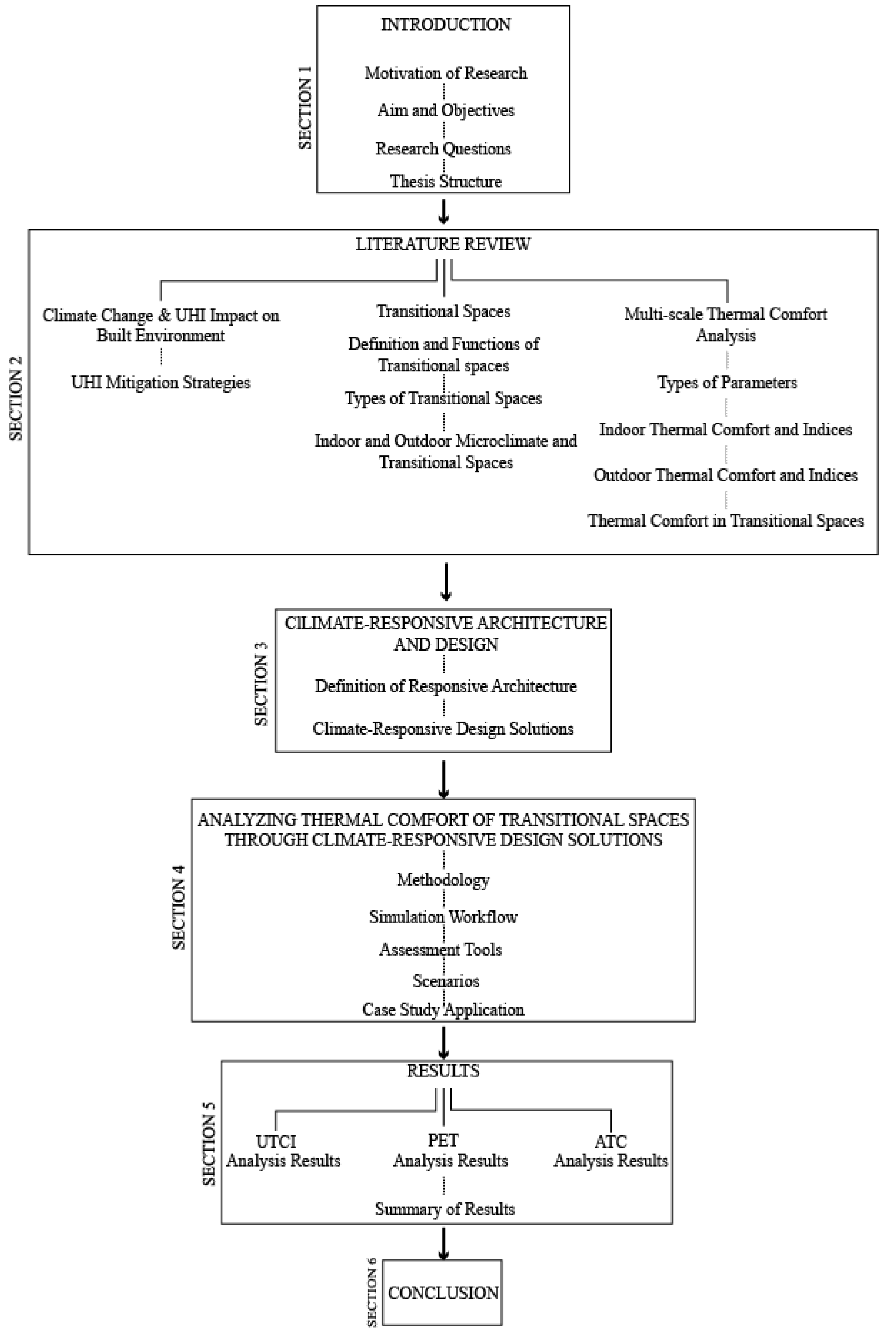



Figure 1.2. Thesis structure workflow

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Climate Change and Urban Heat Island Phenomenon Impacts on Built environment

According to the IPCC 2014 report, for the last three decades, the earth's surface temperatures have been gradually increasing before 2014 when monitored, originating in 1850 (Pachauri et al., 2014). Cities now experience significantly differing temperatures from their surroundings due to increased urbanization, rising global warming, and climate change (countryside). Due to the high quantity of exposed surface per unit of ground cover, urban areas typically absorb more solar radiation than flat, open terrain. Additionally, due to the absence of vegetation in urban settings, a greater proportion of incoming energy is converted to sensible heat. In contrast, in rural regions, energy is transferred to latent heat. Consequently, heat is retained inside the urban fabric and slowly released at night, creating an temperature increase in cities. (Budhiraja et al., 2020). Urban Heat Island phenomenon is defined as cities having higher temperature values than suburban areas and was first realized in London by Luke Howard (Howard, 1833). The UHI effect results from several different factors interacting with one another. These factors include the surface cover, the heat released by anthropogenic activities, and the characteristics of urban areas, such as geographic features and climatic conditions (Yamamoto, 2005). In addition to that, technological advancements contribute to the UHI effect, especially with the use of air-conditioning. In addition to increasing heat production and localized rising temperatures, more air conditioners affect cooling demand and human comfort (X. Li et al., 2019). On a broader scale, the usage of more air conditioners increases the generation of greenhouse gases due to the increasing energy consumption (Grimmond, 2007). UHI is composed of four distinct types (Stewart & Mills, 2021):

a- The canopy-level UHI (CUHI) is calculated using the near-surface air temperature recorded underneath roof height.
b- Boundary Level UHI (BUHI) is determined by air temperature measurements taken significantly above the height of city structures.
c- The Surface Level (SUHI) is calculated using the average temperature of the ground, walls, and rooftops that constitute an urban area;
d- Substrate UHI (GUHI) is calculated using the average temperature of the soil under the ground.

Variances in air temperature between urban and rural areas are mostly found at night, but the most significant differences in radiant surface temperature are recorded around midday. Strong microscale fluctuations in surface temperatures resulting from changes in radiant load, shading, and differences in surface thermal and radiative properties are the primary driver for SUHI (Voogt & Oke, 1997). It means that both open spaces and built environments in urban should be considered simultaneously since they affect each other.

Due to climate change on a global scale and urban heat island effects on a local scale, the building stock is under thermal stress, increasing the energy consumption necessary to cool interior areas (Ricci, et al., 2021). People prefer to spend almost all their time inside because of the disagreeable temperature fluctuations between indoors and outdoors (Al Horr et al. 2016). Since studies on the performance of buildings or urban environmental performance studies focus mostly on a non-holistic approach, integration of building performative aspects and urban performance in the early design stage can help simultaneously achieve environmental quality goals such as daylight and outdoor comfort (Natanian & Auer, 2020).

### 2.1.1 UHI Mitigation Strategies

Reduced vegetation and evapotranspiration, increased presence of dark surfaces with low albedo, and elevated levels of anthropogenic heat output all contribute to the heat island effect, which is a consequence of the changing nature of contemporary cityscapes (Stone et al., 2010). Consequently, an urban area's surface conditions will directly influence the selected UHI mitigation techniques. Negative impacts of UHI observed over time give a roadmap to develop mitigation strategies (Mohajerani et al., 2017). Within this context, numerous mitigation techniques have evolved, such as pavement materials, green surfaces, and low albedo surfaces, within the scope of urban surfaces as well as evotransporative approaches such as water elements, evotransporative and water retentive surfaces, and green and blue infrastructure are also diversified. These techniques aim to reduce the warming effect of urban surfaces by focusing on solar reflectance, emittance, and evapotranspiration levels. The 80+ method is clearly documented in the Cooling Singapore project guide (Ruefenacht & Acero, 2017). Various cooling measures are evaluated in nine categories: vegetation, urban geometry, water bodies and features, materials and surfaces, shade, transport, energy, glossary, and people. In accordance with this measure, building strategies are classified as cool roofs, cool facades, dynamic and active façades, shading on buildings, window-wall ratio, and buffer zones.

In general, as well as specific categories, UHI evaluation and development of mitigation strategies depend on the condition of cities. Urban environments change over time as a result of varying levels of urbanization. In some cities, as a result of rapid urbanization, high-rise building construction increases, while in some cities, the development is slower, and the construction progresses in this direction as an example (Grimmond, 2007). In order to conduct more precise and region-specific analyses, Oke and Steward developed the "local climate zone" (LCZ) classification for UHI, which had previously been studied using two different climate zone classifications, rural and urban (Stewart & Oke, 2012). Each LCZ has a unique mix of surface structure (building/tree height and spacing), cover (previous fraction), fabric (albedo, thermal admittance), and metabolism (anthropogenic heat flow); thus, each LCZ has a differentiating characteristic (Stewart et al., 2014).

It has been observed that mitigation strategies developed for UHI focus on cities, (UN Department of Economic and Social Affairs, 2018) since cities' use of fossil fuels (coal, gas, and oil) is the major contributor to anthropogenic CO2 emissions, which are the primary driver of climate change (Stewart & Mills, 2021).
Based on their research into the microclimate and thermal simulation of partial applications, Chatzidimitriou et al. (2013) concluded that the use of cool pavement material, the installation of trees, the use of vegetation shading canopies, the presence of water spots, and the evaporation of vegetation all have a negligible impact on the air temperature but a much larger impact on surface temperature. Similarly, In simulated scenarios, Battista et al. (2020) concentrated on the lack of green zones and water resources and examine mitigation strategies such as enhancing urban vegetation to create shaded areas and employing cool pavements and green canopy. Using digital methods like parametric modeling and multi-objective optimization, Loh & Bhiwapurkar (2022) notably concentrated on developing a design workflow for balancing the indoor and outdoor environment. (Prihatmanti & Taib, 2017) focus on transitional spaces integrating balconies with greenery to overcome decreasing green ares in cities causing rise in UHI. Similarly, Golasz-Szolomicka & Szolomicki, (2019) represents application of vertical greenery in highrise buildings examining Bosco Verticale in Milan, Nanjing Vertical Forest Tower in Nanjing, in Australia, Hotel Oasia Downtown in Singapoure and latly, Beirut Terraces in Beiurut. Research presents that integration of vertical gardens provide a reduction of the UHI greenhouse effect, improvement air quality and energy efficiency influencing heat transfer between interior and exterior environment and protection from UV radiation. Based on the scope of UHI mitigation analysis, building porosity, passive cooling systems, building form, building material and surface and vegetation will be evaluated within different scenarios in this thesis.

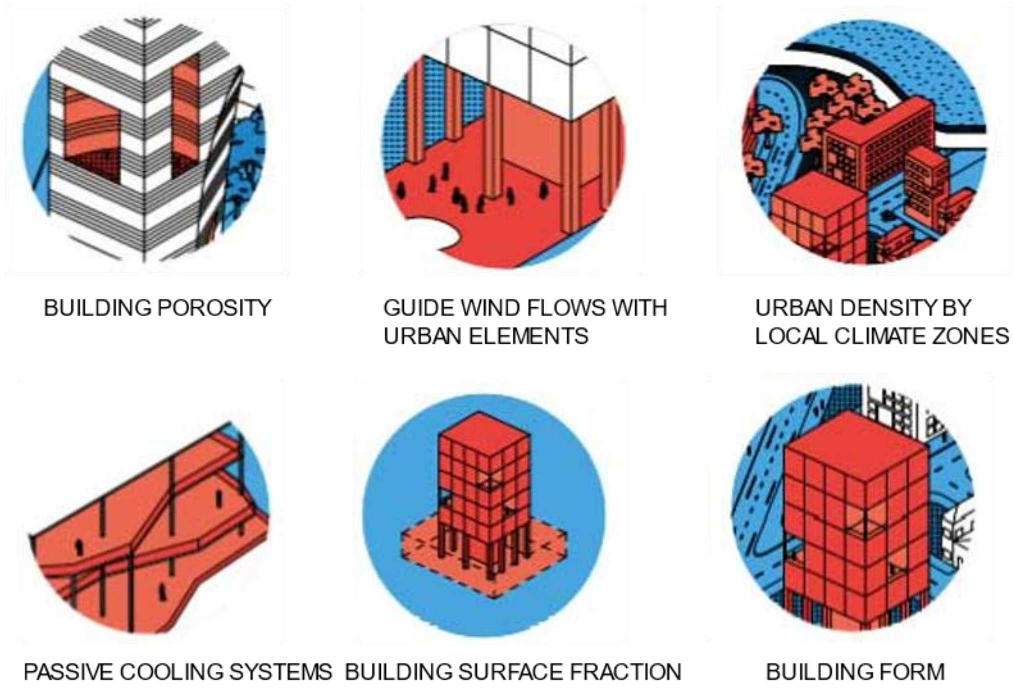



Figure 2.1. Strategies for mitigation of UHI impact (Ruefenacht & Acero, 2017)

## 2.2 Transitional Spaces

Transitional spaces, which interact with indoor and outdoor areas and are described as buffer zones, have been used as a passive cooling strategy since the past, but are still seen as potential areas in order to reduce energy consumption and create comfortable spaces that interact with the outdoor ((Baiz & Fathulla, 2017; Cantón et al., 2014; Kwong & Ali, 2011; R. Li, 2007; Pitts, 2013; Pitts & Saleh, 2006; Sher et al., 2019; Soflaei et al., 2016; Taleghani et al., 2014). Within the scope of this research, in order to examine the impact of transitional spaces on user comfort as a passive cooling method, the definition, kinds and functions of transitional areas to be evaluated are outlined below.

### 2.2.1 Definition and Functions of Transitional Spaces

#### 2.2.1.1 Definition of Transitional Spaces

The definition of Transitional spaces includes many different definitions, as the word transient allows for different interpretations, but the most general definition is; spaces located in-between indoor and outdoor environments. A transition space is an area that processes a movement from one condition to another, is positioned between outside and inside settings, and acts as both a buffer space and a physical link, in addition to functioning as a circulation channel for the building(Chun et al., 2004). It is an important part of any public structure, occupying a great deal of space (Padmaperuma et al., 2020; Pitts & Saleh, 2007). At this point, if the concept of transitional space is to be reconsidered in line with the purpose and scope of the study since it is a concept that includes many different definitions, in this study transitional spaces hold on definition below:

*Spaces that mediate between indoor and outdoor environments and provide a comfortable space for users by protecting them from undesirable factors*.

#### 2.2.1.2 Types and Functions of Transitional Spaces

Transitional spaces can be incorporated into building design as a strategy to create a response to the environment by concentrating on the placement of the balcony to reduce the room's exposure to heat and by incorporating wide terraces that can be used to create a garden that serves as a natural sunshade (Lima & Hamzagic, 2022). In the case of UHI mitigation performance, balconies can improve ventilation performance up to %80 besides indoor air quality and natural ventilation and 1.5-2.5 m depth balcony can reduce daylight by 30-35% (Ribeiro et al., 2020).

Figure 2.2. Vernacular Turkish house balcony  (external sofa) attachment (Bozdogan, 1996)

Since ancient times, buildings have included transitional spaces to offer passive cooling and locations for people to socialize in the courtyard and atria.  Traditional courtyard houses are one of the best examples of climate-responsive architecture since they were created, paying particular attention to the climatic requirements as well as the socio-cultural contexts in which they were built (Soflaei et al., 2016). The courtyard provides needed shelter from the sun in hot areas, dissolves the continuity of wind-generating microclimates in cold climates, and increases the porousness of buildings (through courtyards) to allow for air circulation in humid regions (Rodríguez Álvarez, 2021).  In traditional Anatolian architecture, courtyard spaces (avlu, havlu, hayat, bahçe) are accepted as multipurpose spaces and highly influential factors in shaping dwelling units. As a result of excavations conducted in Central Asia, it is discovered that the earliest dwellings were buildings with small courtyards and adjacent small properties (Cezar Mustafa, 1977).

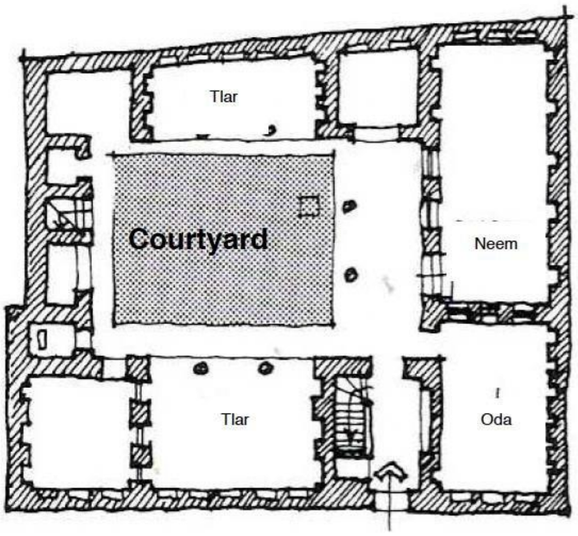



Figure 2.3. Ground floor plan drawing (Schoenauer, 2000)

The courtyard, where the shadow constantly changes at various times of the day, is a focal point for the transition to all units and a multifunctional space where many activities are held. Closed and semi-open spaces are arranged around this important space. However, this sequence is not random but the product of a conscious design strategy. In general, there are summer places in the south of the courtyard and winter places in the north. In some residences, in addition to the summer and winter spaces, there are autumn spaces to the east of the courtyard and spring spaces to the west. The positions of the seasonal sections around the courtyard are indicators of strategies to avoid or benefit from the sun (Bekleyen et al., 2014).

In addition to the courtyard spaces, at the beginning of the 19th century, metal and glass became essential parts of architecture. This changed the old style of courtyards and turned the old idea of a courtyard house into the fundamental idea of an atrium (Li, 2007). Atrium spaces can perform as a solar collector and buffer zone, reducing the parent building's convection and conduction heat loss, and integration to the ventilation system saves energy (Baker & Steemers, 2000).

Figure 2.4. Atrium ancient times, (Encyclopædia Britannica, n.d.)

Figure 2.5. Case Study Building Section represents breezeways and transitional spaces

In conclusion, transitional spaces have been included in our living spaces since the past in order to adjust effectively to climatic conditions. In contemporary high-rise buildings, semi-outdoor areas can be seen in the form of balconies, atria, courts, decks, and terraces, all of which have varying degrees of influence on the building's shape. Within the scope of this research, atrium spaces, balconies, and terraces are included in a case study to examine passive methods for increasing user comfort and minimizing cooling energy demand in high-rise buildings.

### 2.2.2 Types of Transitional Spaces

The definition of Transitional spaces includes many different definitions, as the word transient allows for different interpretations, but the most general definition is; spaces located in-between indoor and outdoor environments. A transition space is an area that processes a movement from one condition to another, is positioned between outside and inside settings, and acts as both a buffer space and a physical link, in addition to functioning as a circulation channel for the building. It is an essential part of any public structure, occupying a great deal of space (Pitts & Saleh, 2007)Chun et al., (2004), divide transitional spaces into three categories according to their relationship with the building, which provides to consider related components; type 1 is referred to lobbies and entry atriums which are transitional spaces contained within a building (Gamero-Salinas et al., 2021).  Type 2 indicates balconies, porches, and corridors covered streets or arcades attached to building and under the influence of outdoor conditions. Type 3, as bus stations, pavillions, and pergolas, are essentially outdoor rooms directly influenced by their materials and design. Similarly, Pitts & Saleh, (2007) categorize transitional spaces into four different types according to interaction with the rectangular building.The first one is a linear transition in front of the shorter facade; the second is an area in the middle portion of the long facade of a building; the third is a space ran parallel to the longer axis of the building, and the last one is the external perimeter corridor around the outside of the building. However, when space is considered between indoor and outdoor environments, semi-outdoor spaces can also be counted as transitional spaces. An example is the semi-outdoor spaces in high-rise buildings, which are integrated into the building so that users can experience the outdoor environment. These zones, which are divided into 5 themselves, are, respectively, perimeter buffers, sky terraces, breezeway atria, horizontal breezeways, and vertical breezeways (Gamero-Salinas et al., 2021a) .

In this case, covered space connected to the building (or between facilities, where outdoor conditions predominate, such as a balcony, corridor, and courtyard/atria zones, will be the focus type of transitional space.

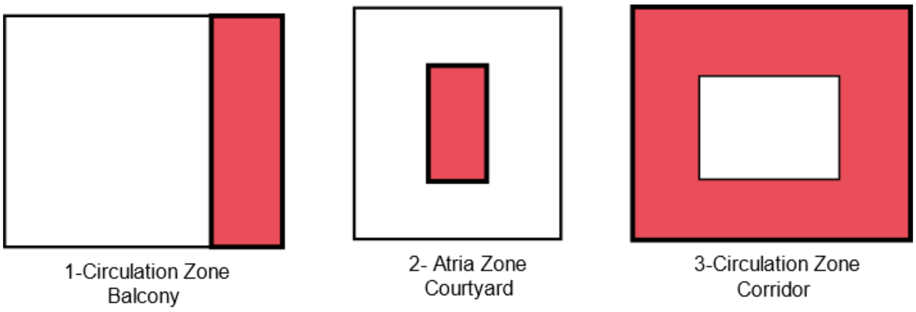



Figure 2.6. Types of transitional spaces

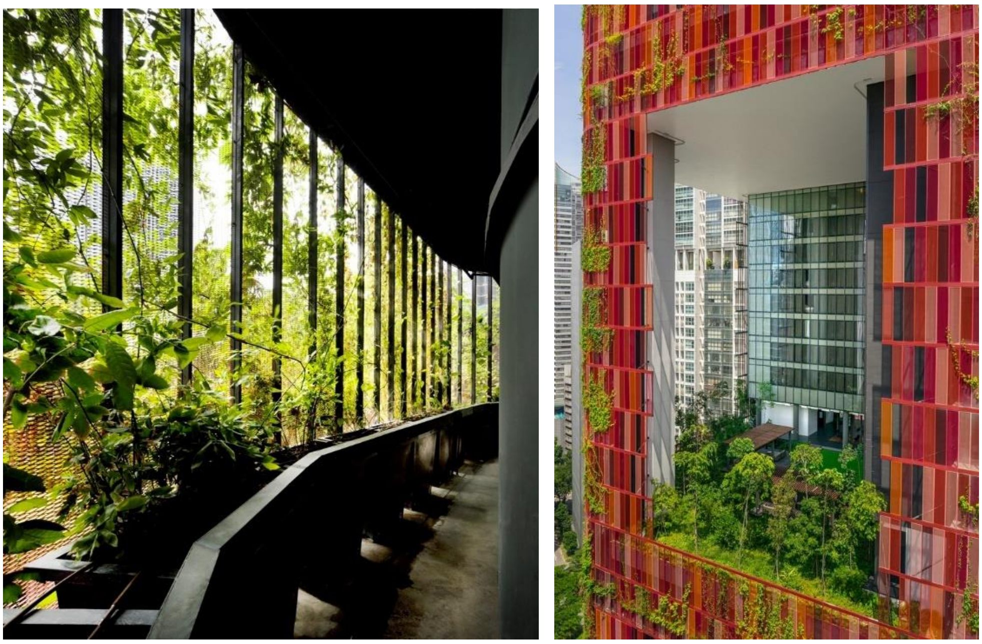


Figure 2.7. Examples of the contemporary transitional spaces from Oasia Hotel in Singapore (circulation zone left, sky terraces right)(Kopter & Bingham Hall, 2016)

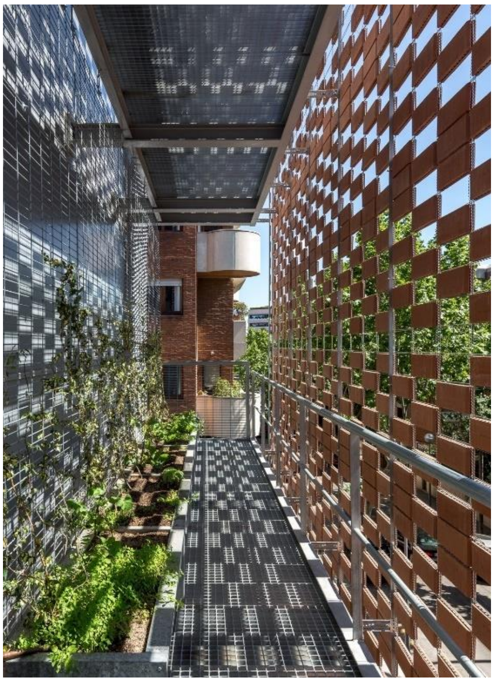


Figure 2.8. Examples of the contemporary transitional space Teresianas School, Bercelona Spain (García, 2014)

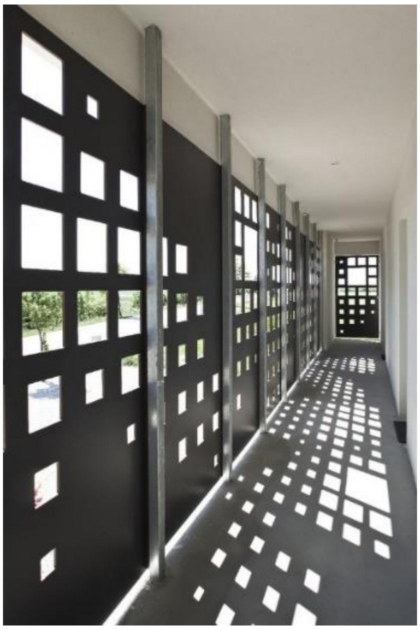


Figure 2.9. Examples of the contemporary transitional space Caldor Hotel (Wurnig, 2009)

### 2.2.3 Indoor and Outdoor Microclimate and Transitional Spaces

The temperature and dynamic characteristics in the atmospheric layer that are directly impacted by the underlying surface are what constitute the microclimate of a particular area. At the local level, surface characteristics that regulate the transfer of radiation, energy, momentum, and water between the ground and the atmosphere are the primary determinants of climate (Hu et al., 2016). Radiation, temperature, humidity, wind speed, and pressure (density) are climate variables considering microclimate for a specific location (Rotach & Calanca, 2015). According to this definition, urban microclimate depends on its own physical environment and the characteristics of cities as a result of the interaction between the surrounding physical context (Oke, 1988). Wind speed and direction, local heat transfer conditions, air, and building surface temperatures, and ultimately building thermal and energy loads all interact extensively among buildings and their surrounding microclimates ((Leon) Wang & Shu, 2021)

Continuous global warming and climate change affect urban microclimate and may impact indoor environmental conditions and indoor thermal comfort via energy efficiency (Yi & Peng, 2014). For the assessment of the effects of urban heat islands on buildings, indoor microclimate condition analysis is crucial in addition to urban microclimate evaluations ((Leon) Wang & Shu, 2021). The indoor microclimate of a building consists of measurable physical factors such as air and energetic exchanges between the atmosphere, objects, and people. Physically, this may be represented as an open system that exchanges mass and energy with the surrounding structures (Fabbri et al., 2019). Indoor thermal comfort neutrality is strongly connected to the outdoor temperatures for free running buildings. Naturally ventilated indoor environment and outdoor temperatures provided high correlation ($r^2$=0.91)(de Dear & Brager, 1998)
In addition to thermal comfort, the energy consumption of a building relies on factors such as solar loads, outside air temperature, and air velocity. In this case, it is crucial to examine the impact of urban microclimate changes on energy usage ( de La Flor & Domínguez, 2004) since energy usage affected directly greenhouse emissions for operational energy use(Yi & Peng, 2014).

In order to decrease energy use intensity in buildings, passive strategies have gained attention. Transitional spaces which provide interaction with natural environment bridges between indoor and outdoor environment and gained attention for energy saving potential. In transitional spaces, indoor and outdoor climate is modified without mechanical controller and this provides a dynamic behaviour (Pitts, 2013). As an example to transitional spaces improving microclimate, courtyards provides thermal regulation in the case of higher temperatures(Diz-Mellado et al., 2021). Similarly, veranda as a transitional spaces, provides a sun protection preventing interior spaces from overheating and direct solar radiation(Taib et al., 2014). In the higheise building, transitional spaces also named semi-outdoor spaces affects microclimatic and thermal conditions. For instance, while vegetation decrease the ambient temperature, higher amount of voids increase solar radiation. However, thermal comfort performance of semi-outdoor spaces depends on type( skycourt,balconies,terraces,atria) of the transitional spaces attached to the building (Gamero-Salinas et al., 2022).

The thermal comfort analysis of transitional spaces, which is regarded as a passive cooling approach, will be assessed within the context of this study based on indoor and outdoor thermal comfort studies as it is impacted by interior and outdoor environmental conditions.

### 2.3 Multi-Scale Thermal Comfort Analysis

Thermal comfort definition is "…that condition of mind that expresses satisfaction with the thermal environment"(ASHRAE, 2017). Two main models underpin thermal comfort knowledge the steady-state heat-balance theory model (Fanger, 1970) and the adaptive model (de Dear & Brager, 1998).  The use of these models, which were originally created to assess interior air quality, has been expanded to include outdoor settings (Shooshtarian et al., 2020). Because this study adopts a holistic point of view, it has been analyzed in the literature review in terms of the thermal comfort of indoor, outdoor, and transitional environments, along with the chronological progression of improvement.

Humans, the main concern in the thermal comfort analysis, are homeothermic, which means they can maintain their core temperature to a limited degree through thermoregulation, even under extreme cold or heat. The core temperature should be stabilized at around 36.5 degrees Celsius (Choi & Loftness, 2012). The core temperature will be substantially higher or lower than usual when the human body is subjected to extreme thermal disturbances, and the human body's control is unstable. The human body experiences to some extent when the core temperature reaches a particular limit for an extended period of time (greater than 1 hour and higher than 38.5°C or less than 35°C)(Boregowda et al., 2012). As a result, numerous research has focused on the human body's thermal and cold reactions, as well as how people interact with their surroundings (Fiala et al., 1999). In this respect, A number of thermal comfort models based on people's thermal sensibility to the environment have been developed since the 1970s (Zhao et al., 2021)They have steadily become an essential element of thermal comfort research. Thermal comfort models are helpful for analyzing our comfort in our environment because they allow us to reduce the amount of energy we spend trying to regulate our body temperature with the aid of external factors. Comfort can be anticipated using these models in contexts where the user is exposed to various conditions, which is an essential consideration when designing user-friendly buildings. The thermal comfort standards currently most used and discussed in new comfort model trials: ASHRAE 55-2016 and ISO 773. are based on Fanger's model (ISO, 2005). This model is one of the most well-known. However, it is unsuitable for outdoor and sleeping environments since it uniformly considers the environmental circumstances. Similarly, because it is based on the adult age range as a metric, the model is not suited for thermal comfort analyses for the elderly. In this respect, The first classic thermal comfort model is the PMV model (Predict Mean Votes), based on Fanger's human thermal balance equation. When Fanger's PMV model (Fanger, 1972) s integrated with the thermal regulation theory of the human body, it is shown that the human body is able to attain a state of thermal comfort in a building under a certain combination of heat and humidity circumstances (Zhao et al., 2021). As a result, the PMV model, which uses the ARSHREA55- 2004 Standard 7-point scale,(Ashrae, 2004) is often used to assess the thermal comfort of the indoor environment (Schellen et al., 2013). The PMV model, on the other hand, was developed with the assumption that the space to be conditioned would be static and homogenous throughout(Zhao et al., 2021) It is inapplicable to dynamic situations since it assumes uniformity and a constant condition throughout, excluding areas like courtyards (M. A. Humphreys & Fergus Nicol, 2002).

Thermal comfort models distinguish according to the environment that will be applied. Höppe mentions two main factors causing a difference between indoor and outdoor thermal comfort as psychological and physiological aspects (Höppe, 2002) At this point, the expectation of a certain thermal situation is essential in a subjective analysis and the case of satisfaction. However, in addition to psychological factors, the difference between indoor and outdoor thermal comfort also depends on physiological effects. At the beginning of this difference, we have to adapt to conditions outside our control, although there is a more controllable environment indoors. Perera et al. (2020) separated the adaptive opportunity into three different processes:

• Physical adaptation (behavioral adjustment)
• Physiological adaptation (genetic adaptation or acclimatization)
• Psychological adaptation (habituation or expectation)

### 2.3.1 Types of parameters

Occupant thermal comfort is determined by the body's ability to maintain a stable core temperature, which in response is impacted by two primary sets of factors (de Dear & Brager, 1998) : personal and ambient parameters.
The heat balance of the body determines the thermal comfort of individuals within buildings. Two key types of variables that influence the body's thermal balances are personal parameters and ambient parameters (Enescu, 2017).

**Personal parameters;**

Specifically, the following are examples of personal parameters that represent occupant characteristics:
• **Clothing insulation** Clo units (1 clo =155 m2 oCW*) are used to quantify the thermal insulation provided by an item of clothing (Icl).
• **Metabolic heat rate,** The rate at which a person's body creates heat, is measured in met units (1 met = 58.2 W m2) (internal heat generation of the body).

**Ambient parameters;**

Environmental parameters affecting occupant comfort.

- **Air Temperature :** Factor affects the magnitude of heat that is lost via convection from the surface of the body to the surrounding environment, or vice versa if the air temperature is higher than the temperature of the skin.(Havenith, 2005)

- **Radiant Temperature :** This parameter, which can be thought of as the average temperature of all the walls and objects in one's living area, impacts how much radiant heat is transferred from the skin to the surroundings. Radiant heat transmission occurs when the environment's temperature is higher than the body's natural temperature, as happens while working in the sun or around very hot things. (Havenith, 2005)

- **Surface Temperature:** The temperature of the items in contact with the body influences heat transfer through conduction. In addition to the object's temperature, its properties, such as conductivity, specific heat, and heat capacity, are important for conductive heat transfer.(Havenith, 2005)

- **The air velocity**Air velocity [m s-1] is the rate at which the air flows over a specified distance in a specified time.When air velocity reaches 40 fpm or low temperatures are coupled with air movement, discomfort can emerge (Bandarupalli, R. H.,2007).

- **The relative humidity**: RH, is calculated by dividing the observed (actual) maximum saturation of the atmosphere by the water vapor pressure that the air is capable of holding at a certain temperature.(Dainoff, 2001).

### 2.3.2 Indoor Thermal Comfort and Indices

Thermal comfort is altered by the thermal interaction between the body and its surroundings. Six important parameters influence this thermal interaction: air temperature, air velocity, humidity, mean radiant temperature, clothing insulation, and metabolic rate (d'Ambrosio Alfano et al., 2011). The first four variables determine the characteristics of the surrounding environment, while the latter two are "personal" variables that might differ across individuals.

The Predicted Mean Vote (PMV) model, which Fanger made in 1972, is the one that is most often used to evaluate the indoor thermal environment. It presupposes that responses to thermal stimulation are entirely physiological and unaffected by factors such as ventilation and climate. For thermal evaluation, PMV employs the use of two occupant criteria (clothing value and metabolic rate) and four interior parameters (mean radiant temperature, air temperature, relative humidity, and air velocity) (Mui et al., 2020).

Due to inconsistencies between the PMV model and field surveys, the model's generalizability has been questioned, and Humphrey discovered a substantial correlation between indoor comfort temperature and external climate, indicating that climatic factors may have a significant impact on thermal comfort in buildings with natural ventilation (Humphreys, 1978; Mui et al., 2020). As a result, de Dear and Brager created an adaptive model of thermal comfort that considers how people adapt to their surroundings (Brager & de Dear, 1998). In contrast to the PMV/PPD model, the Adaptive Thermal Comfort model (ATC) is used in both ASHRAE Standard 55-2017 and EN 15251 for naturally ventilated buildings (Albatayneh et al., 2019). Thus, adaptive thermal comfort, which is a function of both the potential for change and the actual temperatures obtained, and it can enlarge the comfort zone with significant impacts on the operation of the cooling system, can be assessed through this model. Soflaei et al., (2020) investigates the design of courtyards as a passive technique for achieving interior thermal comfort and improved energy efficiency in contemporary U.S. residential structures.

Similarly, in this study, which aims to analyze the user comfort of using transitional spaces within the scope of climate-responsive design solutions, the ATC model will be used for indoor thermal comfort analysis.

#### 2.3.2.1 Indoor Thermal Comfort Indices

**a- Predicted Mean Vote (PMV)**

The PMV index only predicts reactions in a steady-state air-conditioned environment. (Katić et al., 2016). The PMV index is calculated using the Fanger comfort equation for human body heat Exchange (Fanger, 1972). Four physical factors (air temperature, air velocity, relative humidity, and mean radiant temperature) and two personal factors determine the PMV index (metabolic rate and clothing).

**b- Adaptive Thermal Comfort Model (ATC)**

ASHRAE 55 is the basis for the European thermal adaptive comfort standard BS EN 15251, and the temperature at which people feel most at comfortable is determined in the same method (similar equations but with different coefficients). The equation that can be used to determine the adaptive thermal comfort temperature for free-running buildings, often known as the comfort temperature Tc, is as follows: (Albatayneh et al., 2019)

$$T_c = 17.8 + 0.31 \times T_o$$

*To: Outdoor Running mean temperature (◦C)*

*Tc: Comfortable temperature (◦C)*

At indoor air speeds at or below 0.1 $m.s^{-1}$ Operative Temperature may be taken as (Nicol & Humphreys, 2010):

$$T_{op} = 1/2T_a + 1/2\ T_{MRT}$$

*Top: Operative temperature (◦C)*

*Ta : Air Temperature*

*$T_{MRT}$: Mean Radiant Temperature*

### 2.3.3 Outdoor Thermal Comfort and Indices

Previously, it was commonly considered that indoor thermal comfort theory generalizes to outdoor settings without modification in the lack of actual outdoor thermal comfort studies.(Spagnolo & de Dear, 2003) Because studies on indoor thermal comfort are widespread and production is higher in this direction, the foundation of studies for outdoor thermal comfort began with the examination and adaptation of indoor thermal comfort indices, and indices such as UTCI and PET emerged later for outdoor thermal comfort (Johansson et al., 2014; Potchter et al., 2018).

#### 2.3.3.1 Outdoor Thermal Comfort Indices

**a- Predicted Mean Vote (PMV) ,**

The Predicted Mean Vote (PMV) is the average thermal sensation vote of a group of individuals (from -3 to +3 for hot), and it is connected to the Predicted Percentage of Dissatisfied (PPD), which reflects the number of persons who are dissatisfied with the thermal environment (Coccolo et al., 2016). The model is described in detail in ISO 7730 (ISO, 2005). After being initially defined for the indoor setting (Fanger, 1972), and termed the "Klima-Michel-Modell," PMV and PPD were later adapted to outdoor conditions by using weather data as input, adding the short and longwave radiations fluxes, including data about activity and clothing (Jendritzky & Nübler, 1981).

**b- Universal Thermal Climate Index (UTCI)**

The Universal Thermal Climate Index (UTCI) was established by a multidisciplinary group (Błazejczyk et al., 2010). Air temperature, humidity, wind speed, and radiation are all taken into account by the UTCI index to determine an individual's level of comfort in the outdoors (Grifoni et al., 2017). UTCI uses these elements in a human energy-balance model to predict a person's heat or cold stress. UTCI is an outdoor-only thermal comfort index. It's one of the most widely utilized "feels-like" temperatures used by meteorologists and has become the worldwide standard for describing the sensation of outdoor temperatures (Ladybug Tools., 2022).

$$\mathbf{UTCI = f\,(T_a;\, T_{mrt};\, v_a;\, v_p) =}$$

$$\mathbf{= T_a + Offset\,(T_a;\, T_{mrt};\, v_a;\, RH)}$$

*Tmrt = Mean Radiant Temperature*

*Va = Wind Speed*

*RH = Relative Humidity*

*Ta = Air Temperature*

*f : UTCI uses a big 200-term polynomial approximation. This polynomial was derived from thousands of simulations with Fiala human energy balance model and survey results of adaptive clothing behavior in the outdoors.*

Employing $T_{sr,m}$, and rearranging the Stefan-Bolzmann law by introducing the (local) radiative heat-exchange coefficient hR (W·m22 ·K21), the energy exchange is calculated by

$$q_R = h_R \cdot (T_{sf} - T_{sr,m})$$

qR of a body element sector represents the sum of the partial heat exchanges between this sector and the surrounding structures (walls, windows, etc.), which may have different surface temperatures

Tsr,m, the mean temperature of the surrounding surfaces, or mean radiant temperature MRT can be used

$h_R$ (W·m22 ·K21), the energy exchange is calculated

The value of Tsr,m is defined as the temperature of a fictitious uniform envelope ‘‘seen’’ by a sector, which causes the same radiative heat exchange with the sector as the actual asymmetric enclosure. MRT is defined similarly, but it refers to a fictitious uniform black envelope.

Tsf: Temperature of Surface of body sector sf Surface of body sector

h: Surface heat transfer coefficient (W·m$^{-2}$ ·K$^{-1}$) r :Node number

### 2.3.4 Thermal Comfort Analysis in Transitional Spaces

PET thermal comfort indices are often employed in outdoor thermal comfort studies, but they can be utilized in transitional environments since they use the same climatic variables for comfort indexes, including air temperature, relative humidity, air velocity, and mean radiant temperature (de Freitas & Grigorieva, 2015). The mean radiant temperature is the value that is derived from the interaction of the wind speed, air temperature, and radiation from the environment. Mean radiant temperature (MRT) is the most significant parameter determining human energy balance and has the greatest impact on thermos-physiological comfort indexes, such as PET or PMV(Soflaei et al., 2020). PET thermal comfort index is preferred to evaluate thermal comfort in transitional spaces such as canopy, sky-court, balcony, rooftops, which are highly influenced by outdoor environment conditions (Taib & Ali, 2016,Lin et al., n.d., Kwon & Lee, 2017). (Zhang et al., 2020) Diz-Mellado et al., (2021) emphasize usage of PET index in semi-outdoor spaces according to adaptive comfort model evaluation results. Considering the hybrid condition of transitional spaces such as courtyard spaces and perimeter buffers, PET will be used to evaluate thermal comfort in transitional spaces in this study.

**Physiological Equivalent Temperature (PET)**

The Physiological Equivalent Temperature (PET) is the ambient temperature at which the heat budget of the body is managed in a typical inside environment (without wind and solar radiation) with the same core and skin temperatures as under complex outside conditions. (Höppe, 1999). PET and SET* are both based on the two-node model, however SET* is calculated after subjecting the model to comfort conditions, whereas PET may be utilized for stable and unsteady situations.

The purpose of PET is to determine what temperature in a controlled environment would produce the same physiological response as the environment being studied.

As the foundation for PET, the Munich Energy Balance Model for Individuals (MEMI) proposes the following equation as the human body's energy balance: (Coccolo et al., 2016):

$$M + W + R + C + E_{D} + E_{Re} + E_{Sw} + S = 0$$

(M = metabolic activity, W = physical effort, R = body net radiation, C = convective heat flow, ED = latent heat flow, ERe = sum of heat flows for heating, ESw = heat flow due to sweat evaporation.)

**Calculation of PET** :

Regarding the indoor environment used as a reference, the following assumptions are considered for the PET calculation: Tmrt = Ta, the average radiant temperature, is the same as Ta, the average air temperature. - The speed of the wind (or air velocity) is always v = 0.1 m/s. - The moisture has been adjusted to 12 hPa, which is about the same as a relative humidity of 50% when the temperature is set to Ta = 20°C (Höppe, 1999).

Walther & Goestchel, (2018) show calculating stages as follows:

- Estimation of Tsk, Tc, and Tcl

- Solving the operating temperature human energy balance equation (see Appendix A) using the derived Tsk, Tcl, and Tc values.

Ultimately, the resultant air temperature is equal to PET.

| PMV | PET(°C) | UTCI (°C) | Thermal Perception | Grade of Physiological stress |
|---|---|---|---|---|
| -3 | < 4 | < -40 | Very Cold | Extreme cold stress |
| | | -40 to -27 | | |
| -2.5 | 4-8 | -27 to -13 | Cold | Strong cold stress |
| -1.5 | 8-13 | -13 to 0 | Cool | Moderate cold stress |
| -0.5 | 13-18 | 0 to +9 | Slightly Cool | Slight cold stress |
| 0 | 18-23 | +9 to + 26 | Comfortable | No thermal stress |
| 0.5 | 23-29 | | Slightly Warm | Slight heat stress |
| 1.5 | 29-35 | +26 to +32 | Warm | Moderate heat stress |
| 2.5 | 35-41 | +32 to +38 | Hot | Strong heat stress |
| | | +38 to +46 | | |
| 3 | >41 | >46 | Very Hot | Extreme heat stress |

Figure 2.10. Relationship between PMV, PET and UTCI and relationship of PMV with outdoor thermal comfort

# CHAPTER 3

# CLIMATE-RESPONSIVE ARCHITECTURE AND DESIGN SOLUTIONS

The concept of responsiveness and architecture are beginning discussed for over 50 years based on the participation of users to design. Nigel Cross pointed out designers are not able to predict changing conditions of environments and adverse impacts and side-effects on their projects (Cross N. & Design Research Society, 1972). Technological developments and computer-aided design enabled designers' participation at different design levels. Today possible impacts of changing conditions can be predicted easily via simulation tools, and response mechanisms for the built environment can be created thanks to technology. This chapter will analyze how responsive architecture emerged and developed over 50 years and can be beneficial to mitigate UHI impacts with the application of climate-responsive design solutions.

## 3.1 Definition of Responsive Architecture

Responsive architecture takes into account the current condition of the environment. It enables buildings to respond in a receptive or sensitive way to changing form, materials, colors, and natural features by incorporating technological and environmental possibilities (García-Luna Romero & Flores Leal, 2022). Information received from the external environment transforms as a response to sensory elements in buildings. In 1975, Negroponte, a pioneer of the responsive architecture concept, stated that each individual could be their architect, and participation would be achieved by very personal computing machines (Negroponte, 2021). According to this proposal, machine intelligence will be a personal interface between user needs and a resilient and intelligent infrastructure which means buildings will be able to understand user needs and respond with intelligent systems (Negroponte, 2021). Representation of intelligent and responsive environments can be seen in 1960's utopian projects such as "Walking City" by Ron Herron, presenting transformable robotic structures, "Fun Place" and "Generator" by Cedric Price, structures transforming themselves to meet the needs of occupants (García-Luna Romero & Flores Leal, 2022; Kolarevic & Parlac, 2015). These envisioned designs laid the foundation for the relationship between buildings and the environment to be energy efficient, sustainable, and resilient. Today, based on this approach, intelligent, adaptive, transformable, and kinetic architectural elements are actualized and applied all over the world.

Considering the relationship of the building with its surrounding, it can be analyzed from two different perspectives: building-environment adaptation and reporting-user adaptation. At this point, the façade is a crucial component within the scope of building adaptation with its limiting and connecting relationship with both environments. James (2006) emphasizes the importance of façade for interior and exterior conditions, explaining why façade retention is important for building adaptation. In this case, while the façade represents historical and architectural characteristics, it also provides indoor air quality and space configuration adapting to modern conditions.

In the examples of responsive architecture, for the first time in the 90s, great interest in adapting the façade element to changing conditions increased, and the building envelope, rather than being the energy barrier of the building energy harvesting from the environment and channeling it where it is needed through shading and ventilation systems (Kolarevic & Parlac, 2015). Today, based on this approach, intelligent, adaptive, transformable, and kinetic architectural elements are actualized and applied all over the world. Al Bahar Towers in Dubai is one of the most well-known examples of dynamic shading on the facade, along with Melbourne's Council House 2, ThyssenKrupp's Headquarters, Austria, Kiefer Tech Showroom building, and the Brisbane Domestic Terminal Carpark constructed in 2006.

### 3.1.1 Climate Responsive Design

The built environment occupies an essential place in terms of energy consumption and climate change due to both embodied and operational energy consumption and greenhouse gas emission. With the development of environmental technologies in the late 19th century, the building became a comfort-providing space rather than an environmental mediator. Especially with Modernism, lighter and more transparent building designs were realized by creating suitable comfort areas thanks to the electrical and mechanical systems of the buildings (Gill et al., 2007a, 2007b). In this way, indoor conditions completely independent of outdoor conditions were created with automated systems, and the building material and form became independent from outdoor conditions, which means more conditioning led to more independence from environmental factors (Addington, 2009).

However, although this situation provides different experiences in terms of architectural design, it has become widespread over time. It has encouraged the use of building energy, which has led to an increase in the effects of global warming and climate change (IEA, 2019). At this point, the global energy crisis and climate change impacts increase the necessity to develop energy-saving and UHI mitigation strategies. Considering the role of building concerning its surrounding environment and function, Hastings (1989) claims that buildings interact with their environment in 3 different ways; climate-insensitive, climate-combative or climate-responsive.

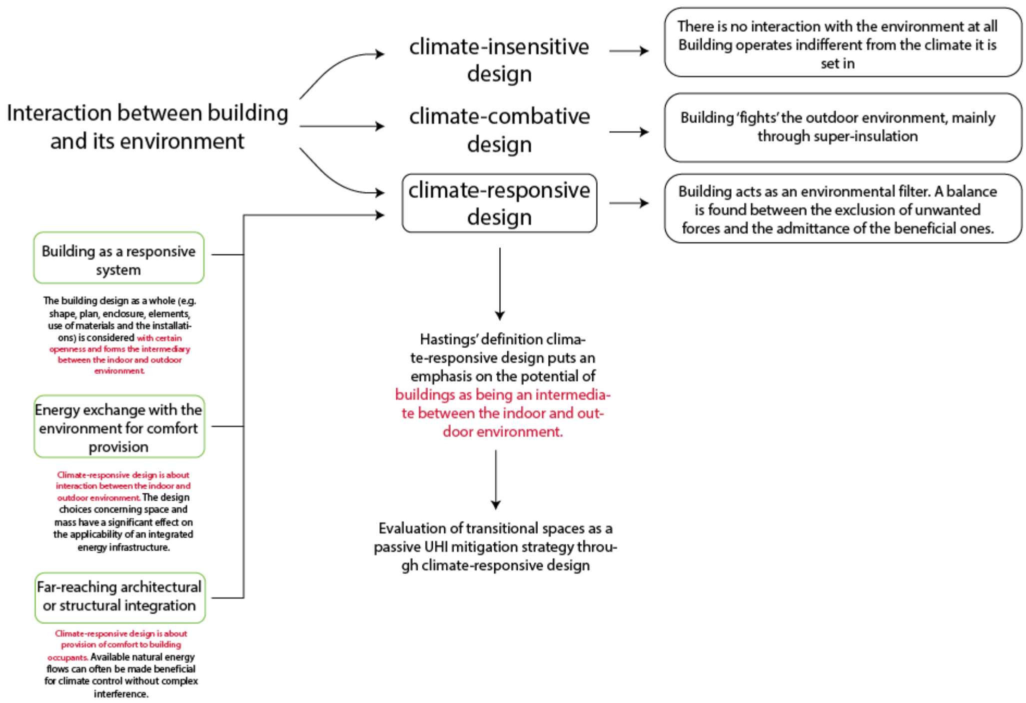



Figure 3.1. Building interacts with environment in 3 different ways (Hastings, 1989)

The climate-intensive design represents artificial lighting and HVAC for interior spaces, which means buildings are dependent on mechanical systems and independent from the outdoor environment. In climate-combative design, building insulation properties develop considering outdoor conditions insulated to avoid outside interaction. In this case building site is essential only to determine the insulation level in the building. According to Hastings (1989), the problem with this design approach is preventing outdoor interaction is not convenient all the time because outdoor interaction can be beneficial. However, in climate-responsive design, the building acts as an environmental filter accepting beneficial conditions and rejecting adverse conditions. According to this approach, outdoor conditions are analyzed, and building design develops, encouraging positive effects and limiting undesirable conditions. Currently, climatic design applications on vernacular architecture, in which mechanical conditioning systems are not integrated, can be given as an example. Local dwellings that were constructed in the past are created according to the principles of vernacular architecture, which are based on utilizing the most effective use of natural resources such as the sun and the wind (Bodach et al., 2014). In a summary, climate-responsive urban design is crucial to the concept of sustainability because it encourages individuals to spend less time indoors and more time outside, improves the potential for pedestrian comfort and activity in outdoor spaces, and decreases the need for air conditioning (Erell et al., 2012).

## 3.2 Climate-Responsive Design Solutions

Vernacular architecture is seen as a model for climate-responsive design solutions due to the fact that space conditioning was established utilizing natural methods and our predecessors used locally available materials to build comfortable environments (Mohammadi et al., 2018). Natural ventilation, courtyards, green roofs, shading device, orientation of building can be given as examples of vernacular architectural design solutions (Bekleyen et al., 2014; Mohammadi et al., 2018; Yang et al., 2020) As a tool of climate-responsive architecture, combined with human-centered and biophilic design, the atrium is gaining increasing attention among architects and landscape architects for its integration with long-term policies and strategies implemented after the Paris Climate Agreement (Paris, 2015). Bioclimatic architecture, also known as sustainable design, is a building technique that considers the local climate and employs a range of passive solar systems to improve energy efficiency. Passive solar technologies are heating and cooling methods that do not rely on mechanical systems, such as those that use natural shade to restrict solar radiation. In the winter, bioclimatic buildings are designed to take advantage of solar gains and decrease exposure to low temperatures; in the summer, they are sheltered from the sun and cooled using a range of techniques such as utilization of renewable energy (Tzikopoulos et al., 2005).

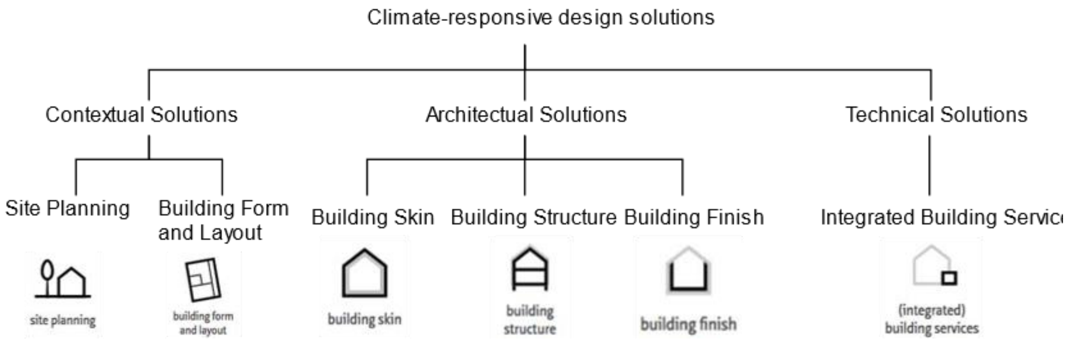



Figure 3.2. Climate responsive design solutions

The objective of the building's climate-responsive design approach is to explore the temperature control techniques suitable to the building's comfort space. Aim is adjusting the building environment to provide a suitable interior thermal environment for daily human activities by taking into account the climatic changes across locations and using the relevant measures to increase the thermal comfort of inhabitants. This strategy bases the selection of building technology on the interaction between climatic conditions and human requirements (Ghisi & Felipe Massignani, 2007; Lee & Givoni, 1971).

Contextual and architectural climate responsive design solutions have been thoroughly investigated in three categories. Primarily, climate-responsive façade characteristics and development, followed by form and layout including transitional spaces and lastly, landscaping and vegetation owing to its application in outdoor and transitional areas and the application of green roofs.

| DESIGN PRINCIPLES | CLIMATE-RESPONSIVE DESIGN SOLUTIONS | | |
|---|---|---|---|
| | Contextual | | Architectural |
| | Site Planning | Building Form and Planning | Building Skin |
| Passive Solar Heating | shading from onsite vegetation | | |
| Solar Shading | | | operable window system external solar shading |
| Natural Ventilation | | | operable window system |
| Natural Illumination | | | operable window system |
| Natural Air Cooling | cooling from shaded areas | | |
| Thermal Buffering | | thermal zoning buffer zone(atrium, balcony,terraces) | |

Figure 3.3. Climate-Responsive Design principles and solutions applied in case study(by Author)

### 3.2.1 Climate-Responsive Façade Design

Facades are the main constituent of the building envelope, which serves as a partition between the interior and outdoor surroundings, and has a significant influence on the indoor air quality, building efficiency, and, subsequently, the user's satisfaction. Today, with the increasing need for energy-efficient building components and design and the development of technology, approaches to building façade and envelopes also evolved. Perino et al. (2015) describe this paradigm shift as from "static, generic to dynamic, adaptive, responsive and customized" depending on the season, user preferences, and needs building envelope could be adjusted. In this case, Climate responsive façades provide a new approach compared to static barriers and fixed performance of the façade functioning as a physical shield between indoor and outdoor environments. In response to fluctuations in outdoor boundary conditions, the qualities and arrangement of building facades determine the degree of change in indoor settings (Looman, 2017). In this situation, in order to meet the specific indoor environmental quality and energy efficiency requirement, climate-responsive facades are an option that adjusts to changing circumstances both inside and outside the building (Soudian & Berardi, 2021).

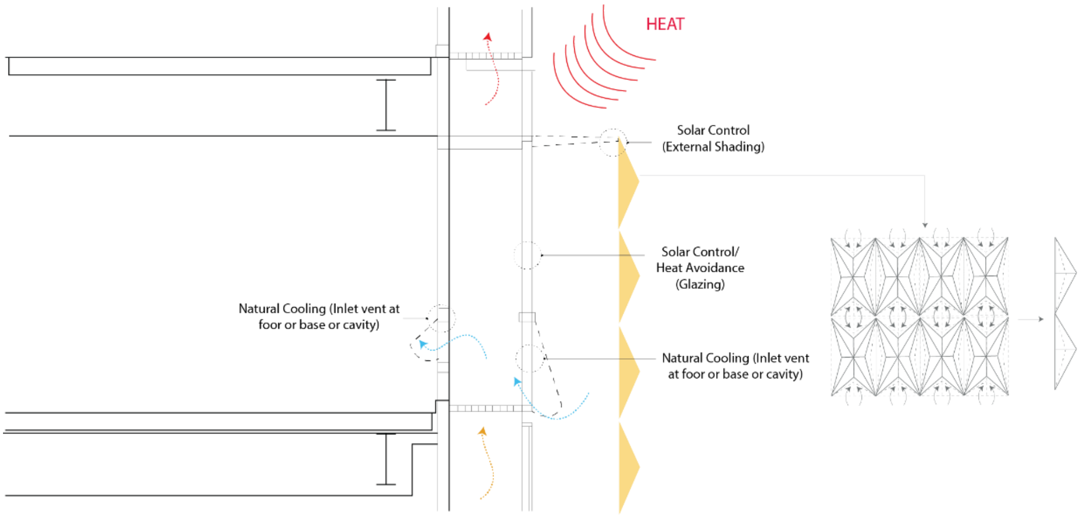



Figure 3.4. Climate responsive façade section with kinetic shading device (by Author)

Many shapes, such as kinetic and dynamic facades, have arisen as a result of advanced technology to maximize the influence of the building façade on the building and the environment. As articulated, the main principle of these is that buildings should be able to adapt dynamically to continually changing environmental circumstances while being energy efficient. At this point, the most common form of façade development is Adaptive façade (AF), defined as a building envelope that can frequently change its functions (thermal, structural) over time in reaction to weather changes to reduce energy use. Several variations of AF, including smart, intelligent, dynamic, responsive, advanced, and kinetic façades, have been used by engineers, architects, and researchers (Hosseini et al., 2019; Iken et al., 2019; Johnsen & Winther, 2015; Liu et al., 2015; Taveres-Cachat et al., 2019).

The design of the adaptive facade has two main directions to be focused on materials and components. Component-oriented facade design includes moveable parts in the mechanical system to manipulate conditions such as kinetic facades and sensor-based controlled shading devices. Material-oriented adaptive facades emphasize responsive materials can change physical properties according to dynamic climatic conditions, such as passive adaptive (photochromic and thermochromic) and active controllable (electrochromic) adaptive windows. According to the findings of  Alonso et al.( 2017), effective design may enhance the energy efficiency of thermal conditioning and improve urban environments inside and outdoors.Similarly, Fox et al. ( 2018) and Soudian et al.( 2021) focus on energy efficiency and impacts on urban conditions, such as urban heat mitigation using technologies for multifunctional climate-responsive building envelopes. Recent research on existing responsive facades shows that they significantly reduce carbon emissions and improve energy efficiency (Grobman et al., 2017).  It is possible to achieve a 20% decrease in carbon emissions and a 50% reduction in energy usage with such technologies (Karanouh & Kerber, 2015). As observed, climate-responsive building envelopes are identified as a component that regulates multiple environmental loads through dynamic responses of different elements. However, those applications also require energy consumption, so as pointed out by Kolarevic et al. ( 2015), the adaptive façade approach has limits since it includes complex systems and requires additional energy to operate the dynamic effect of the façade could be provided by components designed to enhance their embedded responsiveness,' which is responsive to outdoor thermal variations in order to ensure indoor comfort, without the need for energy supply and following a very linear and basic technological configuration. (Menges et al., 2021) . Consequently, further research is needed to address the climate-responsive building envelope as a controller of outdoor thermal variations to ensure indoor thermal comfort and, simultaneously, as a player in the quality of the outdoor environment.

Since its introduction in 1989, the responsive facade system has expanded in scope and capability thanks to innovations in geometry, mechanism, smart sensors (including light, temperature, and touch sensors), and actuating technology (including engine, gas, and fluid operators) With the advancement of technology, these systems, which were initially controlled by switches, have progressed to central control, which is still the most reliable. For example, the Council House 2 Building was completed in 2006, the Showroom Kiefer Technic was completed in 2007, the Q1 Headquarters Building was completed in 2010, the Al-Bahar Towers were completed in 2012, and the One Ocean Pavilion was completed in 2012 (Matin et al., 2017).

Aside from examples in practice, labs and institutes such as the MIT Architecture Machine group, founded in 1968, the MIT Media Lab, founded in 1980, the Intelligent Building Institute, founded in 1986, Hoberman Associates, founded in 1990, and the MIT Adaptive Building Initiative (AIP), founded in 2008 (Vel) have all been established to contribute to the development of advanced systems and responsive facades.

According to Matin et al. (2017) , there have been four variables that have played an important role in the development of responsive facades:

**Socio-cultural factors:** The emphasis is placed on the many cultural and social movements that emerged throughout the twentieth century. It is claimed that as a result of the influence of creative and social movements including impressionism, futurism, modernism, and postmodernism impacted the shape and geometry movement of responsive facade systems (Heidari Matin & Eydgahi, 2020).

**Eco-political factors:** Emphasizes that political and economic events such as energy crises, revolutions, and sanctions lead the designers to develop more sustainable, economical design strategies, which have an impact on efficient and optimized responsive facade design development strategies (Heidari Matin & Eydgahi, 2020).

**Environmental factors:** Emphasized raised awareness of the ecological crisis caused by disasters and changing conditions directed architects to develop responses to those issues directly.

**Technological factors:** Emphasizes advancement in technology and provides an a chance to increase the utilization of materials and structures used in responsive facade design and implementation.

### 3.2.2 Building Form and Layout

The building form is an important determinant of environmental performance since form characteristics such as geometry, compactness, and porosity have a significant impact on passive outcomes such as shading, daylight access, and natural ventilation. Building form and geometry is a determined in the creation of air-flow patterns around the building. The placement of openings is crucial in the adjustment of the rate of air change with different levels of air pressure (Olgyay, 2015). The most important design criteria that determine the degree to which interior thermal comfort and energy saving are affected by a structure are its shape and orientation, as well as the surrounding environment. In terms of the overall heat loss of the building, the building form is highly essential since it is connected to the building volume ratio of the total facade area(Oral & Yilmaz, 2002).

Semi-outdoor spaces are incorporated in high-rise buildings because of reducing the effects of the urban heat island effect, increasing passive cooling and outdoor interaction for users. In multi-story buildings, perimeter buffers such as balconies can function as overhangs for glazing below and protection from negative circumstances such as rain and overheating (Givoni, 1998). In addition, the overhang effect created by balconies helps protect the internal area from the harmful effects of UV radiation and alleviates the uncomfortable glare caused by direct sunlight (Ribeiro et al., 2020). Besides overheating and sun protection function, placement, arrangement, and types of an inlet of balconies have a significant influence on the airflow for indoor velocity (Prianto & Depecker, 2002).

The study of Omrani et al. (2017) shows that an inverse correlation between balcony depth and indoor air velocity and cross ventilation shows a significantly better performance in contrast to single-sided ventilation under the same circumstances.

Another form of an attribute to promote cross ventilation and green space in highrise buildings is sky terraces provided at the intermediate stories of a building (Gamero-Salinas et al., 2021a). The design of sky terraces and the "spaces between" provide a future work environment that is greener, more compassionate, and more intelligent (Reinke, 2020). As an example of sky terraces designs applied to office buildings, Tencent Global Headquarters in Shenzhen, ACROS building in Fukuoka, The Republic in Austin, and Main & Gervais in Columbia, can be shown. Sky gardens (sky terraces supported with greenery) can give many advantages over other macro-scale greenery concepts, including protection from the urban heat island effect, increased biodiversity, and aesthetic enhancement. Thoroughly incorporating these systems into buildings can provide some indirect energy advantages by cooling the ambient air, thereby energy consumption utilizing air conditioning systems (Raji et al., 2015).

### 3.2.3 Landscaping Design and Vegetation

The presence of vegetation in urban areas provides various benefits, including climatic, ecological, social/psychological, and economic advantages. Since plants absorb less solar radiation during the day and emit more at night than buildings and other urban hard surfaces, a lack of vegetation around buildings contributes to higher urban temperatures (Givoni, 1998). Urban canopy layers comprising trees and buildings are significant. Oke (1989) emphasizes the presence of trees in urban context and forest cause different impacts on the environment because trees have the potential to act as urban climate modifiers. The presence of vegetation at a location provides a cooling impact in limited areas owing to shading, as well as inhibit radiation penetration (Shashua-Bar & Hoffman, 2000).

In the climate-responsive design of buildings for the built environment, the building functions as a filter, concentrating on the removal of detrimental influences and the use of positive ones(Hastings, 1989).  Based on the impact of landscape architecture on UHI and microclimate, climate-responsive landscape design considers designs for unexpected and expected effects of climate change and UHI(Lenzholzer & Brown, 2013) In this situation, it is necessary to enhance site-specific circumstances, such as making locations more appealing for recreation, more diversified for flora and fauna, or more thermally comfortable (Lenzholzer & Brown, 2013).

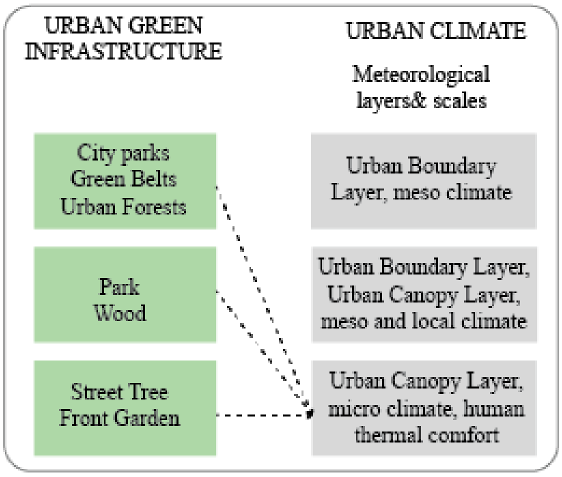



Figure 3.5. Meteorological layers Green feature applications in different scales, adapted from (Klemm, 2018)

# CHAPTER 4

# ANALYZING THERMAL COMFORT OF TRANSITIONAL SPACES THROUGH CLIMATE RESPONSIVE DESIGN SOLUTIONS

In this chapter, the method for analyzing the impact of climate-responsive design solutions used to promote user comfort is described in depth. First, the methodology of research is discussed, and then the simulation intervals and case study scenarios were described. Explanations of the calculations and parameters used at each stage of the five-step simulation procedure are provided. Prior to the comfort study, the energyplus tool was used to gather the ambient characteristics necessary for UTCI, PET, and ATC computations.

## 4.1 Methodology

With increasing urbanization and climate change, the amount of fossil fuel for electrical energy has increased and buildings are responsible for 40 percent of CO2 emissions(U.S. Energy Information Agency, 2019). At this point, there is a great need for more sustainable and energy efficient building designs to reduce both UHI and cc and CO2 emissions. Climate responsive design is one of the approaches adopted to reduce the effects of UHI and CC (Abergel et al., 2021; Attia & Gobin, 2020). At this point, UHI and CC mitigation strategies are used as passive strategies increase thermal comfort and reduce energy consumption and emission (Kaihoul et al., 2021). This research evaluates  transitional spaces for thermal comfort and cooling strategy using climate-responsive design as a passive method for reducing urban heat island impact. In this case, this study based on a multi-scale quantitative evalution methodology to assess the effect of transition spaces on user comfort by applying climate-responsive design solutions, using building energy simulation program and thermal comfort analysis tool for data collection. Obtained data from simulations are compared to observe impacts of changing applications on user comfort. Since there is no specific BPS tool to evaluate the performance of transitional spaces and increase the accuracy of the study, three simulation tools are used to perform holistic and multi-scale quantitative assessment: EnergyPlus, Honeybee and Butterfly. In the first phase, the urban model of Ankara, Turkey's Balgat neighborhood with its dense concentration of high-rises was generated in RhinoCeros using CadMapper and then imported into Grasshopper. The 15-storey hypothetical office building model to be analyzed was modeled in the Honeybee program with materials and components. In Stage 2, the building model obtained with honeybee was simulated with EnergPlus to obtain building thermal performance data between 12-13 pm on 21st July, which is Coolind Design Day. Two different aspects, the contextual and the architectural, are used to analyze climate-responsive solutions. Afforestation and wind factors at the neighborhood scale were evaluated using four distinct scenarios to assess the influence of contextual interventions. Architectural solutions, on the other hand, were investigated in 12 different scenarios, including the base scenario, in three distinct contexts: preventative, spatial, and both preventive and spatial. Dynamic shading was implemented as a preventative measure on all facades except the north side. A balcony that functions as a canopy has been used both preventively and spatially. As spatial interventions, atriums and sky terraces were utilised. These applications were used alone and in combination, and their results were evaluated. Twelve explanatory scenarios of climate-responsive design solutions have been developed to illustrate the concept.

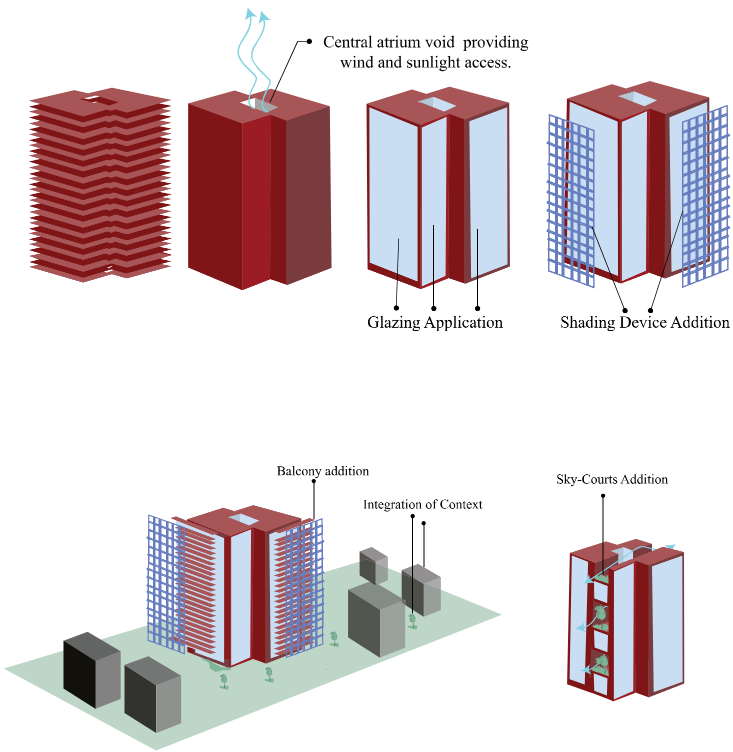



Figure 4.1. Building form generation process schematic diagram

Building model to assess impact of form variables on occupant thermal comfort is generated in accordance to literature review (Gamero-Salinas et al., 2021b, 2021a, 2022; Loh & Bhiwapurkar, 2022; Ruefenacht & Acero, 2017; Xiang & Matusiak, 2022) .

Climate-responsive design solutions listed below :

- **Preventive Application:** Shading Device
- **Both Preventive and Spatial Application:** Balcony
- **Spatial Application:** Atrium
- **Spatial Application:** Vegetated Sky -terraces

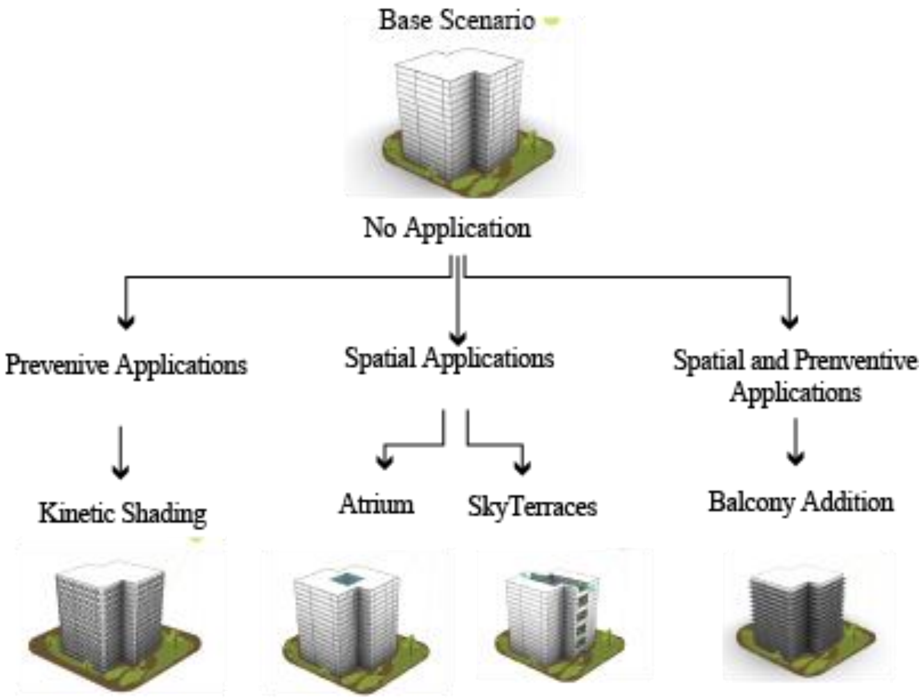



Figure 4.2. Climate-responsive design solutions evaluated through simulation scenarios

As a result of combining multiple applications, twelve scenario is generated and explained detail in following Scenarios section.

The simulation process is divided into stages according to micro-urban to building scale analysis. In this case, Honeybee thermal comfort analysis tool, and 15 stories mid-rise Office building is analyzed in four different levels: Street level, 5th-floor height, 10th-floor height, and lastly 15th, 4 m floor height.

In this context, firstly UTCI analysis for layout and vegetation analysis, and then thermal comfort analysis with PET in transitional areas as semi-outdoor spaces will be analyzed at Stage 3. As it is a naturally ventilated building, the ATC model was used to examine indoor thermal comfort in Stage 4 of the workflow. In the fifth and final stage, thermal comfort analysis results were assessed and compared based on scenarios. Data gathered from these analyses were represented as a matrix and compared results in 12 different scenarios and levels. Since wind speed is an essential indicator of thermal comfort and sensation, outdoor CFD analyses are conducted via the Butterfly tool. Thus, comprehensive thermal comfort analysis is aimed at integrating different simulation tools.

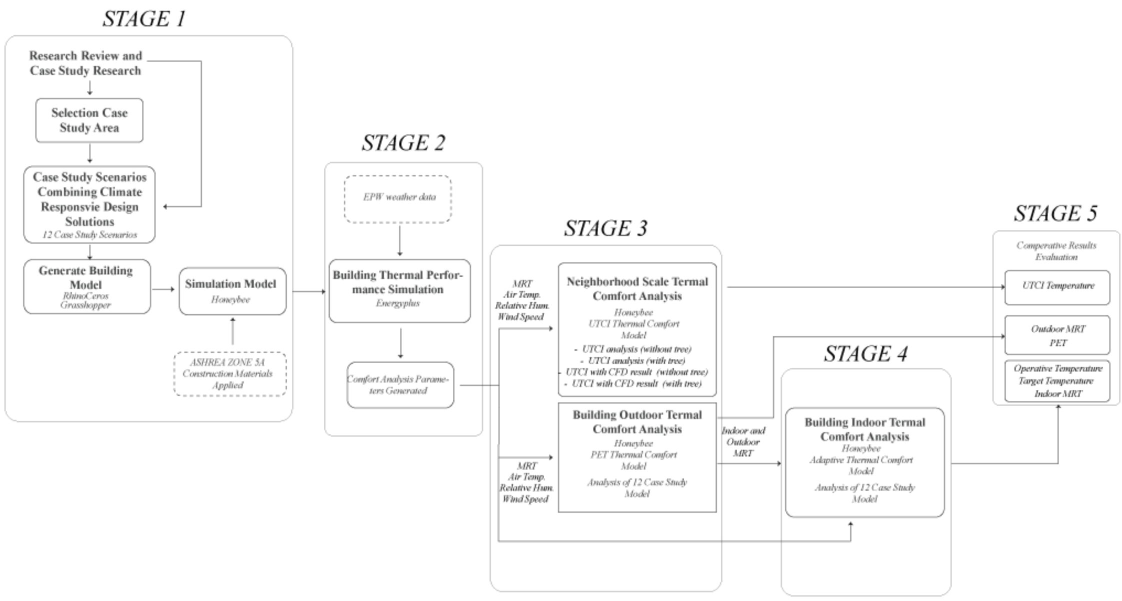



Figure 4.3. Methology flowchart

### Simulation Workflow

In the study, which adopted multi-scale approach, the simulation process was examined at the building scale and the micro-urban scale. A hypothetical 15-story office building model was created by creating the urban model of the Balgat region of Ankara city. Necessary parameters for thermal comfort tools in Ladybug Honeybee tools were obtained using EnergyPlus Tool and Butterfly CFD tool. By introducing the 15-story building and its urban environment, wind speed data were obtained at four different levels, where thermal comfort analysis will be evaluated. In the building where natural ventilation is used in line with the application of climate-responsive design principles, the Adaptive thermal comfort model is used for indoor thermal comfort analysis.

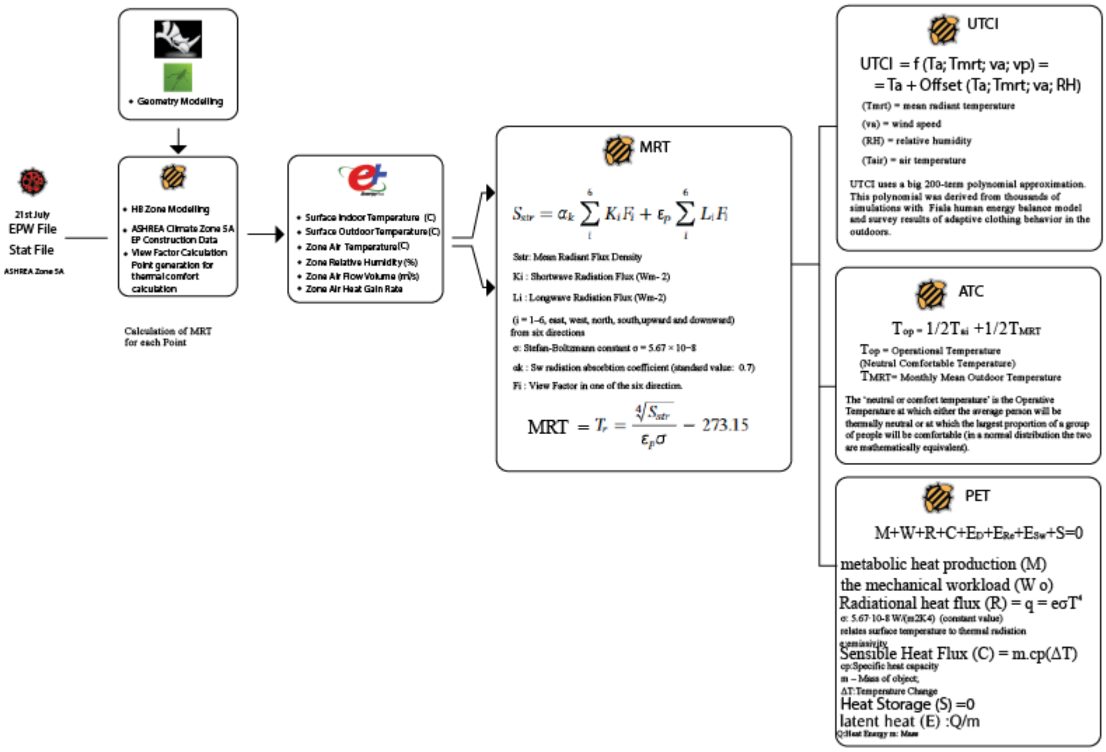



Figure 4.4. Simulation Workflow

**Assessment Tools**

Within the scope of this research, multi-scale thermal comfort evaluation was conducted utilizing Ladybug, Honeybee and Butterfly tools, which were built as environmental analysis tools in the Rhino grasshopper program and integrated with EnegyPlus. The building model was converted into the grasshopper addon to be presented to EnergyPlus using the Rhino application. Thus, access to the relevant data for the thermal comfort study is supplied through the generated building model. In this part, the EnergyPlus and ladybug tools employed will be explained in detail.

**EnergyPlus Simulation Software**

Energy consumption simulation software for the whole building Engineers, architects, and researchers use EnergyPlus to simulate a building's utility needs (such as heating, cooling, lighting, plug, and process loads) and water usage.

EnergyPlus indicates capabilities and features such as; simultaneous resolution of the circumstances in the thermal zone, A significant number of built-in control schemes for the HVAC and lighting, the generation of surface temperatures, and the provision of thermal comfort (U.S. Department of Energy, 2020).

### Ladybug Tools

Ladybug tools were first introduced by Sadeghipour Roudsari as a plugin utilizing early design stages to analyze environmental impacts on building design (Roudsari & Pak, 2013). Using standard EnergyPlus Weather files (epw) in Grasshopper, Ladybug provides a variety of 2D and 3D interactive climate visualizations to assist in design decision-making at an early stage. Integrating with visual programming environments enables quick feedback on design adjustments and a high degree of customization. Ladybug also helps the assessment of early design possibilities through solar radiation studies, view analysis, and sunlight-hours modeling (Sadeghipour Roudsari & Mackey, 2018) Users may create, run, and monitor the outcomes of daylight and radiation simulations in Radiance and energy models in EnergyPlus/OpenStudio with Honeybee with the integration of the Grasshopper and Rhino CAD.

## 4.2 Scenarios

Simulation workflow of this study comprised of 12 different scenarios generated by the combination of four climate-responsive design solution methods; shading application, corridor perimeter balconies, atrium and porosity with sky terraces.

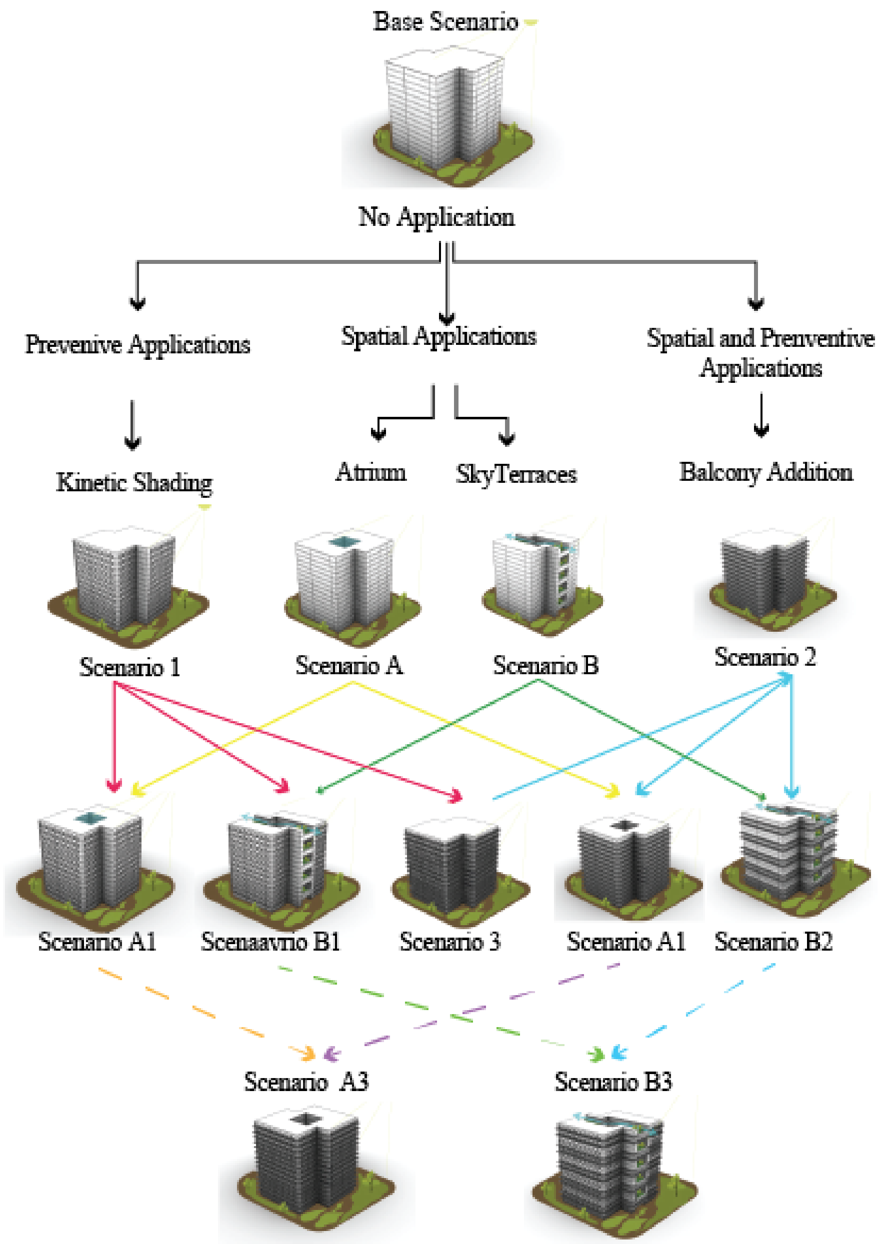



Figure 4.5.Climate-responsive design interventions between scenarios and their relations with each other.

- Base Scenario(Sc0) : Base Scenario is the scenario in which there is no climate-responsive design intervention and the lean state of the building is present. Based on this scenario, the negative and positive effects of the interventions were analyzed.
- Scenario-1(Sc1) : It is the scenario in which the shading device has been applied to base scenario as preventive strategy, the fundamental scenario. In comparison to base scenario, the impact of the shading device will be studied.
- Scenario-2(Sc2) : As a transitional zone, a 1.5-meter-deep balcony was constructed to the perimeter of the structure in this scenario as both preventive and spatial application.. Comparing ScBase with Sc-1, the usage of balconies, occupant comfort, and the use of transition areas as a cooling method will be examined.
- Scenario-A(ScA): It the case in which just the atrium is provided as spatial solution. This situation may be contrasted to the baseline condition, and the positive and negative impacts of atrium use can be examined.
- Scenario-B(ScB): In this scenario using vegetated sky terraces, the cooling performance of sky terraces as transition spaces and their impact on the internal and outdoor microclimate are studied by comparing them to base scenario as a benchmark.
- Scenario-3(Sc3): It is a combination of Scenario 1 and Scenario 2, and its purpose is to evaluate the impact of integrating balcony and shading devices.
- Scenario-A1(ScA1): The addition of a shading device to Scenario A allowed the analysis of different design application solutions.
- Scenario-A2(ScA2): In the scenario with balcony added to Scenario A, it is aimed to observe multiple effects similarly.
- Scenario B1(ScB1): It is the variation of Scenario B with a shading device added.

- Scenario B2(ScB2): In the scenario where a balcony is added to Scenario B, it is intended to study the impact of using balconies and sky terraces around the perimeter of the structure.
- Scenario A3: It is a combination of Scenario A1 and Scenario A2 , therefore the use of atrium, shade, and balcony is evaluated.
- Scenario B3: In this scenario, all climate-responsive measures are adopted.

## 4.3 Case Study Application

The effect of climate-responsive design solutions on user comfort was examined in 5 different stages. Stage 1 includes the selection of the case study area, and the selection of the building model and context model suitable for the scope of the study. Then, the hypothetical building model in the case study area determined in Stage 2 was created in the Rhinoceros program and integrated into building performance analysis tools with grasshopper. Also, at this stage, building surface temperature and CFD analyzes were carried out on the 21st of July, the cooling design day, in 12 different scenarios, in order to obtain the necessary data for outdoor and indoor thermal comfort analyses. Stage 3 has outdoor thermal comfort calculation was made in neighborhood scale. At this stage, UTCI analysis was performed using ladybug Honeybee tools. In addition, PET thermal comfort analysis was conducted to see the effect of the interventions on the transitional and surrounding outdoor spaces. In the next step, the indoor comfort analysis at the building scale was made using the ATC (Adaptive Thermal Comfort) index, and natural ventilation was taken into account. In Stage 5, all results are presented and analyzed. All the steps are explained in detail below.

#### 4.3.1 Stage 1: Definition of Characteristics of Case Study Area

With the increase in built areas in cities and the loss in green areas, rapid urbanization and population expansion have exacerbated the emergence of urban heat islands. The quality of life in cities, the energy consumption of buildings, and the quality of the environment in dwellings are all negatively impacted by urban heat island-induced climate change, which is a local reflection of climate change.


Figure 4.6.Case study area Ankara Balgat District

Within the scope of this study, Balgat, where high-rise bussiness buildings are intense in the Ankara region has been selected. The Balgat region, which was described as a central village in the past, has been transformed over time with rapid urbanization. It is surrounded by main roads like Mevlana Boulevard, Çetin Emeç Boulevard, and Türkocağı Street, as well as skyscrapers like a business center and hotel that are getting taller every day on Mevlana Boulevard(Sezen, 2014). In this case, 15 storey high-rise Office building will be evaluated in the simulation assessment.

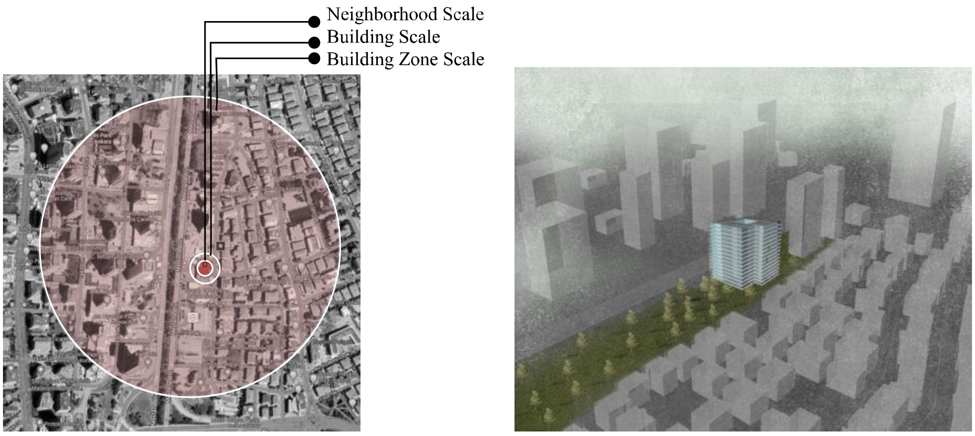



Figure 4.7. Case study evaluation regions based on neighborhood, building and zone scales(Left) and Case building model representation in context(right).

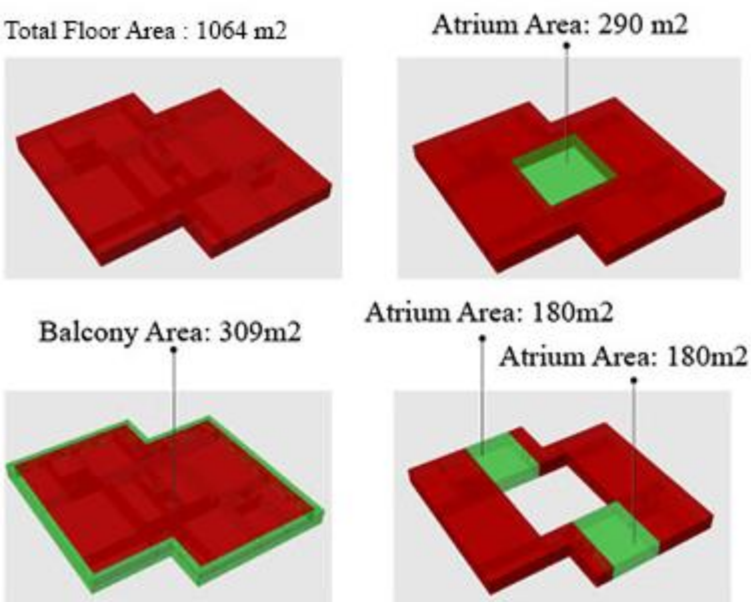



Figure 4.8. Floor Area of Transitional Spaces

Table 4.1 Average EnergyPlus Weather data 21st July between 12-13 pm.

| Microclimatic Parameters | Metric | Value |
|---|---|---|
| Dry Bulb Temperature | °C | 23.85 |
| Relative Humidity | % | 41.95 |
| Wind Speed | $m/s$ | 3.85 |
| Diffuse Solar Radiation | $W/m^2$ | 407 |
| Global Horizantal Radiation | $W/m^2$ | 788.5 |

Table 4.2 Building construction material properties

| Building Components | Construction Name | Material Name | Thickness | Thermal Conductivity | Density | Specific Heat | U Value |
|---|---|---|---|---|---|---|---|
| Floor Materials | ASHRAE 90.1-2004 ATTICFLOOR CLIMATEZONE 1-5 | 1/2IN Gypsum | 0.01 | 0.16 | 784.90 | 830.00 | 12.60 |
| | | Insulation | 0.15 | 0.05 | 265.00 | 836.80 | 0.16 |
| | | 1/2IN Gypsum | 0.01 | 0.16 | 784.90 | 830.00 | |
| Roof Materials | ASHRAE 189.1-2009 EXTROOF IEAD CLIMATEZONE 2-5 | Roof Membrane | 0.00 | 0.16 | 1121.20 | 418.40 | 16.84 |
| | | Roof Insulation | 0.24 | 0.05 | 265.00 | 836.80 | 0.23 |
| | | Metal Decking | 0.00 | 45.01 | 7680.00 | 418.40 | |
| Wall Materials | ASHRAE 189.1-2009 EXTWALL MASS CLIMATEZONE 5 | 1IN Stucco | 0.03 | 0.69 | 1858.00 | 836.80 | 27.34 |
| | | 8IN Concrete HW | 0.20 | 1.72 | 2242.90 | 836.80 | 8.51 |
| | | Wall Insulation [40] | 0.08 | 0.04 | 91.00 | 836.80 | 0.54 |
| | | 1/2IN Gypsum | 0.01 | 0.16 | 784.90 | 830.00 | 12.598425 |
| **Building Components** | **Construction Name** | **Material Name** | **Thickness** | **Solar Transmittsnce** | **Visible Transmitance** | **Visible Reclectance** | **U Value** |
| Glazing Materials | Insulated Window Glazing | sulated Glass Materi | 0.01 | 0.56 | 0.7 | 0.1 | 1.7 |

### 4.3.2 Stage 2 : Simulations for Input Data Assessment

In order to collect the data required for the thermal comfort calculation before the examination of interior and outdoor thermal comfort, twelve distinct scenarios were simulated between 12 and 13 p.m. on 21 July, the day of cooling design, by integrating the context environment. The following parameter values were obtained as a result of these simulations.

- Surface Indoor Temperature
- Surface Outdoor Temperature
- Zone Air Temperature

- Zone Air Flow Volume ($m^3$/s)
- Zone Air Heat Gain

These parameters were obtained by using weather data in order to perform PET and ATC analysis. Thus, it is aimed to observe the effects of climate-responsive design solutions on occupant comfort and UHI.

PET, UTCI, and ATC comfort analyses were done on a 10x10 m2 single zone in order to evaluate the program's usability and the calculating procedure (Fig.4.9,10 and 11). The impact of the interventions on the surface temperature values was determined by calculating the surface temperature values. Similarly, internal and outside temperatures were monitored, and both indoor and outdoor temperature changes were recorded. Analyses were conducted on overhang, shading device, green roof, courtyard, and vegetation uses. The intervention that had the greatest impact on surface temperature and ambient temperature was the installation of an overhang; the operative temperature value reduced by 1.4°C, whereas PET caused a reduction of 1.4°C indoors and 0.2°C outdoors. The outdoor MRT value changed little, lowering by 0.5 °C, whereas the inside value declined by 2.6 °C due to the shading effect. Shading, on the other hand, acted as a barrier to offer shading in the area between the building and the building, reducing the outside PET value by 0.4 °C and the internal temperature by 0.7 °C. The MRT value fell by 1 °C both indoors and outside. Regarding the usage of a green roof surface, it gave the same degree of temperature decrease as an overhang. While it decreased the operative temperature by 0.2 degrees and the MRT by 0.4 degrees in the inside, it had no effect on the outside. The usage of courtyard lowered the inside temperature by 0.2 °C without affecting the external temperature. The PET value increased by roughly 2 °C inside and decreased by around 0.2 °C outside. While outside MRT values declined by 0.6 °C, inside values climbed by 1.2 °C. Lastly, the addition of vegetation led the outdoor UTCI value to decrease significantly under tree canopy. When the outside temperature is 23.85 degrees Celsius, the UTCI index measurement indicates 27 degrees Celsius, indicating that the UTCI index functions differently with PET for outdoor analysis. By accepting UTCI met: 2.4, it is assumed that the user possesses outdoor-appropriate clothes. However, in PET, this condition is assessed by case-specific data entry. Moreover, PET based on a equivalent temperature value which is user would feel the same temperature value if indoor temperature would be equal. However UTCI calculates with 10m above ground level air conditions(wind speed). Among all applications, the most effective application in order to achieve comfortable temperatures is observed as overhang addition.

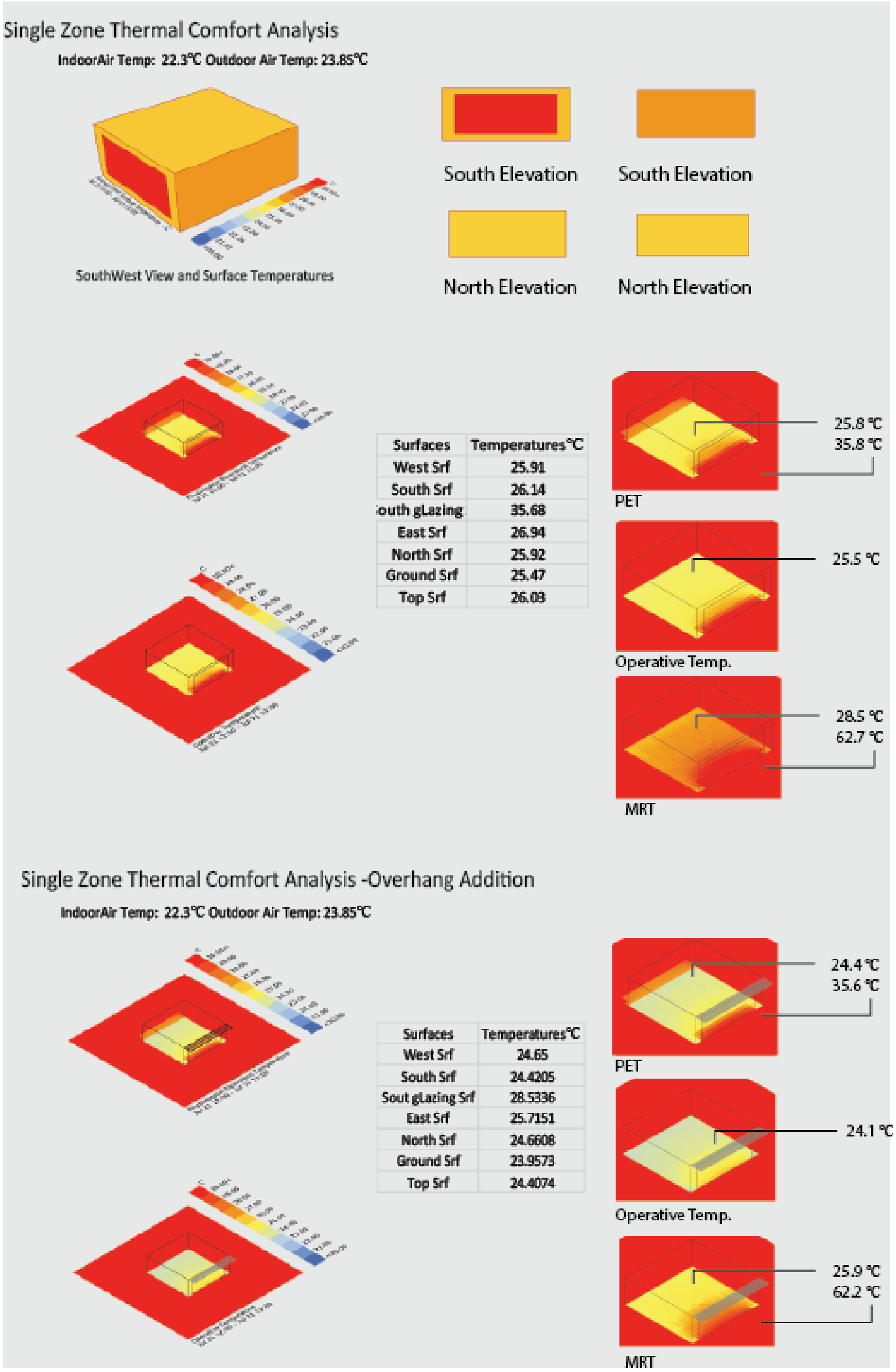



Figure 4.9. Single Zone PET and ATC thermal comfor analysis and overhang addition

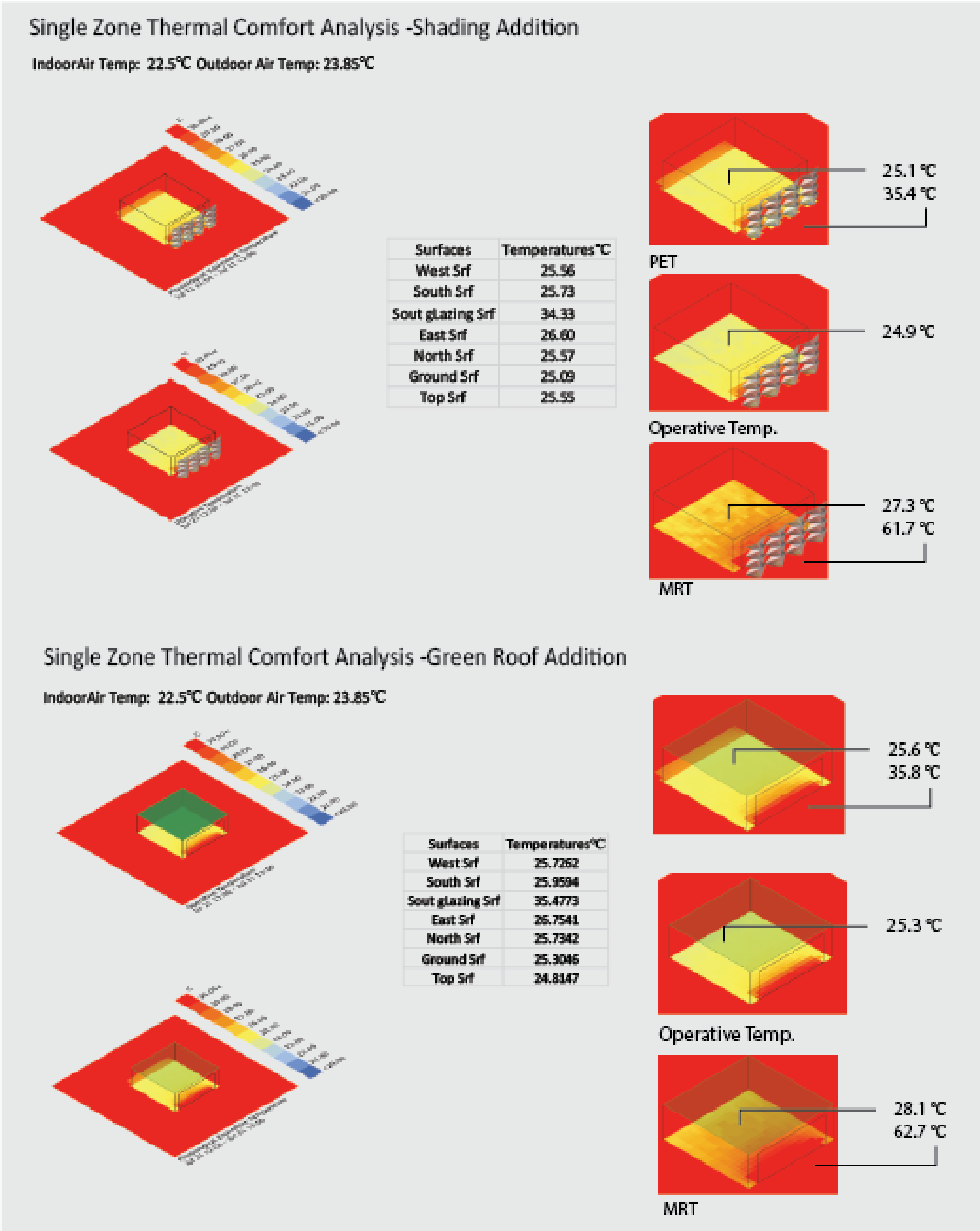



Figure 4.10. Single Zone PET and ATC thermal comfor analysis shading device and green façade application analysis

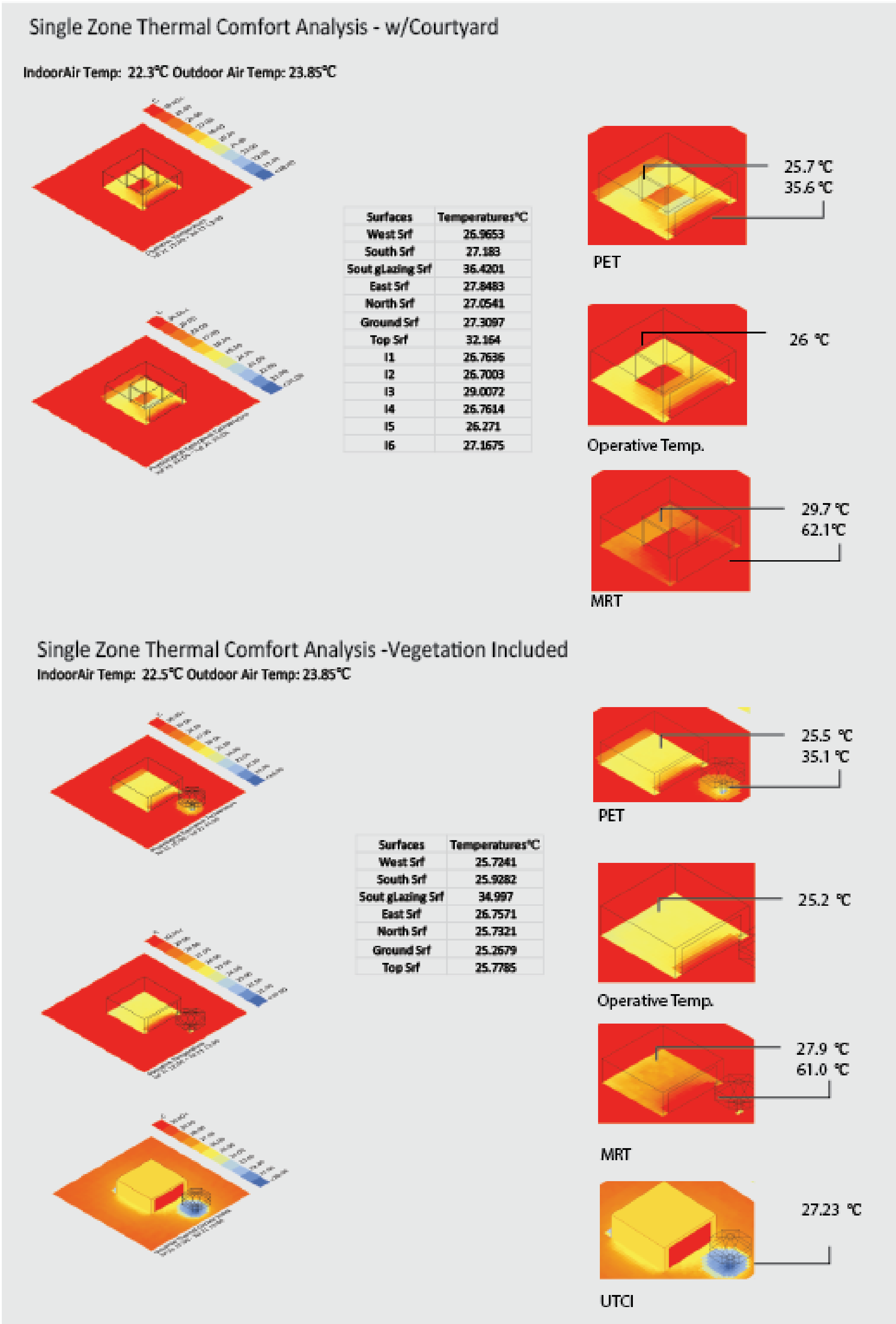
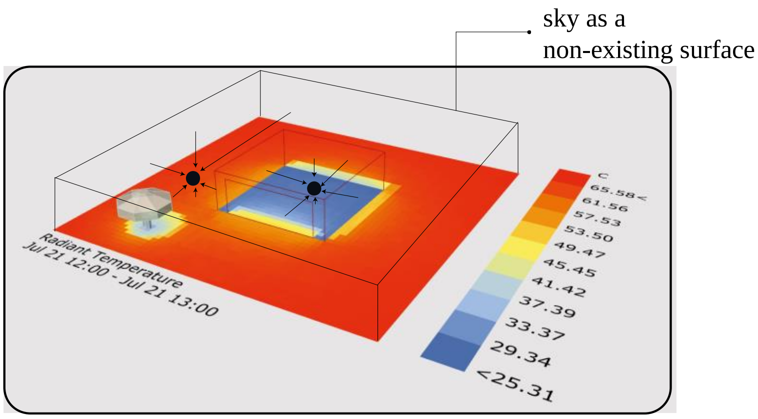



Figure 4.11. Single Zone UTCI,PET and ATC thermal comfort analysis courtyard and vegetation application

**Simulation Process to Obtain Environmental Data**

- ***Step1*** *: Calculation monthly average mean temperature to find revealing outdoor conditions.*
- ***Step2 :*** *Creation a dictionary indicating Zone Surface Names and Temperature values.*
- ***Step3*** *: Creation a dictionary indicating Outdoor Surface Names and Temperature values.*
- ***Step4 :*** *Controlling shading affecting solar transmission and outputs.*
- ***Step5:*** *Creation a meshed sky dome to assist with direct sunlight on occupant.*
- ***Step6 :*** *Sun vector calculation according to location and simulation time.*
- ***Step7*** *: Calculation of air temperatures according to Test Points*
- ***Step8 :*** *Selection relevant air and surface temperatures according to simulation time.*
- ***Step9****: Calculation of the Mean Radiant Temperature (MRT) for each point.*

**Radiation Measurement with View Factor**




Calculation Process of MRT

Figure 4.12. MRT (Mean Radiant Temperature) calculation for a single zone for both indoor and outdoor environments.

**View Factor:**

The term "view factor" refers to the degree to which an individual ‘sees' a specific surface in the room. In this case, assumed ground reflectance value is 0.2 which is between grass and soil reflectance value(An et al., 2017).

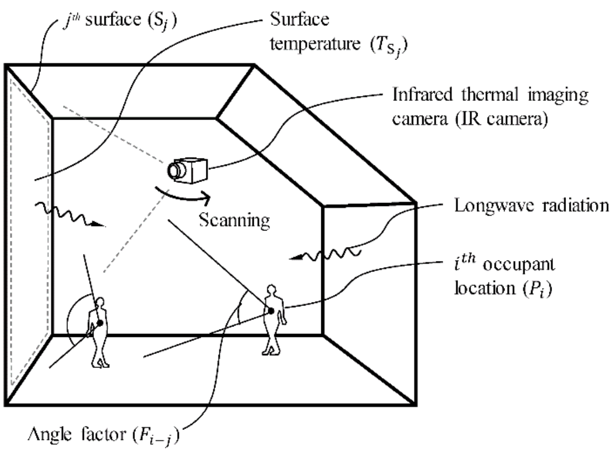



Figure 4.13. View Factor Calculation schematic representation.

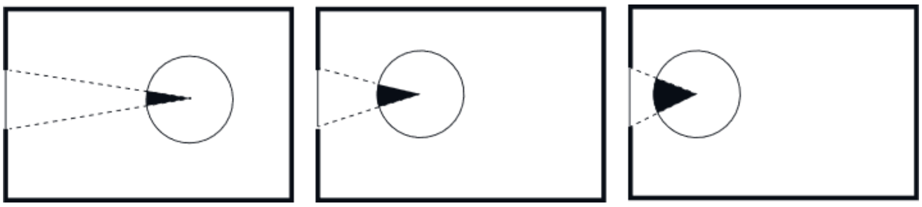


Figure 4.14. Schematic diagram illustrating how geometry influence view factor (Huizenga et. al, 2006)

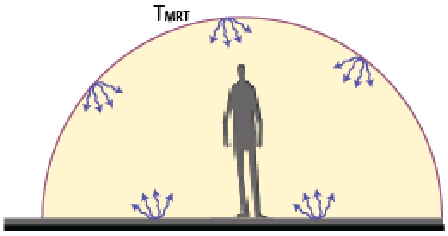



Figure 4.15. Diagram showing the verbal MRT definition of an individual in a space with six different surfaces that are each at a different temperature and are in contact with the body.(Guo et al., 2020)

$$Q_r = \sigma * F_{1\to 2} * (T_1^4 - T_2^4)$$

*Qr: Radiant heat transfer (W/m$^2$) equation between the surface temperatures, $T_1$, $T_2$,,and the view factor, $F_{1\to 2}$.(radiation leaving surface 1 that hits surface 2.)*

$$T_r^4 = \sum_{i=1}^{N} T_i^4 F_{p\to i}$$

MRT allows direct computation of radiant heat transmission to the human body since it adjusts for view factors by weighting surrounding temperatures. the mean radiant temperature Tr involves weighting the surface temperatures, Ti, using view factors (often represented as angle factors between the individual and all the surroundings, Fp-i. (Guo et al., 2020)

$$S_{str} = \alpha_k \sum_{i}^{6} K_i F_i + \varepsilon_p \sum_{i}^{6} L_i F_i$$

*Simultaneous shortwave Ki (through pyranometers) and longwave Li (by pyrgeometers) observations from six directions (i=1–6, east, west, north, south, upward and downward) enables body (Sstr) mean radiant flux density calculation.*(Guo et al., 2020)

$$T_{mrt} = \frac{\sqrt[4]{S_{str}}}{\varepsilon_p \sigma} - 273.15$$

$\varepsilon_p$ *: emissivity of the human body,*

*σ : Stefan*-Boltzmann *constant,*

$K_i$ *: shortwave radiation flux (Wm- 2)*

$L_i$ *: is the longwave radiation flux (Wm-2)*

*αk: is the absorption coefficient for shortwave radiation (standard value 0.7)*

*Fi: view factor in one of the six directions*

$T_{mrt}$ *: MRT*

- ***Step10:*** *Calculation of the point air temperature.*
- ***Step11:*** *Calculation point based relative humidity*
- ***Step12:*** *Computing wind speed.(The UTCI model assumes this meteorological wind speed is 1.5 times the speed of wind at occupant height (1.1 meters above the ground).)*

  *,*

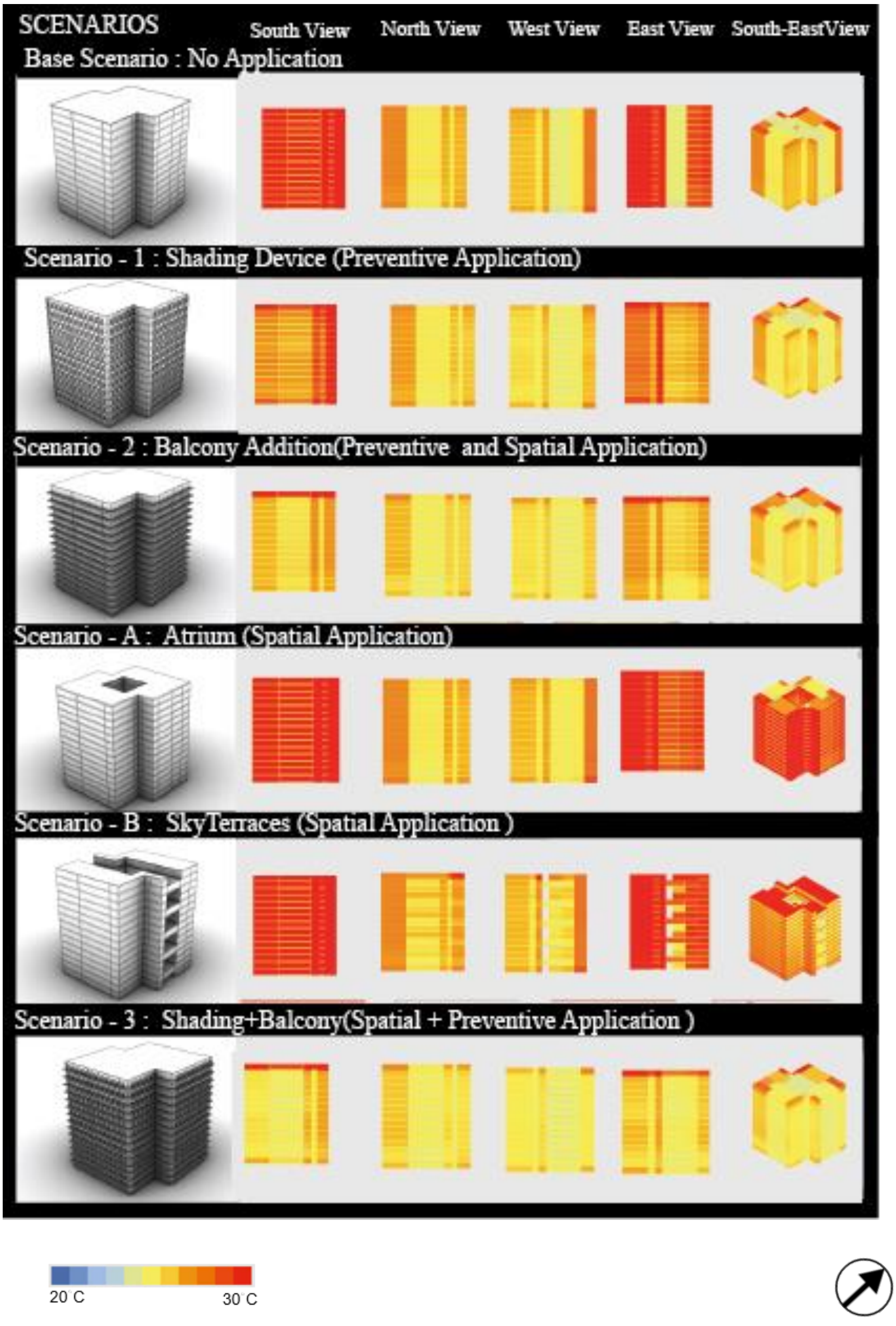



Figure 4.16. Indoor surface temperature analysis results obtained from EnergyPlus analysis for scenarios

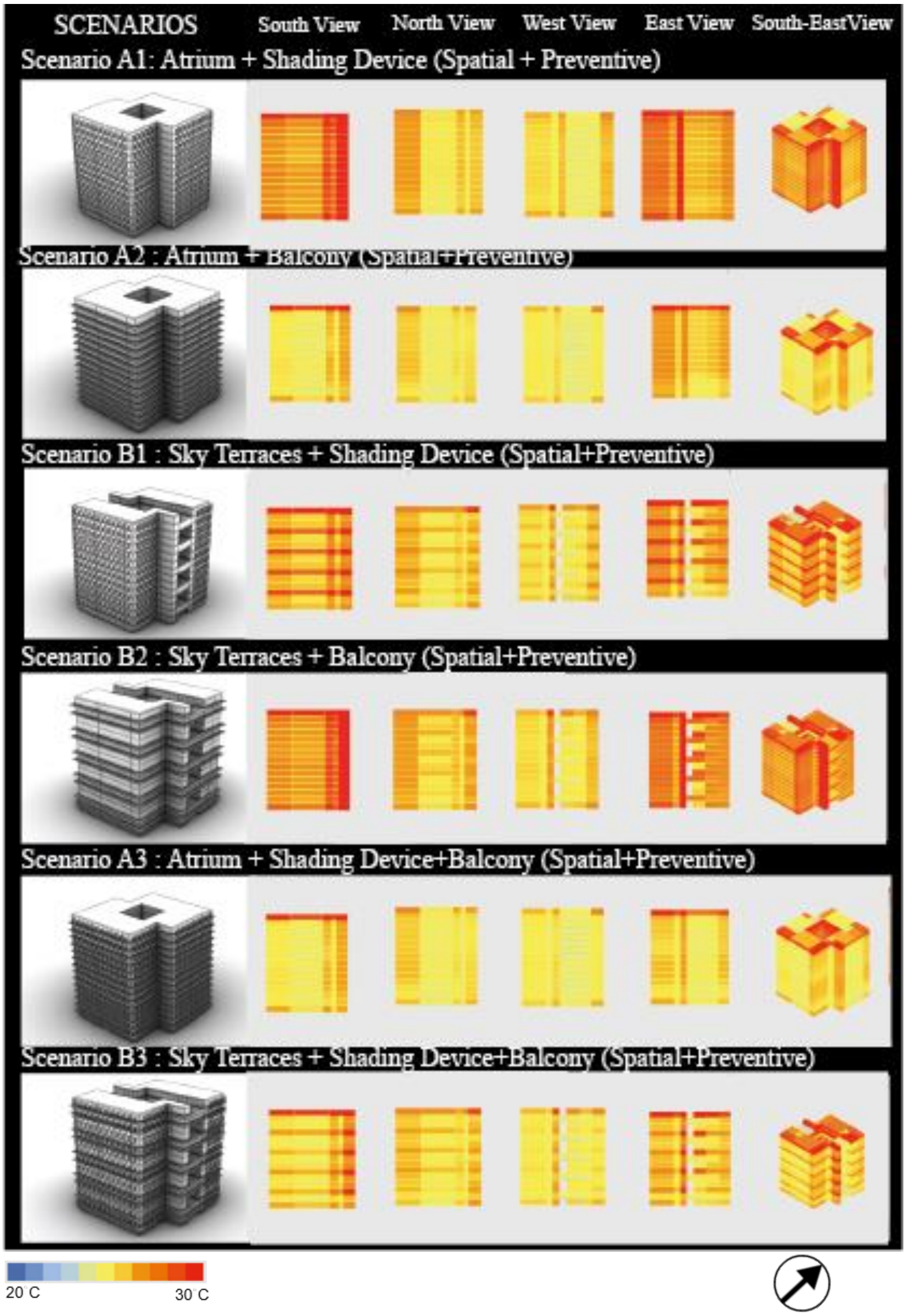



Figure 4.17. Indoor surface temperature analysis results obtained from EnergyPlus analysis for scenarios

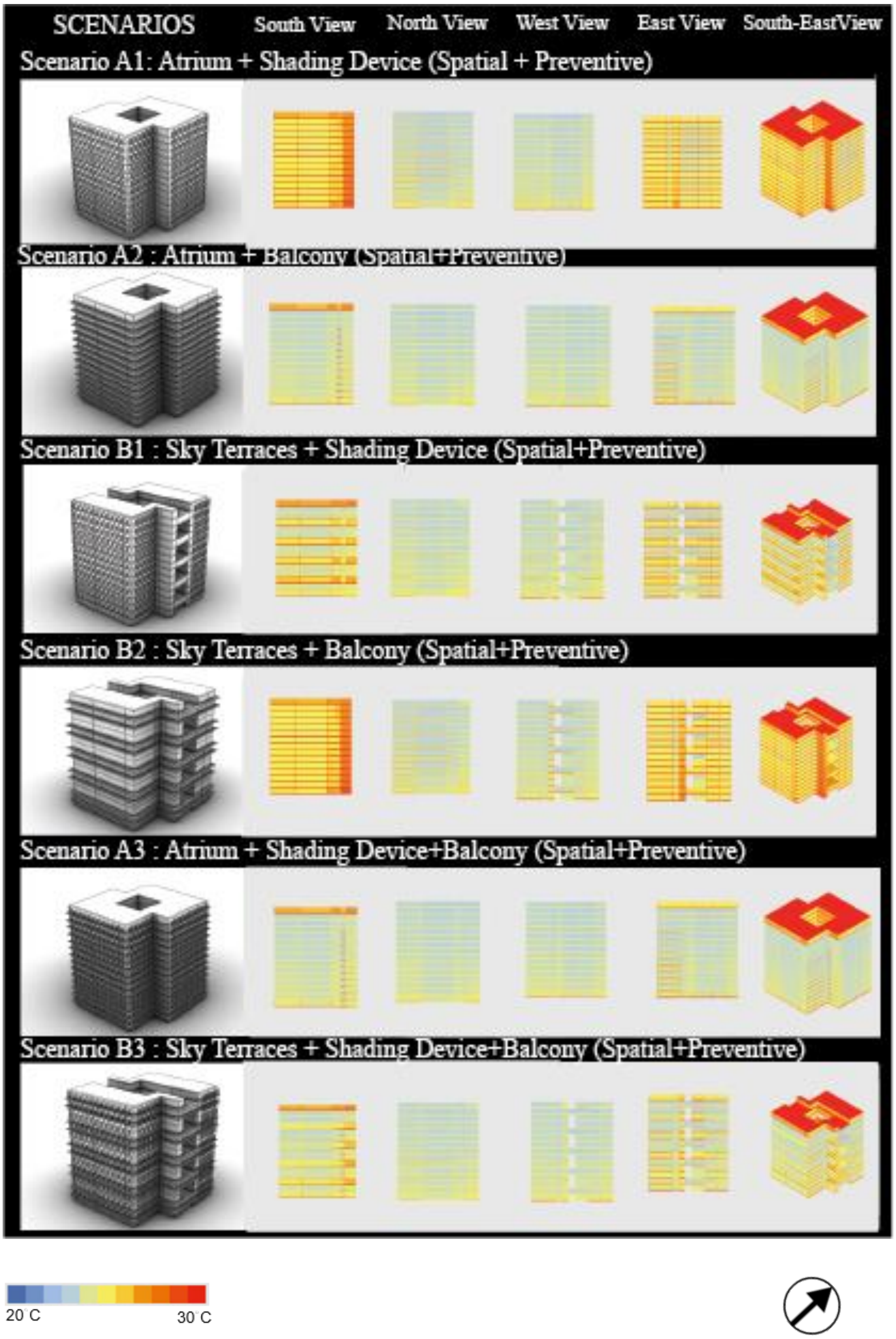



Figure 4.18. Outdoor surface temperature analysis results obtained from EnergyPlus analysis for scenarios

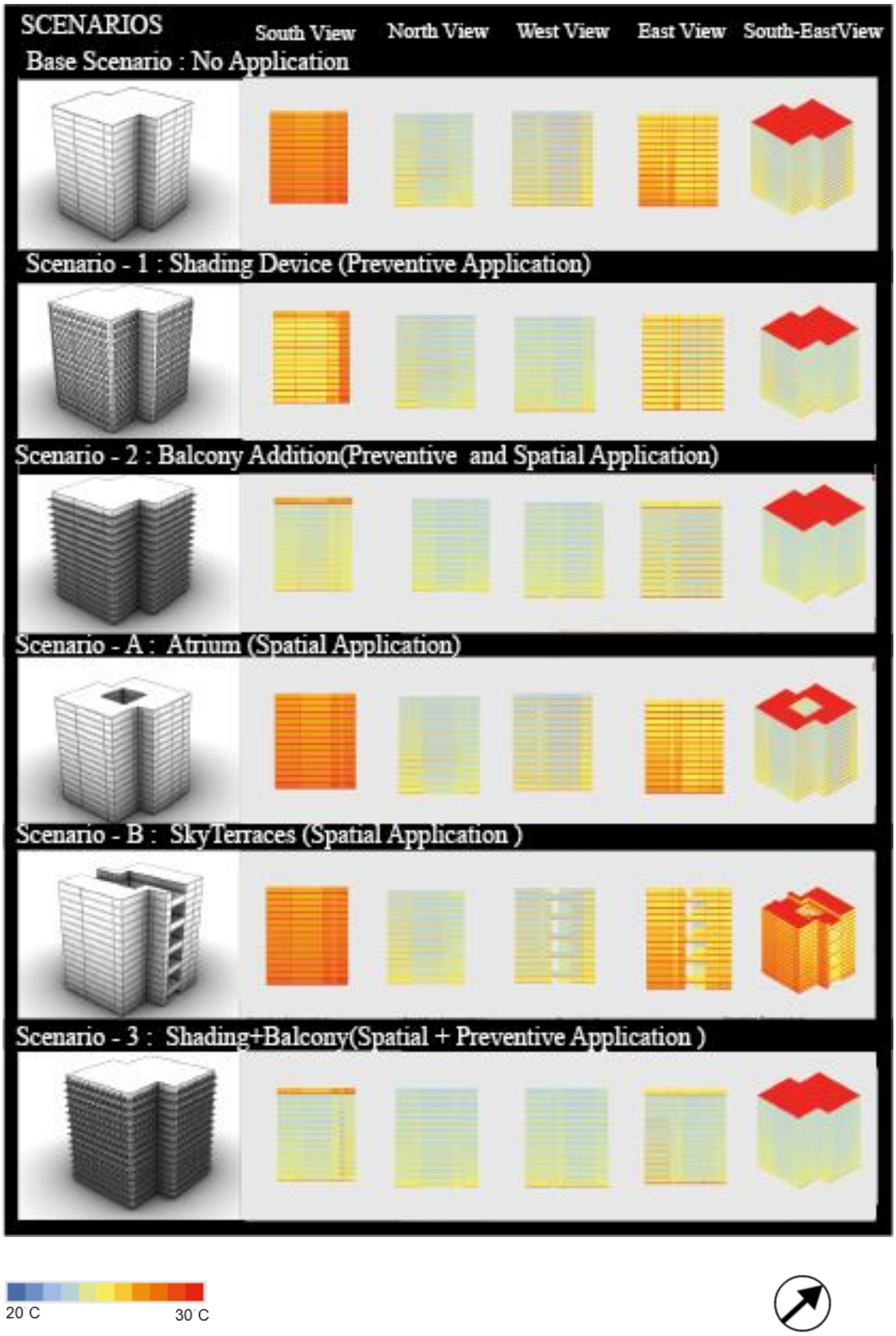



Figure 4.19. Outdoor surface temperature analysis results obtained from EnergyPlus analysis for scenarios

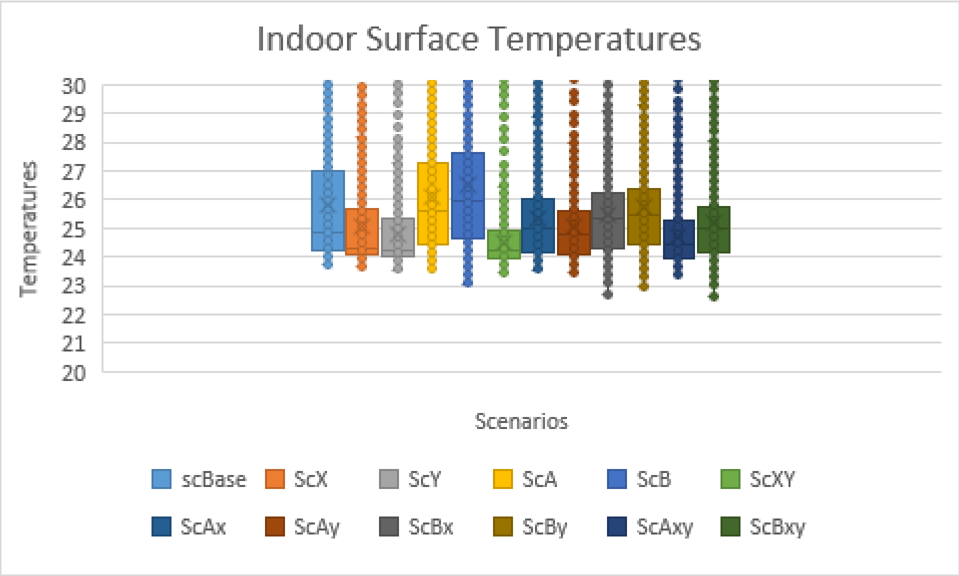



Figure 4.20. Indoor surface temperature analysis results obtained from EnergyPlus analysis for all scenarios

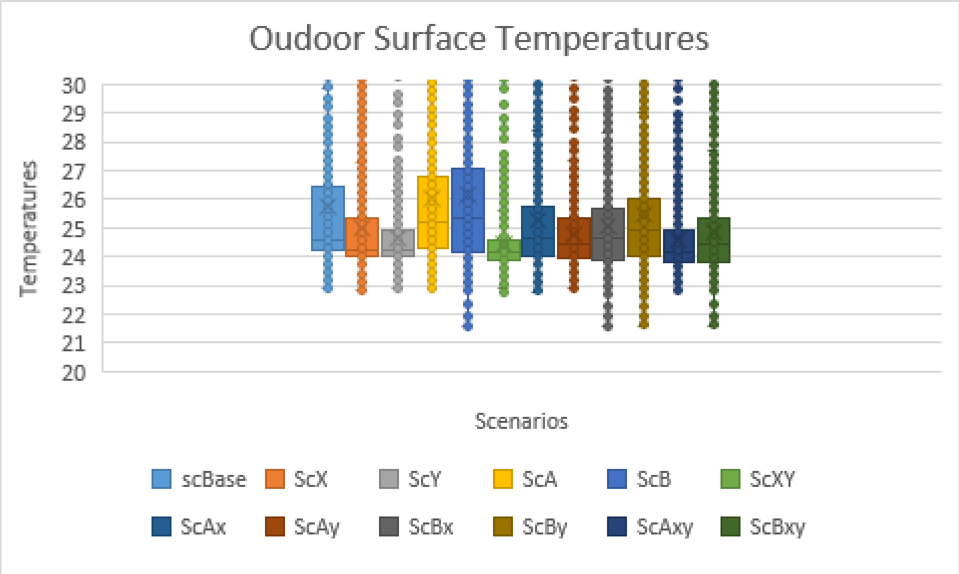



Figure 4.21. Outdoor surface temperature analysis results obtained from EnergyPlus analysis for all scenarios

### 4.3.3 Stage 3 : Simulations for Outdoor Microclimatic Condition Assessment

Cities are changing organisms, it grow up, its morphology is evolving. Urban-specific weather data generation provides more precise results for thermal comfort observing changing conditions.(Kirwan & Zhiyong, 2020) In this case outdoor thermal comfort will be evaluated from neighborhood scale to building scale. In this context outdoor thermal comfort analysis assessed using UTCI thermal comfort and semi-outdoor and building perimeter outdoor area analyzed using PET thermal comfort indices.

**Calculation of UTCI**

4.3 Parameters for UTCI Analysis

| UTCI | Environmental Parameters | Physical Parameters |
|---|---|---|
| **Cooling Design Day 21st July Ankara** | **Air Temperature ℃**<br>**Mean Radiant Temperature ℃**<br>**Relative Humidity %**<br>**Wind Velocity m/s** | **Trees**<br>**Building Form and Context** |

Outdoor microclimatic condition analysis and multi-scale thermal comfort analyzes were performed from the neighborhood scale to the building scale, as mentioned, in order to analyze whether people are comfortable in outdoor conditions. UTCI is calculated in Honeybee using polynomial approximation method via Microclimate Map Analysis component and UTCI_approx data is generated.

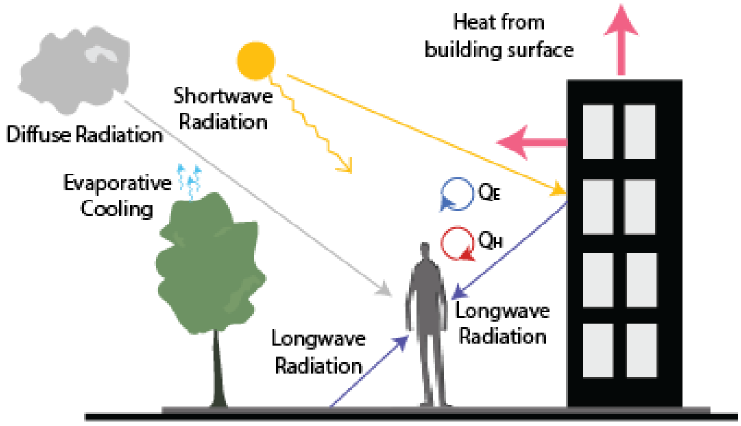



Figure 4.22. Outdoor environmental parameers and user comfort

.UTCI analysis was performed with the help of the parameters in the table above. In order to obtain wind velocity data, the instant average wind speed data of the region to be analyzed was obtained by using the Butterfly CFD tool represented in Figure 4.16. this context,

- UTCI analysis (without tree)
- UTCI analysis (with tree)
- UTCI analysis integrated CFD result (without tree)
- UTCI analysis integrated CFD result (with tree)

Four different UTCI analysis based on tree included and CFD included scenarios in order to understand impact of vegetation and CFD analysis results according to building geometry. Thus, it is aimed to observe the effect of UHI and vegetation use on outdoor thermal comfort through UTCI thermal comfort index. Figure 4.16. and Figure 4.17 represents wind vectors and values around the building.

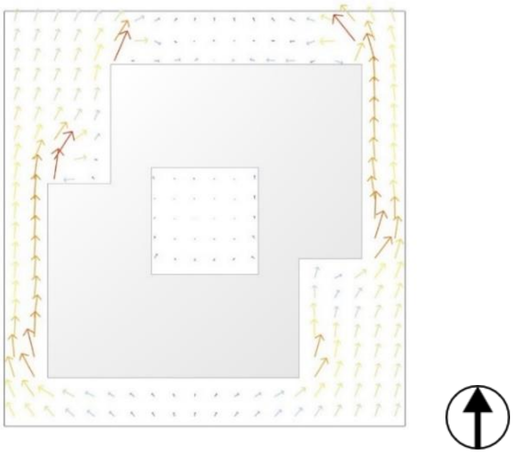



Figure 4.23. CFD analysis results and average wind speed at street level (1 m height)

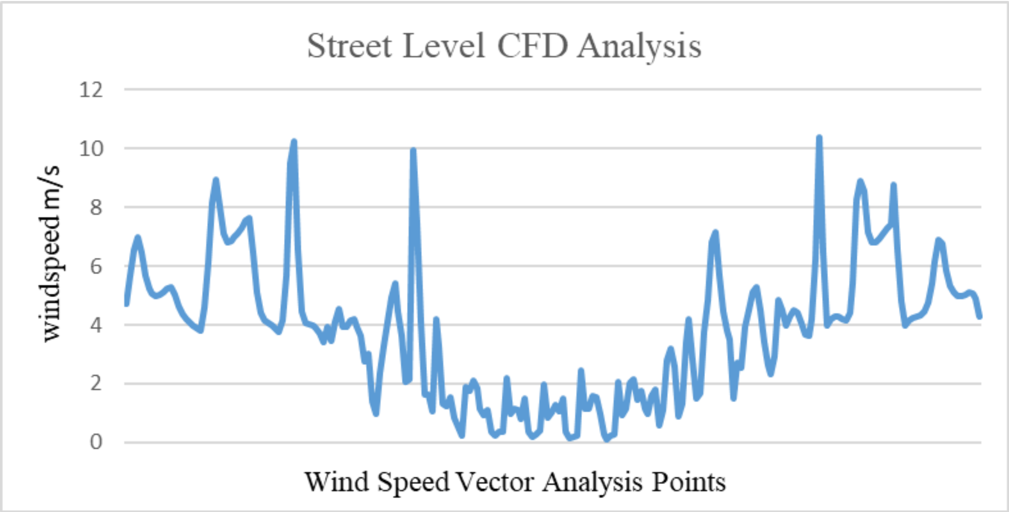



Figure 4.24. CFD analysis result and average wind speed at street level based on analysis surface point (1 m height)

**Calculation of PET (Physiological Equivalent Temperature)**

While UTCI will be used for neighborhood scale thermal comfort analysis, PET thermal comfort index has been used for outdoor thermal comfort in the building perimeter. The "feels like" temperature, or PET, is defined as the operational temperature of a reference environment that would elicit the same physiological reaction in a human subject as the environment under study(Ladybugcomfort.Pet, n.d.). It means that both the skin and the core temperature are at the same temperature. With the help of PET index, thermal comfort analysis will be made in transitional areas such as building perimeter, sky-terraces and atrium areas, and the effect of transitional areas on user comfort will be analyzed at the building scale. In PET thermal comfort analysis, in the analysis made using honeybee PET recipe, outdoor was included in this study, so both indoor and outdoor PET values were measured in 12 different scenarios. Honeybee tool is working in collaboration with Energyplus to assess occupant comfort in different scales. EnergyPlus analysis results are obtained via ReadResultFile component reaching analysis results from .csv file which are surface temperatures, zone air temperature, relative humidity, zone airflow volume zone air heat gain. PET thermal comfort analysis requires calculation of MRT as it mentioned in Section 3 describing calculation methodology of thermal comfort index. However, EnergyPlus analysis results do not include MRT calculation in itself. In this case Honeybee Microclimate Map Analysis Component provides calculation of MRT through view factor points calculation generated by analysis surface and grid divided into 1 m. Microclimate Map Analysis component creates dictionary of zone surfaces and outdoor surfaces in order to reach point MRT values. Thus, calculated MRT values provides application of PET thermal comfort index.

4.4 Parameters for PET Analysis

| PET | Microclimatic Parameters | Physical Parameters | Personal Parameters |
|---|---|---|---|
| **Cooling Design Day 21st July Ankara** | **Air Temperature °C**<br>**Mean Radiant Temperature°C**<br>**Relative Humidity %**<br>**Wind Velocity m/s** | **Shading Element Addition**<br>**Building Form and Context** | **Age: 30**<br>**Pos: Standing**<br>**Met: 2.32** |

### 4.3.4 Stage 4: Simulations for Indoor Microclimatic Conditions and Comfort Assessment

In this stage, thermal comfort in the indoor environment is assessed using Honeybee ATC (Adaptive Comfort Model) thermal comfort recipe component. This component includes necessary ambient and personal parameters to calculate indoor thermal comfort. In this case, twelve different scenarios are introduced to analyze changing design implementation such as; shading device addition, the inclusion of sky terraces with the creation of breezeways, balcony addition as a perimeter buffer zone, and shading function. In contrast to PET analysis, body characteristics are not included in ATC. The environmental and physical parameters listed in the table below are taken into account. Min Indoor temperature set point is determined as 22$^{o}$C. Natural ventilation, considering neutral condition limits (18-23 $^{o}$C), min. It was chosen as 22$^{o}$C, and according to these environmental conditions, indoor thermal comfort analysis was carried out on 12 scenarios.

**Calculation Process of ATC:**

4.5 Parameters for ATC Analysis

| ATC | Microclimatic Parameters | Physical Parameters |
|---|---|---|
| **Cooling Design Day<br>21st July<br>Ankara** | **Air Temperature °C**<br>**Prevailing Air Temperature °C**<br>**Mean Radiant Temperature°C**<br>**Wind Velocity m/s**<br>**M*in Indoor Temp. for Natural Ventilation: 23 C*** | **Shading Element Addition**<br><br>**Building Form and Context** |

ATC, explained in detail in Section 3, is analyzed through the operative temperature calculation. The operative temperature value, defined as comfortable temperature for indoor analysis, is calculated by taking the average MRT and Air temperature in the Microclimate Map Analysis component. Thus, the thermal comfort analysis in a naturally ventilated indoor environment is calculated by the ATC index.

```
def t_operative(ta, tr):

    Get operative temperature from air and radiant
temperature.Args:

        ta: Air temperature [C]

      tr: Mean radiant temperature [C]

        Operative temperature [C]

    return (ta + tr) / 2

        t_prevail: The prevailing outdoor temperature [C].  For
the ASHRAE-55 adaptive

    return 0.31 * t_prevail + 17.8
```

Figure 4.25. Calculation of ATC using Microclimate Map Analysis component from Honeybee tool.

The Microclimate Map Analysis component, also used in PET and UTCI calculations, reaches MRT values in ATC calculation by using outdoor and indoor surface temperature values obtained as a result of EnegyPlus analysis in the same way.

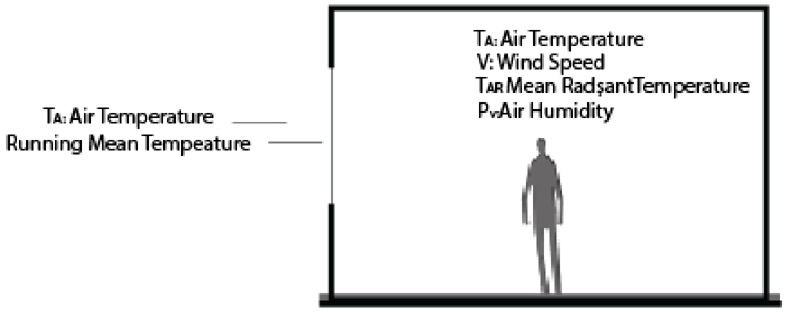



Figure 4.26. Indoor microclimate parameters and occupant comfort illustration

### 4.3.5 Stage 5: Comparison and Assessment of Indoor and Outdoor Thermal Comfort in Transitional Spaces

At this stage, the obtained UTCI, PET, and ATC simulation results were evaluated by considering the areas in which they were analyzed and their relations with each other. Multi-scale evaluations of climate-responsive design solutions applications were made by observing the relationship between the results obtained in assessing these thermal comfort indexes with different evaluation methods. This section is reported under the results section with visuals, tables with results, and graphics showing their relationship.

# CHAPTER 5

# RESULTS

This section presents and evaluates the results of the case study analysis carried out in 5 steps with the simulation tools described in the previous section. As the study progressed from neighborhood scale to building scale, neighborhood analysis was first analyzed with UTCI index, then with PET index in building surroundings and semi-outdoor spaces, and lastly with thermal comfort ATC inside the building, the results were presented in this order.

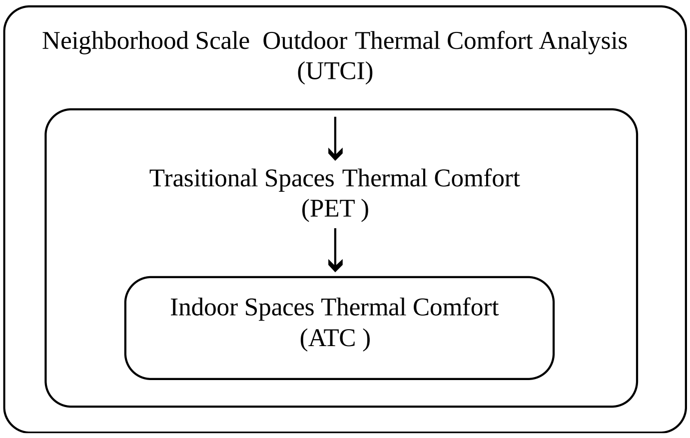



Figure 5.1. Multi-scale thermal comfort analysis schema

Table 0.1 Multi-scale thermal comfort analysis scenarios and applications

<table>
<tr><th colspan="12">SCENARIOS FOR OUTDOOR THERMAL COMFORT ANALYSIS</th></tr>
<tr><td colspan="3">Base Scenario</td><td colspan="3">Including Tree</td><td colspan="3">Integrated CFD result (without tree)</td><td colspan="3">Integrated CFD result (with tree)</td></tr>
<tr><td colspan="3">Scenario-1</td><td colspan="3">Scenario-2</td><td colspan="3">Scenario-3</td><td colspan="3">Scenario-4</td></tr>
<tr><th colspan="12">SCENARIOS FOR TRANSITIONAL AND INDOOR SPACES THERMAL COMFORT ANALYSIS</th></tr>
<tr><th>Base</th><th>Preventive</th><th>Both Spatial and Preventive</th><th colspan="2">Spatial</th><th>Preventive + Both Spatial and Preventive</th><th colspan="4">Preventive +Spatial</th><th colspan="2">Preventive + Both Spatial and Preventive+Spatial</th></tr>
<tr><td>No Application</td><td>Shading Device</td><td>Balcony</td><td>Atrium</td><td>SkyTerraces</td><td>Shading + Balcony</td><td>Shading + Atrium</td><td>Shading + SkyTerraces</td><td>Balcony + Atrium</td><td>Balcony + SkyTerraces</td><td>Balcony + Shading +Atrium</td><td>Balcony + Shading +SkyTerraces</td></tr>
<tr><td>Sc0</td><td>Sc1</td><td>Sc2</td><td>ScA</td><td>ScB</td><td>Sc3</td><td>ScA1</td><td>ScA2</td><td>ScB1</td><td>ScB2</td><td>ScA3</td><td>ScB3</td></tr>
</table>

## 4.4 Evaluation of Simulation Results at Street Scale via UTCI index

Considering the parameters evaluated in the outdoor microclimate analysis, which are air temperature, radiant temperature, relative humidity, and wind velocity, to analyze the effect of environmental conditions more precisely, CFD analysis was performed using the Butterfly tool. The average wind speed data was level 1, also named street level, with 1 m height. At this point, outdoor thermal comfort analysis was performed using UTCI at street level. UTCI comfort analysis is conducted at a 123045.757 $m^2$ area, including surrounding buildings. The UTCI research aims to reach neighborhood scale comfort values by integrating tree and CFD analysis results. The UTCI results, which were examined in 4 different scenarios to analyze the current situation, wind speed data included, and tree-included versions showed that temperatures had lower values when wind speed was included. In addition, tree canopy showed that the temperature values decreased regionally in the areas where trees were added. At this point, it can be said that the specific data obtained by including contextual features affect the results, and the comfort of the trees increases regionally. As described in Section 2, the UTCI temperature value represents “feels-like” temperature combining wind speed, air temperature, radiant temperature, and relative humidity in outdoor conditions. Average temperature values of UTCI matrix temperature values generated by UTCI thermal comfort recipe from Ladybug, Honeybee tools.

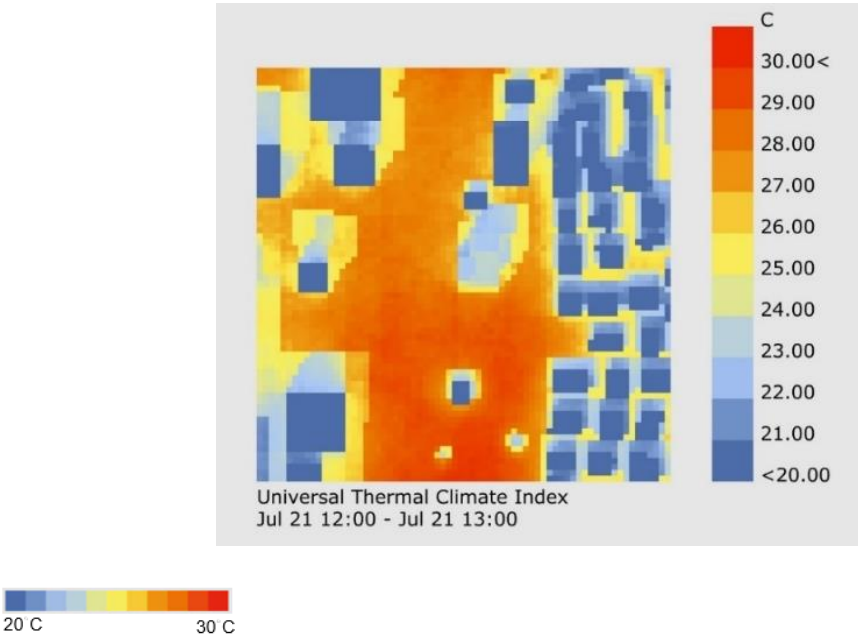



Figure 5.2. UTCI analysis results in neighborhood scale – Without tree canopy and CFD analysis result. 123045-$m^2$

Scenario 1, which does not include wind speed data obtained from CFD and tree canopy, shows that building surrounding areas represent lower temperature values, approximately between 21-23 C Celsius degrees. However, building surrounding area exposed relatively barren compared to the eastern side and has higher temperature values approaching 30 $^{o}$C degrees on the southern side. UTCI point results are represented in Figure 5.2. shows that the highest value is calculated area reached by 30 $^{o}$C degrees in the scenario without tree and CFD results. The lowest temperature values are recorded at around 20 $^{o}$C degrees.

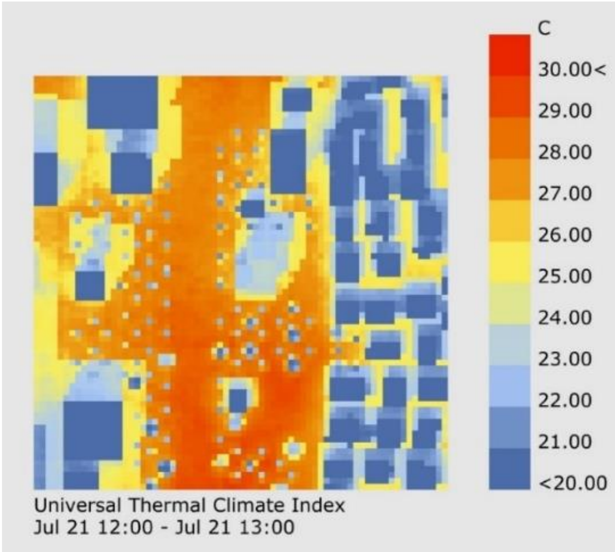




Figure 5.3. UTCI analysis results in neighborhood scale – With tree canopy and without CFD analysis result. 123.045-m$^2$

Similarly, UTCI analysis scenario-1 results in the highest temperature reaching 29.5 while the lowest temperature value is around 20 $^{o}$C. According to Figure 5.3. which demonstrates UTCI temperature values on the urban scale; while building surrounding areas shows the same pattern, temperature values in the area, including tree canopies, decrease compared to outdoor thermal comfort calculation scenario 2.

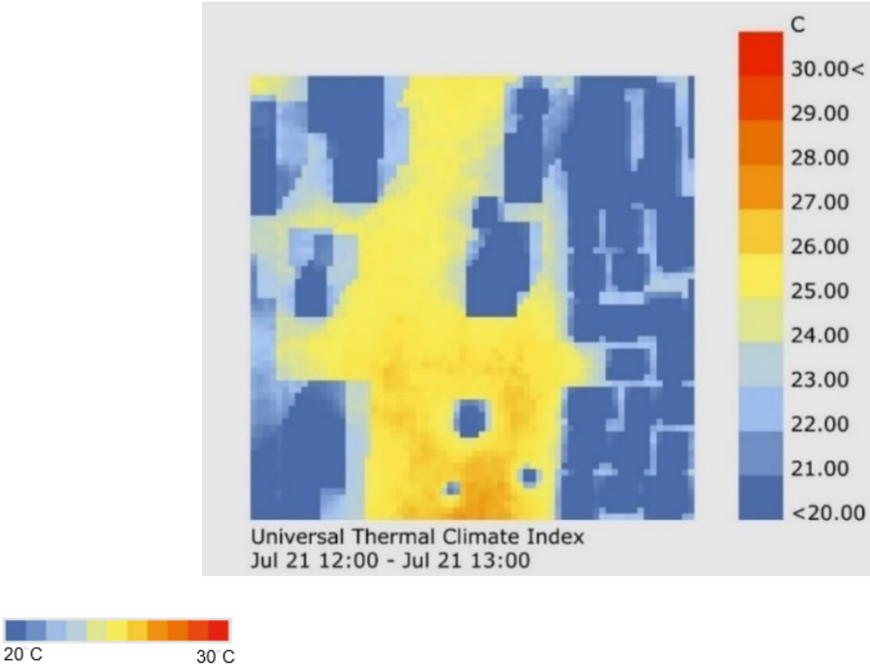



Figure 5.4. UTCI analysis result in neighborhood scale – Without tree Canopy and with Wind Speed Data included

Wind speed data received from CFD analysis at street level integrated into outdoor thermal comfort simulation scenarios 3 and 4. Results show that the integration of wind speed data leads a drastic change in UTCI temperatures compared to omitted scenarios 1 and 2. As in scenarios 1 and 2, the lowest temperature value was 20 degrees Celsius in calculations that did not include wind speed, while in scenario-3 where the wind was included, the lowest temperature reached 15.5 degrees Celsius. In addition, while the highest temperature values were seen in the range of 29-30 degrees, this value decreased to 26.5 degrees in scenario 3.

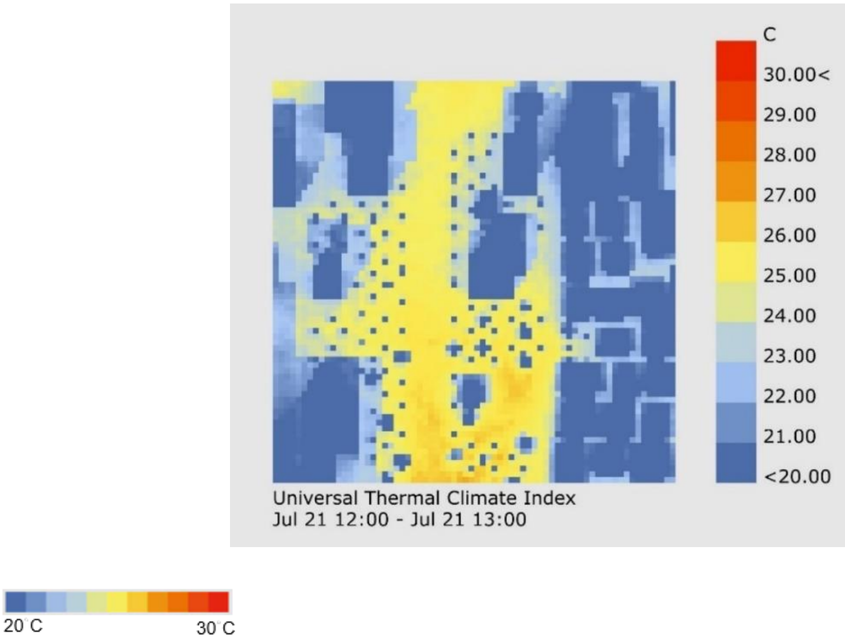



Figure 5.5. UTCI analysis result in neighborhood scale – Tree Canopy and Wind Speed Data included

UTCI analysis, including CFD results and tree canopy results, shows that the highest temperature value reaches 26.5 $^{o}$C while the temperature value of the coolest areas is minimum 15.5 $^{o}$C in a very small area in comparison to the number of points. Similar to the difference in temperature distribution in scenarios 1 and 2, the temperature values in locations with more vegetation were reduced, as it represented in Figure 5.7.

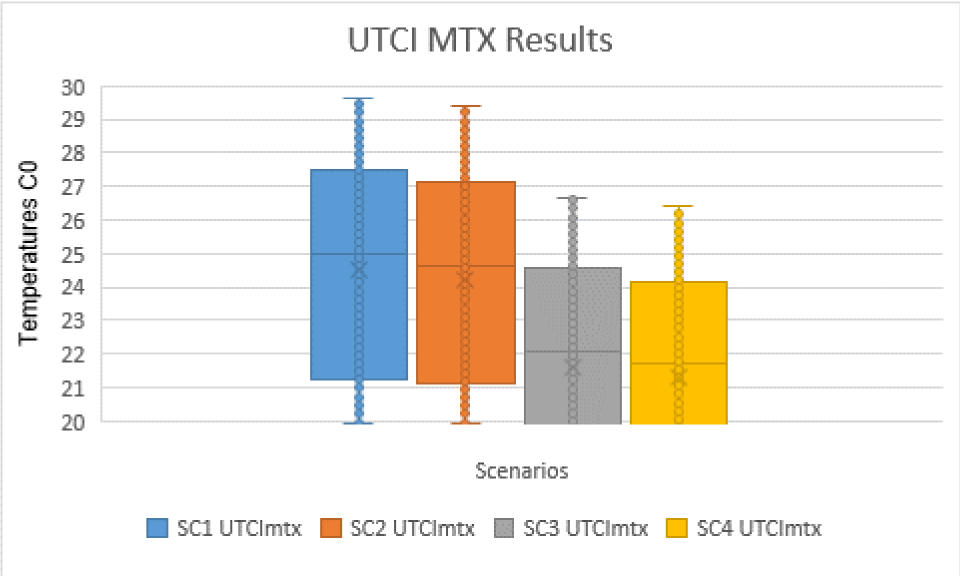



Figure 5.6. UTCI analysis results for scenario 1,2,3 and 4. *(Sc 1 : Without tree and CFD data, Sc 2: Including tree without CFD Sc 3: integrated CFD result without tree Sc4: Integrated CFD result with tree)*

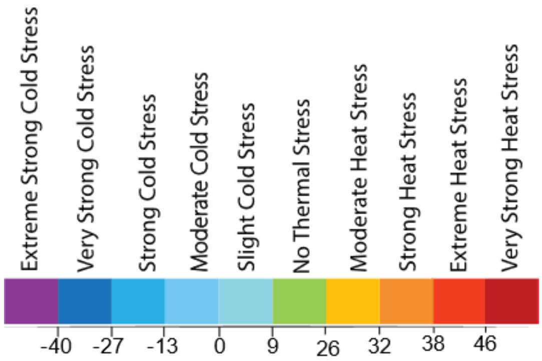



Figure 5.7. UTCI Temperatures and ten-point thermal stress index from extreme cold stress to extreme heat stress.

According to the chart describing thermal stress, the values of the findings of the outdoor thermal comfort analysis fall somewhere between the values indicating no thermal stress and the values indicating considerable thermal stress. It is possible to draw the conclusion that the results achieved by the calculations, including the

CFD results, are within the range in which there is no thermal stress on account of the fact that the maximum temperature values in scenarios 3 and 4 are around 26 degrees. When additional factors, such as the time interval in which the point UTCI temperature values in the scatter plots occur, are taken into consideration, one can reach the conclusion that the outdoor thermal stress experienced by CDD between 12:00 and 13:00 is not particularly severe during this time period. It can be observed that the vegetated area, in which the CFD result is integrated, provides extra opportunities for cool regions, which is particularly essential when taking into account the necessity for a cooler zone.

## 4.5 Assessment of Thermal Comfort in Transitional Spaces via PET index

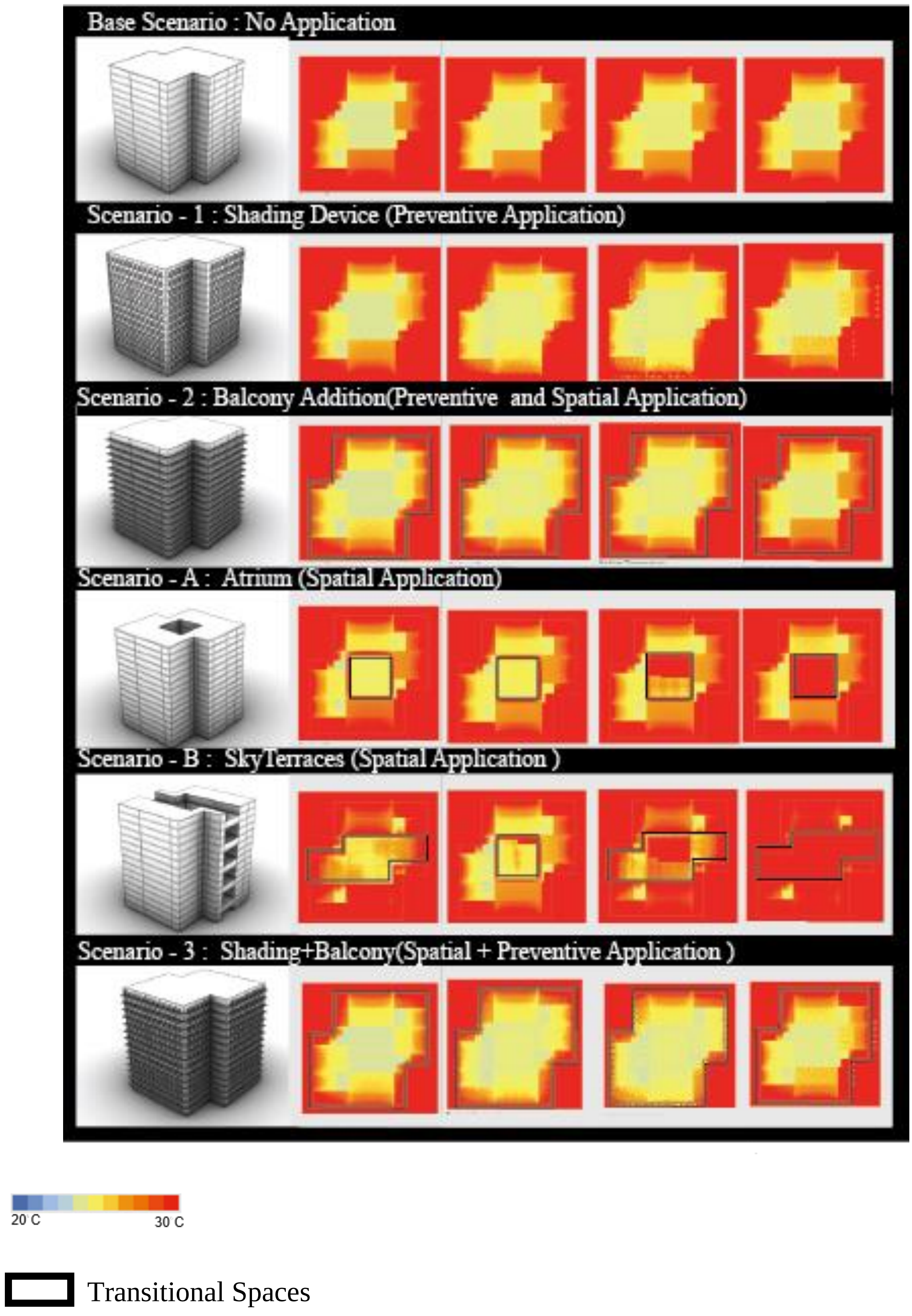



Figure 5.8. PET thermal comfort MRT values for each scenario

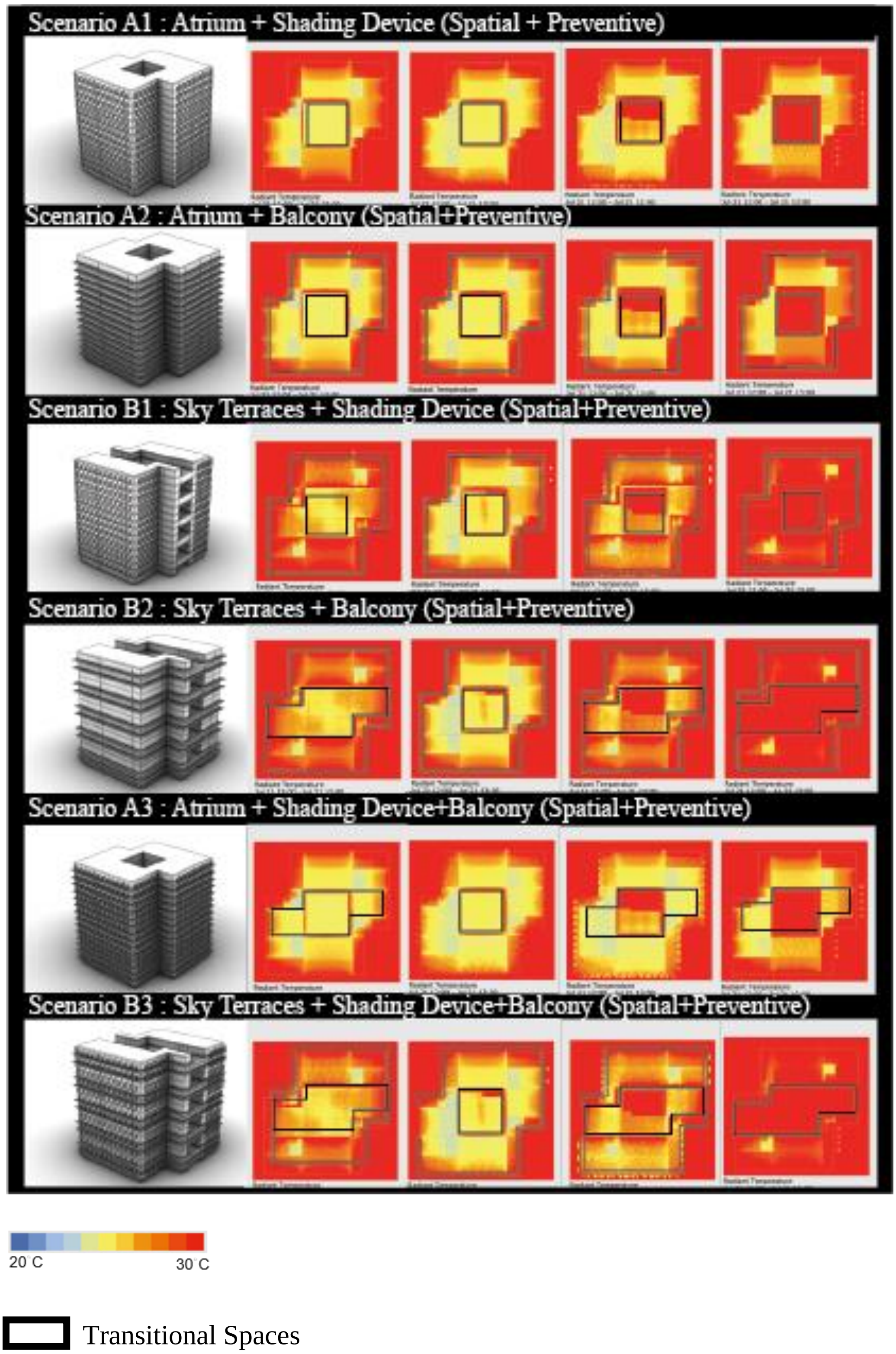



Figure 5.9. PET thermal comfort MRT values for each scenario

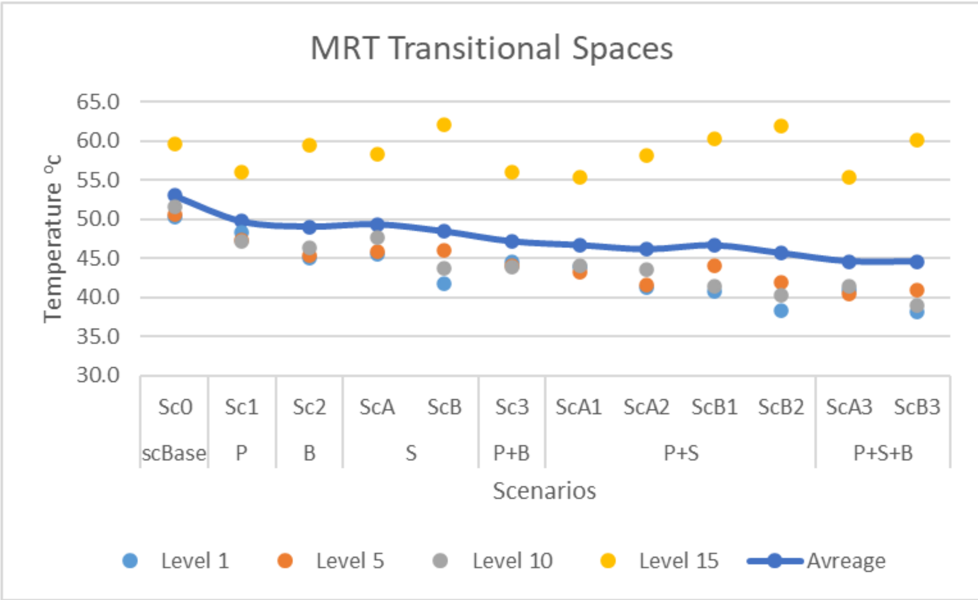



Figure 5.10. PET thermal comfort MRT values for all scenarios

Table 0.2 MRT values for transitional spaces

| **Out MRT** | **scBase** | **P** | **B** | **S** | | **P+B** | **P+S** | | | | **P+S+B** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levels** | **Sc0** | **Sc1** | **Sc2** | **ScA** | **ScB** | **Sc3** | **ScA$_1$** | **ScA$_2$** | **ScB$_1$** | **ScB$_2$** | **ScA$_3$** | **ScB$_3$** |
| **Level 1** | 50.2 | 48.3 | 45.0 | 45.5 | 41.7 | 44.6 | 44.0 | 41.2 | 40.8 | 38.3 | 40.9 | 38.2 |
| **Level 5** | 50.6 | 47.3 | 45.3 | 45.9 | 46.1 | 44.0 | 43.2 | 41.5 | 44.0 | 41.8 | 40.5 | 41.0 |
| **Level 10** | 51.6 | 47.1 | 46.4 | 47.7 | 43.8 | 43.9 | 44.1 | 43.5 | 41.4 | 40.3 | 41.5 | 38.9 |
| **Level 15** | 59.6 | 56.1 | 59.5 | 58.3 | 62.2 | 56.0 | 55.4 | 58.2 | 60.3 | 62.0 | 55.4 | 60.2 |
| Avreage | 53.0 | 49.7 | 49.0 | 49.3 | 48.4 | 47.1 | 46.7 | 46.1 | 46.6 | 45.6 | 44.6 | 44.6 |

PET MRT for semi-outdoor spaces results represented above. In comparison to indoor MRT results, relationship between transitional spaces MRT value and scenarios are represents different pattern. To illustrate, while shading device addition was not effective as balcony, here, shading device addition decrease building perimeter MRT values from 53.0 °C to 49.70 as it can be observed ScBase and Sc1. In addition to that, balcony addition also provided temperature decrease building perimeter at it can be observed from Sc2 , from 53.7 °C to 51.93 °C. Another difference between indoor and outdoor relation can be seen from Sc-A and Sc-B results. While atrium and sky terraces additions affected indoor MRT temperatures negatively, these applications decreased average MRT in transitional spaces. Furthermore, while Sc-B represents highest values for indoor MRT values, in transitional spaces case, except level 15, level1 ,5 and level 10 reaches lower values in comparison to Sc0 . While shading and balcony addition to Sc0 produced lowest MRT temperature indoor spaces, in the transitional spaces, balcony and shading device are not effective as atrium and sky terraces addition. As it can be observe from Sc3,A-1, A-2, B1, B2, A3 and B3, shading device and atrium applications provide MRT decrease around the building. The temperature is reduced more by adding only the balcony to the atrium building form than by adding only a shade element as it can be observed from scenario A1 and A2 results. Only balcony addition to sky-terraces application (Sc-B2), shading device usage (Sc -B1) exhibits more effective results and cause 1 ℃ degrees change in two scenarios. Among these applications the most effective solutions regarding MRT temperatures in transitional spaces and building perimeter area, Sc A3 including balcony, atrium and shading device and ScB3 including balcony, shading and sky terraces with 44.6 ℃ demonstrate the lowest MRT temperatures. In conclusion, Sc A3 and B3 represents the lowest values and shaded areas in terms of thermal comfort in transitional spaces.

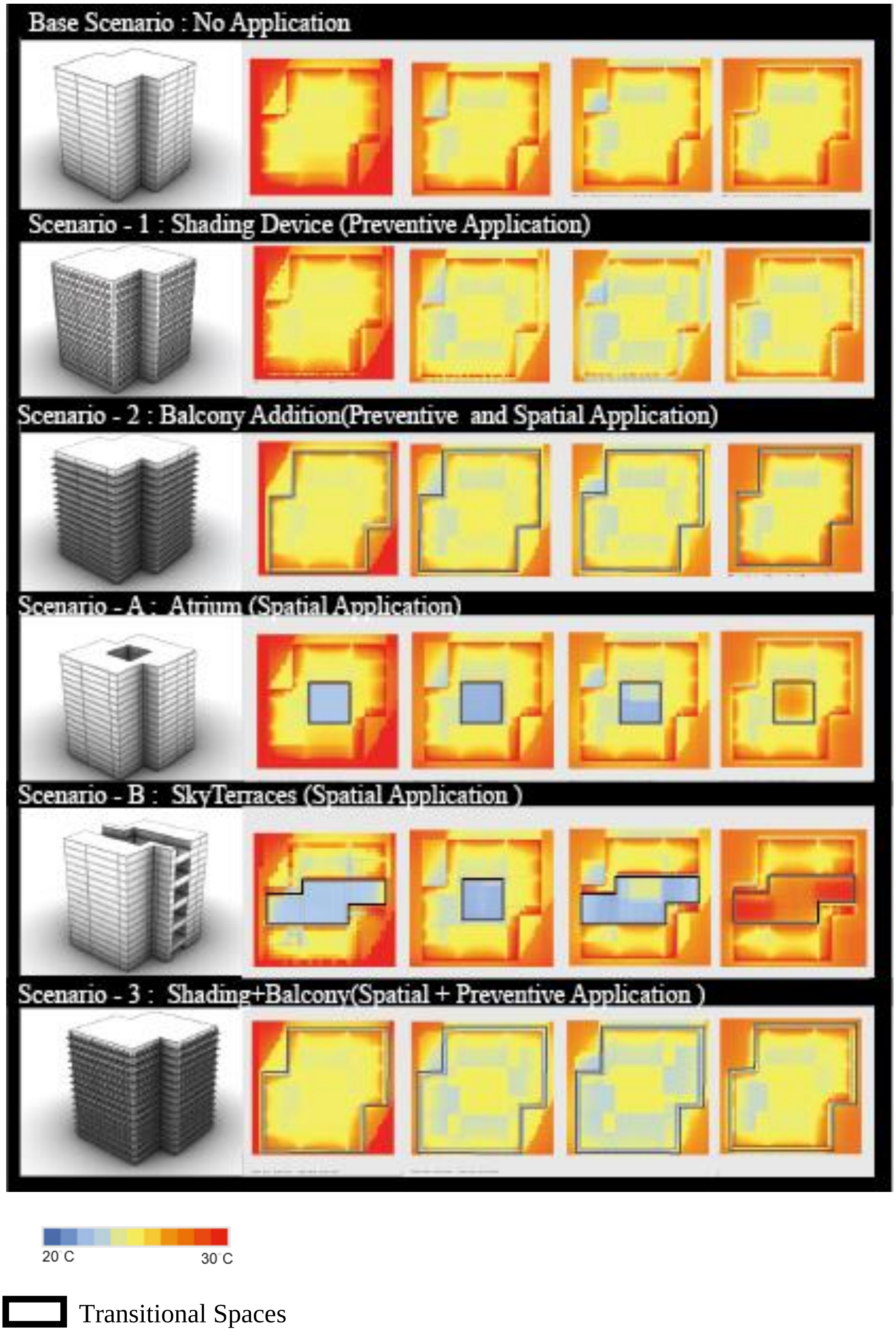



Figure 5.11. PET thermal comfort PET values for each scenario

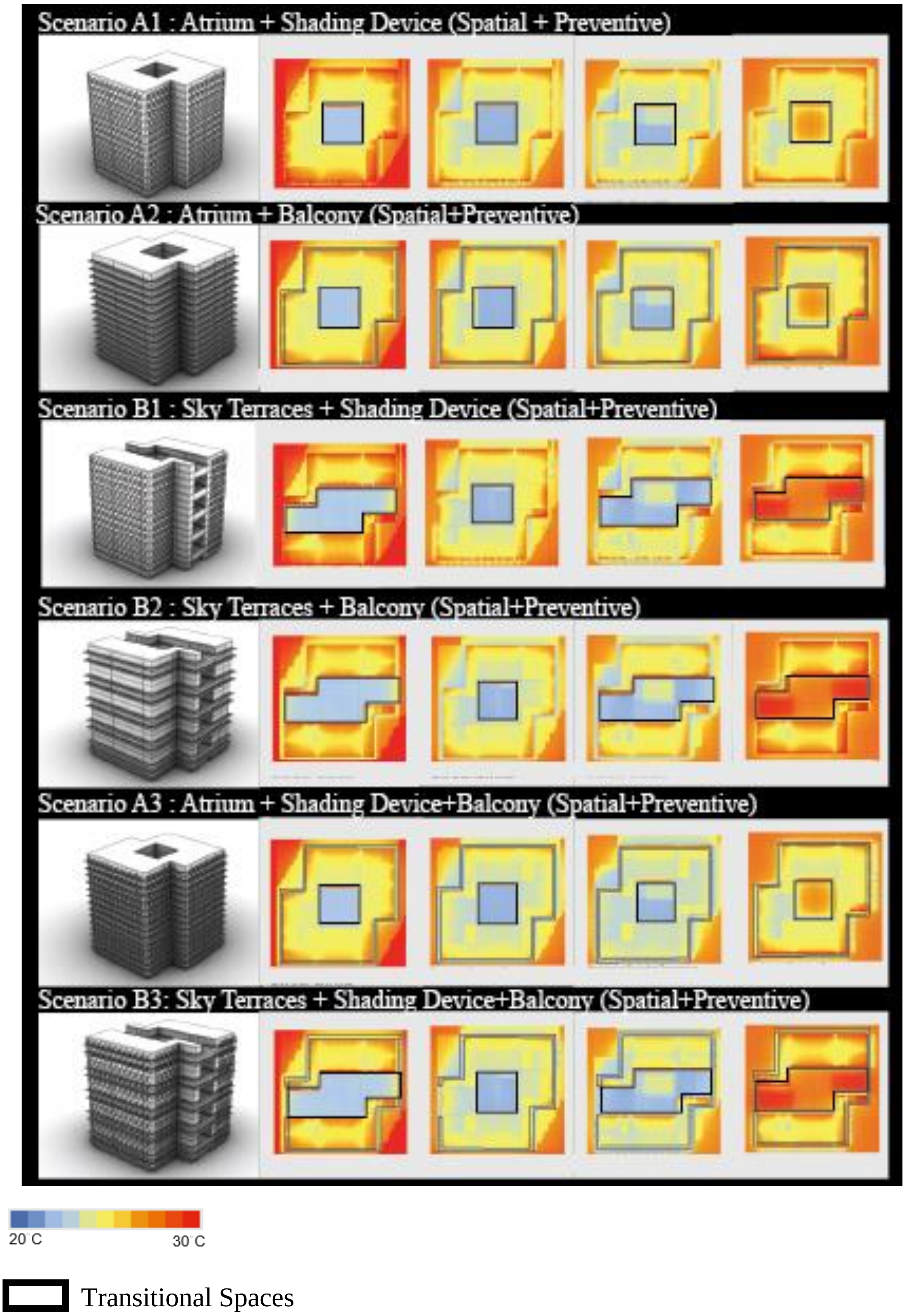



Figure 5.12. PET thermal comfort PET values for each scenario

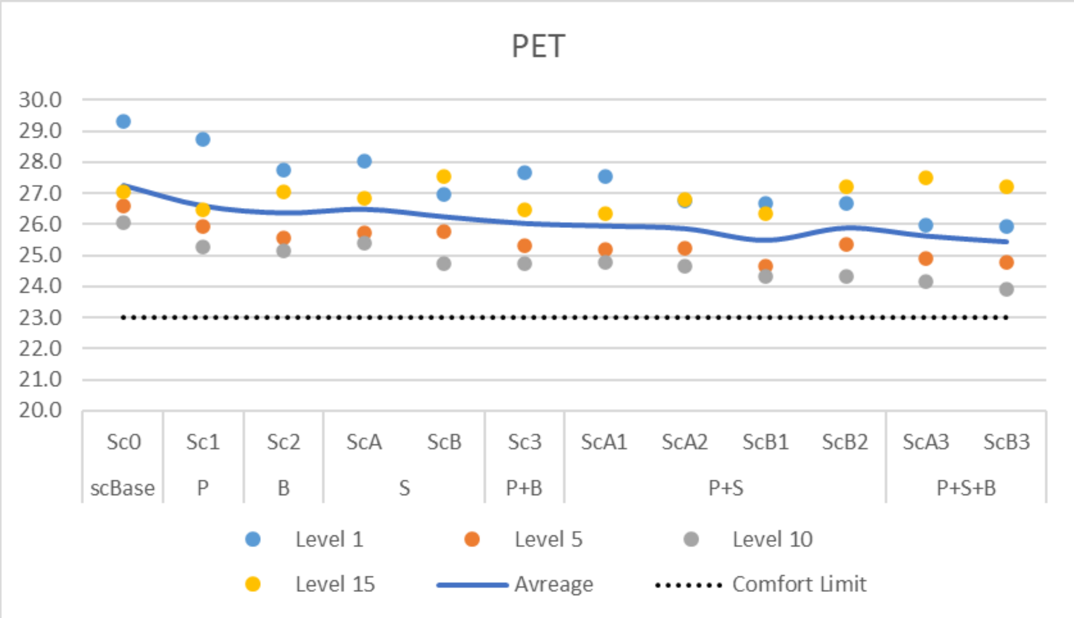



Figure 5.13. PET thermal comfort PET values for twelve scenarios

Table 0.3 Physiological Equivalent Temperature (PET) assessment in different building levels.

| PET | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levels** | **Sc0** | **Sc1** | **Sc2** | **ScA** | **ScB** | **Sc3** | **ScA1** | **ScA2** | **ScB1** | **ScB2** | **ScA3** | **ScB3** |
| **Level 1** | 29.3 | 28.7 | 27.8 | 28.0 | 27.0 | 27.6 | 27.5 | 26.8 | 26.7 | 26.7 | 26.0 | 25.9 |
| **Level 5** | 26.6 | 25.9 | 25.5 | 25.7 | 25.7 | 25.3 | 25.2 | 25.2 | 24.7 | 25.3 | 24.9 | 24.8 |
| **Level 10** | 26.0 | 25.3 | 25.1 | 25.4 | 24.7 | 24.7 | 24.8 | 24.7 | 24.3 | 24.3 | 24.1 | 23.9 |
| **Level 15** | 27.1 | 26.5 | 27.0 | 26.8 | 27.5 | 26.4 | 26.3 | 26.8 | 26.3 | 27.2 | 27.5 | 27.2 |
| Avreage | 27.3 | 26.6 | 26.4 | 26.5 | 26.2 | 26.0 | 26.0 | 25.9 | 25.5 | 25.9 | 25.6 | 25.4 |

Grid-based distributions of PET results are presented in different scenarios and at levels 1.5, 10 and 15. The results show the relationship between the use of double skin façade and the interior and exterior environment of the façade element separating the interior and exterior spaces in the building perimeter. The buffer area, located in the façade area, compensated the effect of the outdoor conditions on the interior, and created more comfortable spaces in the interior.

PET calculation comprise of Air temperature, MRT,Relative Humidity,Wind Velocity and personal parameters including MET, clo, position and age variables. Although MRT and air temperature are the same for other thermal comfort indicators, in the case of PET, these factors might alter the relationship between the findings for each situation.

As determined by MRT calculations, the ScB3 sky terraces including building form with shading and balcony provides the most pleasant temperature values. Similar to MRT findings in transitional spaces, Base scenario, scenario 1,2,3,A, and B exhibit greater temperature values than atriums and sky terraces which are spatial interventions. Among all scenarios, base scenario (Sc0) without any use of climate-responsive design solutions has the greatest value. Temperature differences across scenarios also need consideration. These applications result in a temperature shift of roughly 1.9 degrees Celsius. The addition of shading to base scenario is more beneficial than the addition of a balcony to the perimeter area alone. The inclusion of atrium to Sc0 dropped PET temperature by about 1.3°C. Similarly, merely the addition of sky terraces dropped the temperature from 27.3 °C to 26.2 °C. Addition of shading to scenario A which is ScA1 dropped the temperature by just 0.5 °C, whereas the installation of balcony (ScA2) decreased the temperature by 0.6 °C.

Considering all applications, the most efficient and the closest to comfort condition (23°C ) solution is reached by ScB3 which is including shading, balcony and sky terraces and represents 25.4 °C degrees.

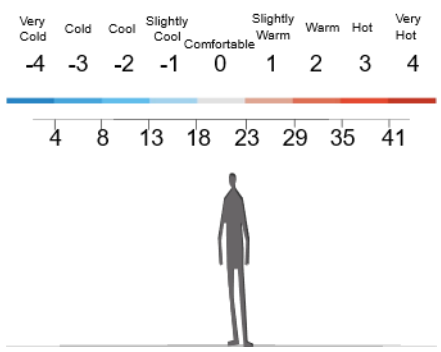



Figure 5.14. PET thermal comfort category according to temperature values

## 4.6 Evaluation of Simulation Results at Building Scale via Adaptive Comfort Model

Adaptive Thermal comfort study conducted by using Adaptive Comfort recipe in honeybee. Aim of the utilizing this component to observe impact of climate-responsive design strategies on indoor thermal comfort in interior areas.

The same findings were obtained for the adaptive thermal comfort study from the MRT calculation done for the PET calculation.

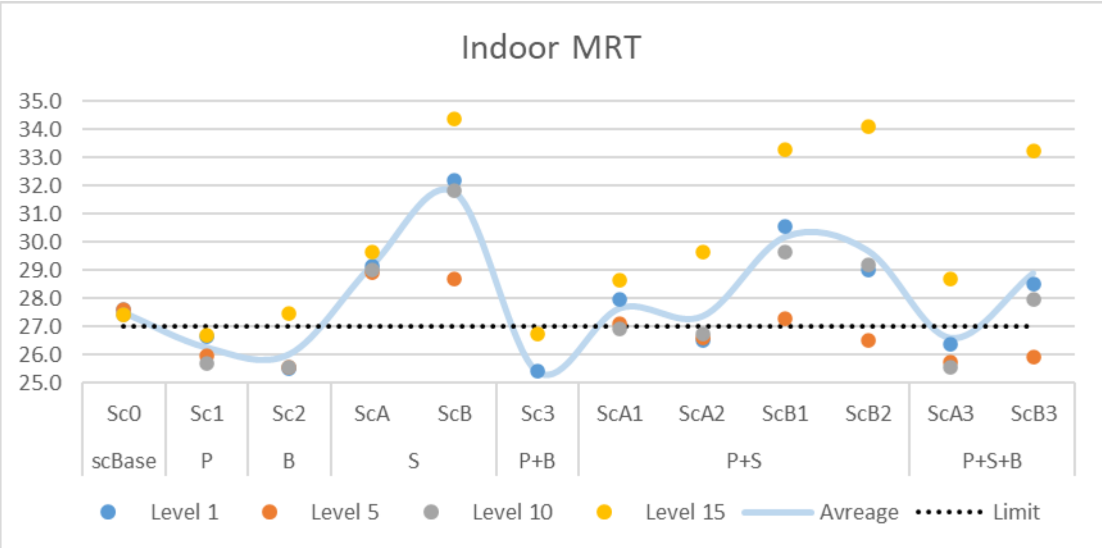



Figure 5.15. Indoor MRT results according to thermal comfort analysis

Table 0.4 Indoor MRT assessment in different building levels.

| Ind. MRT | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levels** | **Sc0** | **Sc1** | **Sc2** | **ScA** | **ScB** | **Sc3** | **ScA1** | **ScA2** | **ScB1** | **ScB2** | **ScA3** | **ScB3** |
| **Level 1** | 27.6 | 26.7 | 25.5 | 29.2 | 32.2 | 25.4 | 28.0 | 26.5 | 30.6 | 29.0 | 26.4 | 28.5 |
| **Level 5** | 27.6 | 26.0 | 25.6 | 28.9 | 28.7 | 24.9 | 27.1 | 26.6 | 27.3 | 26.5 | 25.8 | 25.9 |
| **Level 10** | 27.4 | 25.7 | 25.6 | 29.0 | 31.8 | 24.6 | 26.9226 | 26.8 | 29.6 | 29.2 | 25.6 | 28.0 |
| **Level 15** | 27.4 | 26.7 | 27.5 | 29.7 | 34.4 | 26.7 | 28.6 | 29.6 | 33.3 | 34.1 | 28.7 | 33.3 |
| Avreage | 27.5 | 26.3 | 26.0 | 29.2 | 31.8 | 25.4 | 27.7 | 27.4 | 30.2 | 29.7 | 26.6 | 28.9 |

MRT determined indoor surfaces affected by external circumstances by calculating surfaces surrounding a point where radiant heat exchange occurred. The Scenario-B with the inclusion of sky terraces without shading and balconies has the highest average MRT temperature at 31.8 degrees Celsius. The scenario with the lowest temperature comprises a shade equipment, balconies without sky terraces, and the atrium void itself. Beginning with Base Scenario, the inclusion of shading devices in Scenario-1 dropped the average MRT temperature from 27.5°C to 26.3°C.Similarly, the Scenario-2 balcony addition to ScBase decreased the temperature from 27.5 to 26.0 °. However, as shown in Scenario-3, the inclusion of a shading mechanism and a balcony reduced the temperature to 25.4 degrees Celsius. Scenario-A, the atrium-added variant of Base Scenario , resulted in a significant MRT rise from 27.5 to 29.2 °C. Therefore, the inclusion of an atrium is not beneficial in terms of MRT. The installation of a shading device to the atrium, however, decreases the temperature measurements from 29.2 to 27.7, as shown in Scenario A1. The installation of a shading device to the atrium, however, decreases the temperature measurements from 29.2 to 27.7, as shown in Scenario A1. Similarly, the addition of a balcony to an atrium causes a reduction in MRT, but it is less effective in comparison to shade mechanism as it is visible from Sc-A2. In contrast, both the shade device and balcony application to the atrium form in Sc-A3 reduce the temperature from 29.2 °C to 26.6 °C, as compared to Sc-A. Sc-B2, which has sky terraces and balconies, has a lower temperature than Sc-B, which only contains sky terraces. Consequently, the installation of the balcony results in a substantial temperature drop. In situation ScB1, however, the inclusion of a shading device is less successful as a balcony addition compared to ScB2. The addition of a balcony to Scenario B, which is scenario Sc-$B_2$, results in a temperature reduction from 31.8 to 29.7 ℃. Lastly, Scenario-B3 which includes all climate-responsive design solutions represent 28.9 ℃ average MRT temperature value. Among all scenarios, the most effective indoor MRT temperature condition is reached by Sc-3 which is including balcony and shading device only.

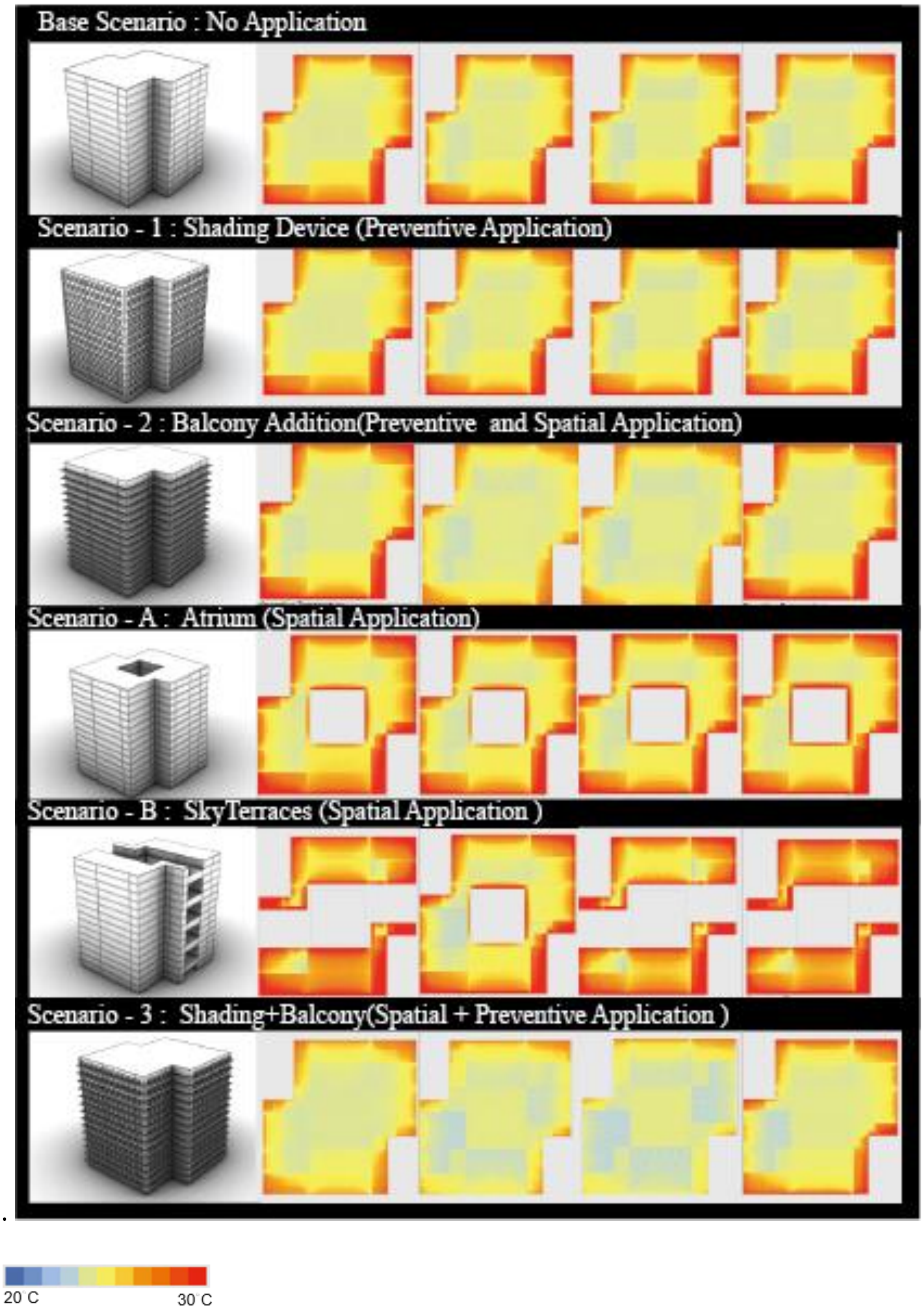



Figure 5.16. ATC thermal comfort Operative Temperature values for each scenario

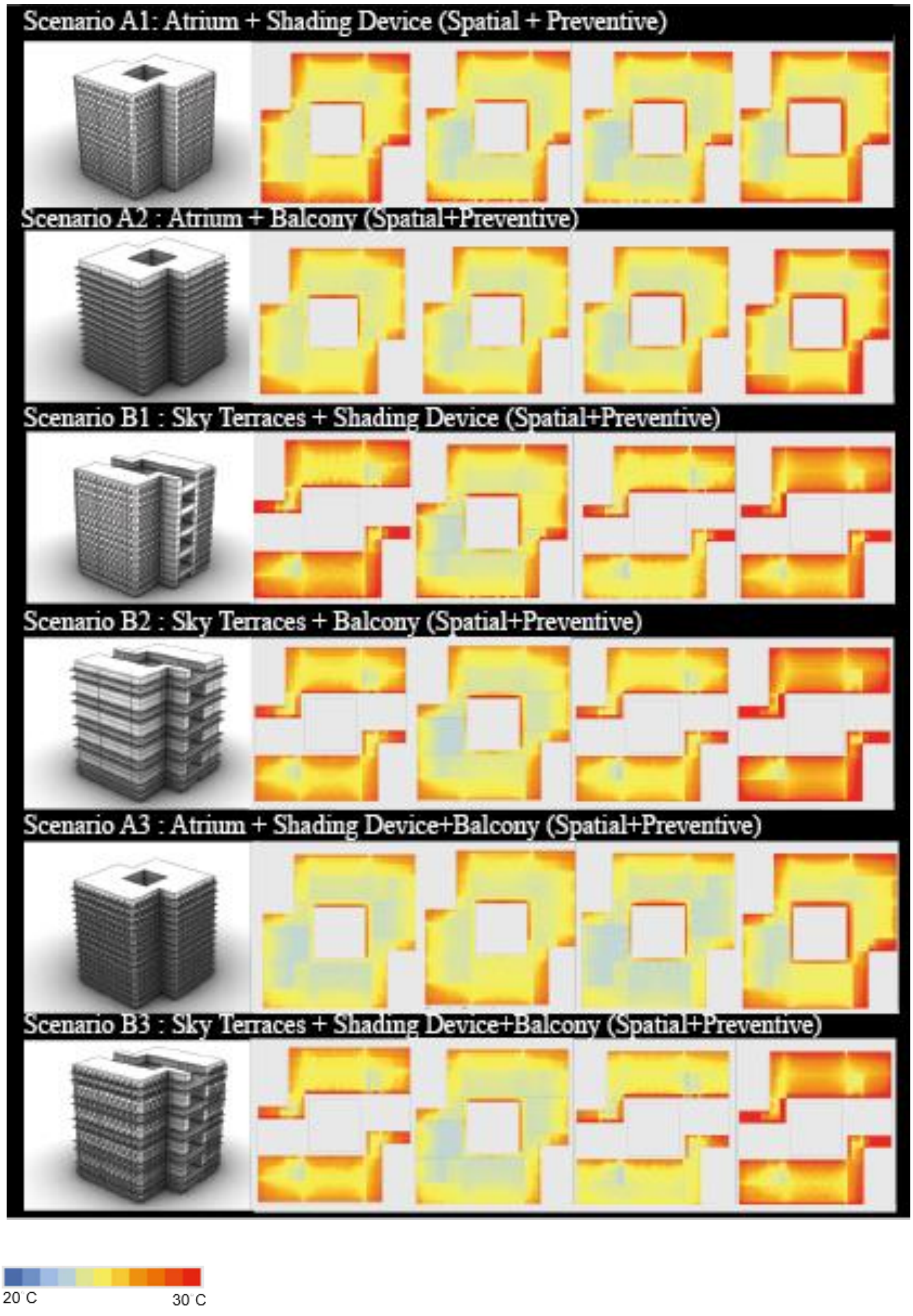



Figure 5.17. ATC thermal comfort Operative Temperature values for each scenario

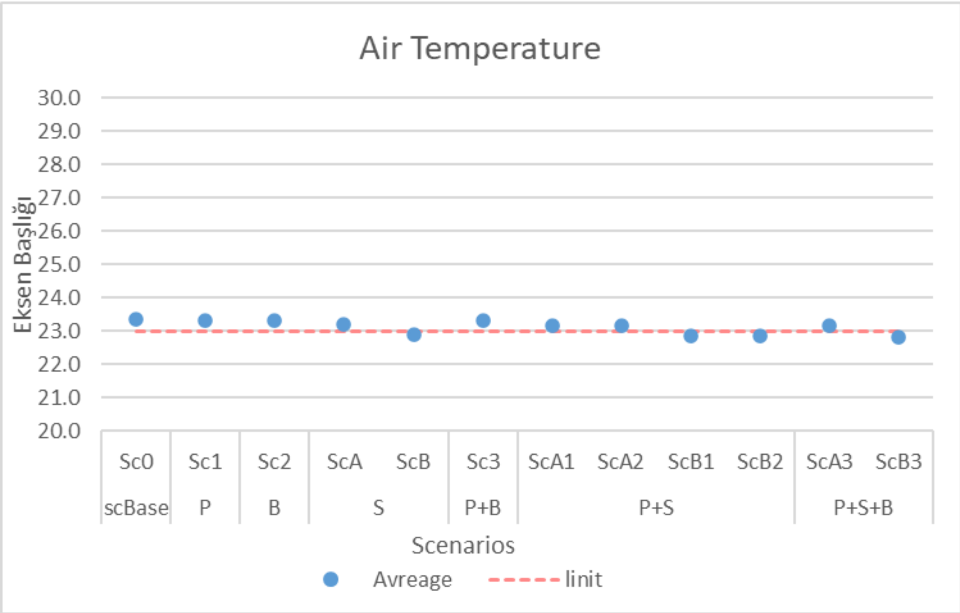



Figure 5.18. Zone Air Temperature represented with comfortable temperature for indoor thermal conditions. (23 °C )

| Air T | **scBase** | **P** | **B** | **S** | | **P+B** | **P+S** | | | | **P+S+B** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Levels | **Sc0** | Sc**1** | Sc**2** | **ScA** | **ScB** | **Sc3** | **ScA1** | **ScA2** | **ScB1** | **ScB2** | **ScA3** | **ScB3** |
| Level 1 | 23.5 | 23.5 | 23.4 | 23.3 | 23.0 | 23.4 | 23.3 | 23.3 | 22.9 | 22.9 | 23.3 | 22.9 |
| Level 5 | 23.3 | 23.3 | 23.3 | 23.2 | 23.2 | 23.3 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 |
| Level 10 | 23.3 | 23.3 | 23.3 | 23.1 | 22.7 | 23.3 | 23.1 | 23.1 | 22.6 | 22.6 | 23.1 | 22.6 |
| Level 15 | 23.3 | 23.3 | 23.3 | 23.1 | 22.7 | 23.3 | 23.1 | 23.1 | 22.7 | 22.7 | 23.1 | 22.7 |
| Avreage | 23.3 | 23.3 | 23.3 | 23.2 | 22.9 | 23.3 | 23.2 | 23.1 | 22.9 | 22.8 | 23.1 | 22.8 |

Table 0.5 Zone Air Temperature assessment in different building levels.

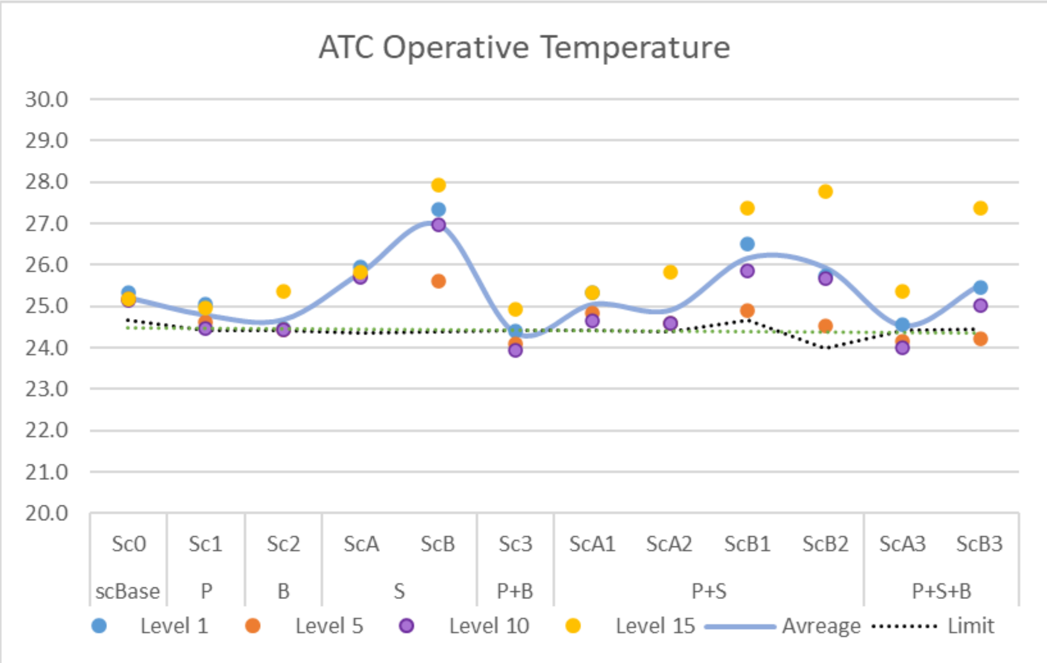



Figure 5.19. ATC Operative Temperature values relationship of each scenario in different levels

Table 0.6 Adaptive Comfort Operative Temperature assessment in different building levels.

| OPT | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 25.3 | 25.0 | 24.5 | 25.9 | 27.3 | 24.4 | 25.3 | 24.6 | 26.5 | 25.7 | 24.6 | 25.5 |
| Level 5 | 25.2 | 24.6 | 24.4 | 25.7 | 25.6 | 24.1 | 24.8 | 24.6 | 24.9 | 24.5 | 24.2 | 24.2 |
| Level 10 | 25.1 | 24.5 | 24.4 | 25.7 | 27.0 | 23.9 | 24.7 | 24.6 | 25.9 | 25.7 | 24.0 | 25.0 |
| Level 15 | 25.2 | 25.0 | 25.4 | 25.8 | 27.9 | 24.9 | 25.3 | 25.8 | 27.4 | 27.8 | 25.4 | 27.4 |
| Avreage | 25.2 | 24.8 | 24.7 | 25.8 | 27.0 | 24.3 | 25.0 | 24.9 | 26.2 | 25.9 | 24.5 | 25.5 |

Table 0.7 Adaptive thermal t comfort temperatures results in different building levels.

| ATC | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Levels | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 23 | 24 | 24 |
| Level 1 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Level 5 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Level 10 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 |
| Level 15 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Avreage | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |

Calculation of the operational temperature is outlined in section 4 as the average air temperature and MRT. As seen in the table above, the connection between scenarios is affected by the MRT derived indoors. Identical to the MRT results, the operative temperature value achieved its lowest point in scenario 3, which had a balcony and shading component. Similarly, the scenario with the greatest degree is the fifth one (ScB), which includes sky terraces. The Honeybee ATC tool offers the following calculation for achieving comfortable temperature conditions: Using the Tcomf equation, the study of thermal comfort interior will be assessed based on the resulting Tcomf values.

$$\text{deg comf: } T_o - T_{comf}$$

deg comf: The difference in degrees Celsius between the operative temperature (to) and the comfort neutral temperature (t comf). Positive numbers imply warm circumstances, whereas negative values suggest colder conditions.

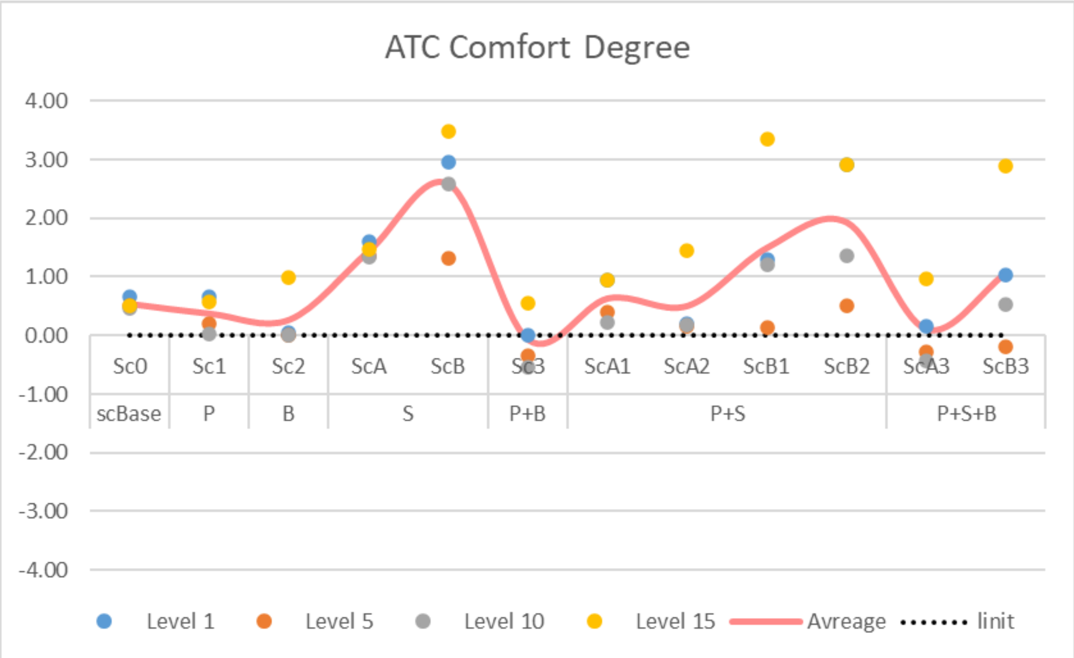



Figure 5.20. ATC Comfort Degree MTX results for each scenario

Table 0.8 Adaptive Comfort Degree Temperature assessment in different building levels.

| ATC | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Levels** | **Sc0** | **Sc1** | **Sc2** | **ScA** | **ScB** | **Sc3** | **ScA1** | **ScA2** | **ScB1** | **ScB2** | **ScA3** | **ScB3** |
| **Level 1** | 0.66 | 0.66 | 0.05 | 1.60 | 2.96 | 0.00 | 0.95 | 0.20 | 1.29 | 2.92 | 0.15 | 1.03 |
| **Level 5** | 0.51 | 0.20 | 0.02 | 1.37 | 1.31 | -0.34 | 0.40 | 0.16 | 0.14 | 0.51 | -0.28 | -0.20 |
| **Level 10** | 0.46 | 0.03 | 0.00 | 1.34 | 2.58 | -0.53 | 0.22 | 0.18 | 1.21 | 1.36 | -0.44 | 0.53 |
| **Level 15** | 0.50 | 0.57 | 1.00 | 1.47 | 3.48 | 0.54 | 0.94 | 1.46 | 3.35 | 2.92 | 0.97 | 2.89 |
| Avreage | 0.53 | 0.37 | 0.26 | 1.44 | 2.58 | -0.08 | 0.63 | 0.50 | 1.50 | 1.92 | 0.10 | 1.06 |

Tcomf is defined as the occupant's preferred temperature. At this point, conditions with a negative DegreeMtx difference will be defined as colder, while those with a positive difference will be labeled as warmer conditions. As can be observed from the MRT and Operative temperature figures, Scenario-B has temperatures that are around 2.6 degrees higher than the target temperature at various levels. Similarly, in scenario 3, temperatures that are around 0.08 °C cooler than the desired value are detected. Based on the average degree comfort results, the scenario with the smallest deviation from the desired temperature is Sc-3 ad Sc-B2, the atrium form, and atrium including balcony with a difference of - 0.08 and 0.1 °C. In the continuation of Scenario 3 and B2, the other scenario with the least difference with the target temperature is scenario 2 with 0.26 °C, followed by scenario 1 with 0.37 °C. Scenario-3, the scenario that includes both balcony and shading element, is the scenario where the interior reaches the coldest state among the scenarios with a difference of -0.08 °C between the target temperature and the target temperature. Scenario Base and scenario A2 with 0.5 °C are subsequent scenarios to scenario 3 . At this point, the application of both the balcony and the shading device causes cooler spaces to be formed which are considerably lower than the target temperature. The use of sky terraces, on the other hand, has an effect that makes interior spaces warmer when only balcony or only shading is used, whereas the use of both balcony and shading device balances this situation and ensures that the difference between the target temperature and the operating temperature is significantly reduced.

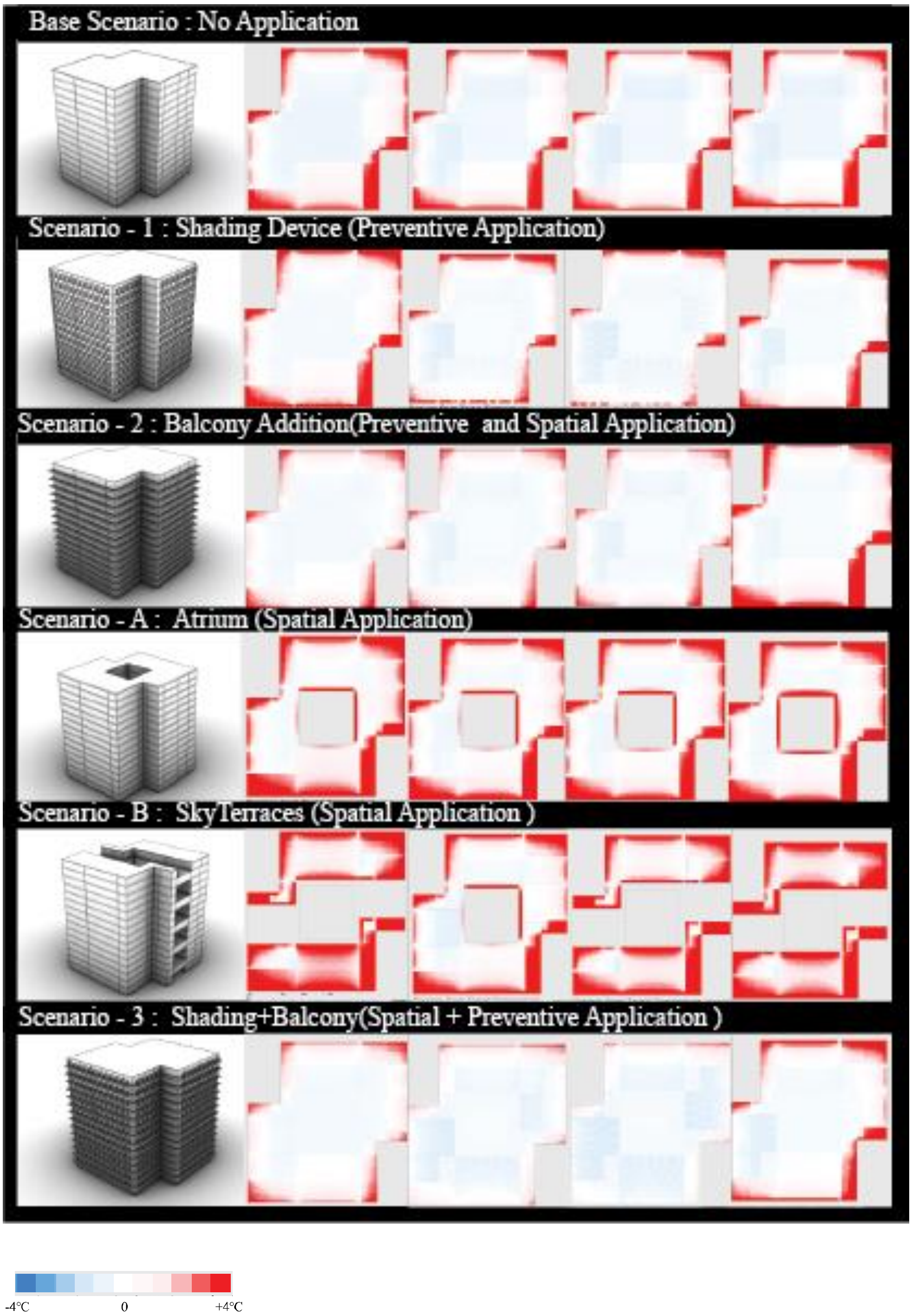



Figure 5.21. ATC thermal comfort degree difference values for each scenario

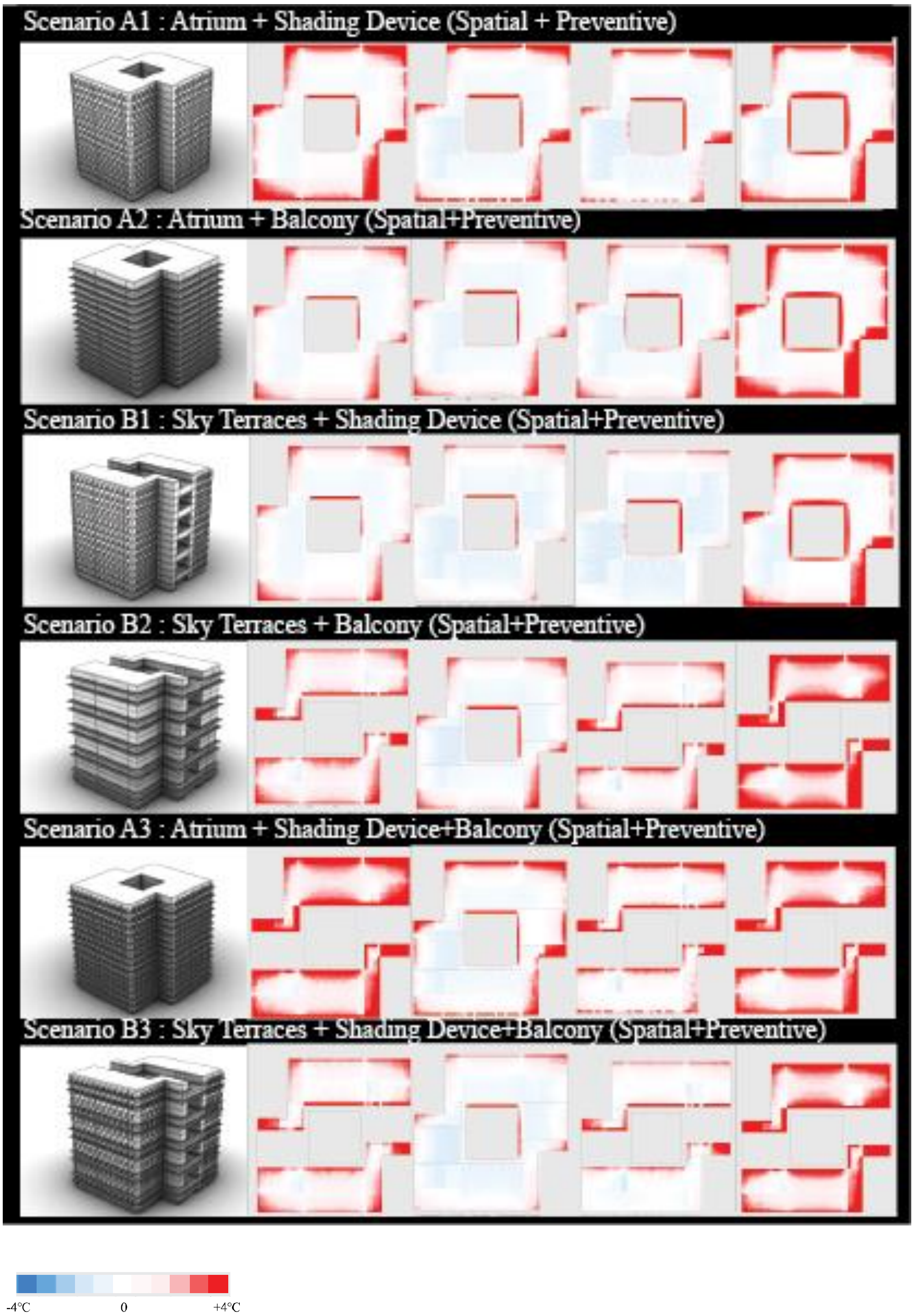



Figure 5.22. ATC thermal comfort degree difference values for each scenario

## 4.7 Summary of Findings

This research examines the investigation of climate-sensitive design solutions from the neighborhood scale to the building size, as well as user comfort and the use of transition areas as a cooling strategy. As a climate-sensitive design solution, four distinct outdoor thermal comfort analyses were conducted, taking into consideration the link between the UHI impact and the surroundings. These scenarios are based on neighborhood-scale reforestation and the incorporation of wind data influenced by the built environment. These scenarios:

- Scenario 1 : UTCI analysis (without tree)
- Scenario 2: UTCI analysis (with tree)
- Scenario 3: UTCI analysis integrated CFD result (without tree)
- Scenario 4: UTCI analysis integrated CFD result (with tree)

At this point, the most effective scenario in thermal comfort analysis at neighborhood scale is scenario 4, where vegetation and wind speed analysis are performed.

Taking into account both the internal and exterior impacts of climate responsive design solutions, the atrium has improved the interior comfort. Nevertheless, the employment of shading devices and balconies enabled the achievement of temperatures that had been lower than the target temperature. Therefore, if it is important to consider passive cooling as a strategy, balconies, and shading systems offer passive cooling in the interior. Except for level 15, which is the top floor, the usage of sky terraces generated a cooling effect with the addition of a balcony and a shade mechanism**.** Similar to the ATC assessment, the findings of the transitional spaces comfort study outside level 15 indicate that the employment of sky terraces, balconies, and shading devices gives a decrease of about 2 °C at levels 5 and 10. In addition, as seen by the average PET values for scenarios A1,A2,A3,B1,B2 and B3, shading devices, atriums, balcony combinations, and sky terraces have a cooling impact in transitional zones. By developing transition zones, it is now feasible to create cooler semi-outdoor spaces surrounding and inside the building. When air temperature, PET, and ATC results were evaluated, climate-responsive design solutions had a cooling effect on air zone air temperature values, especially when evaluated in combination with semi-outdoor transitional spaces. The semi-outdoor transitional spaces integration resulted in lower temperature values compared to base scenario without any application. In addition to that, climate responsive design solutions which are shading device and balcony applications provided passive cooling for both transitional spaces around and within building and for indoor spaces. Which means that, usage of transitional spaces provided passive cooling for both indoor and transitional spaces.

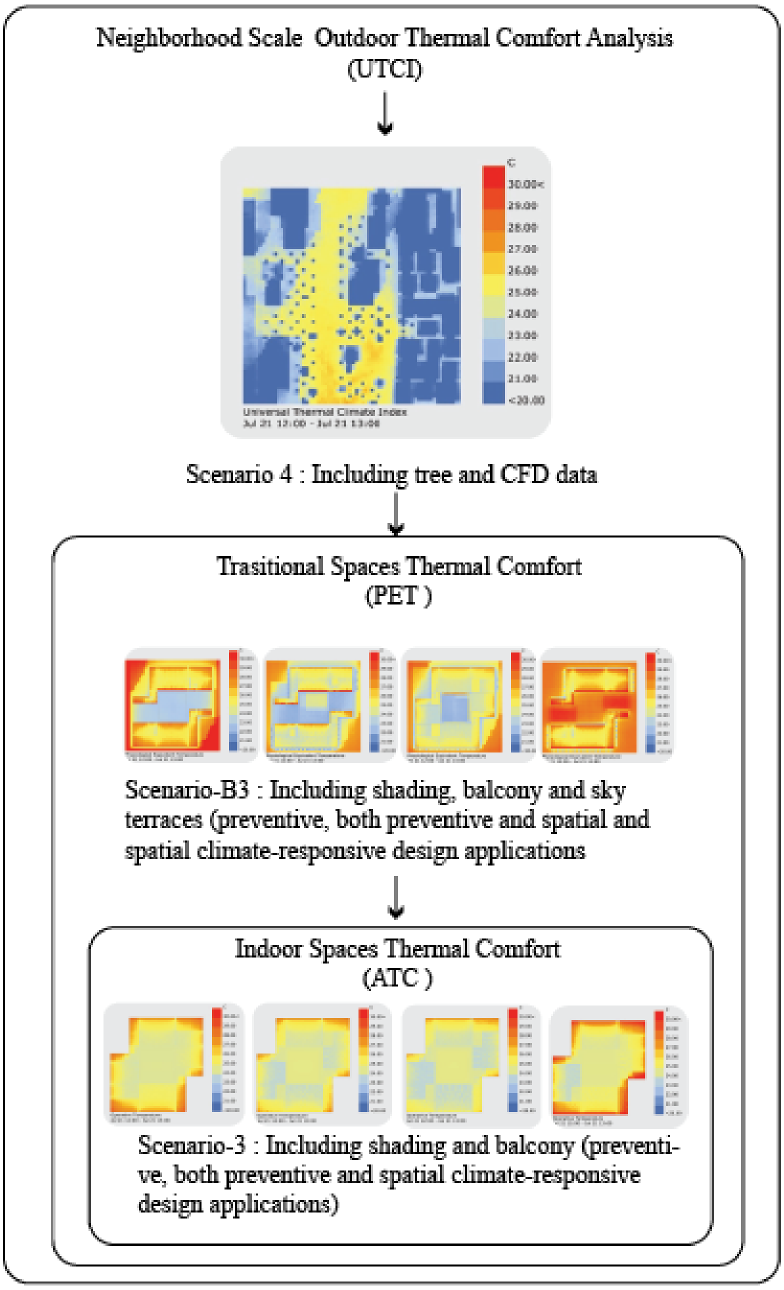



Figure 5.23. The most effective scenarios highlighted and represented above.

When all scenarios were analyzed, scenario 4 was determined as the most suitable scenario for thermal comfort analysis at neighborhood scale. The scenario that has the closest result to comfort conditions in transitional spaces and has the highest passive cooling potential has been determined as scenario B3, which is the scenario that includes all climate-responsive design solutions. Finally, the scenario closest to the indoor comfort conditions and providing passive cooling is scenario 3, which includes shading and balcony.

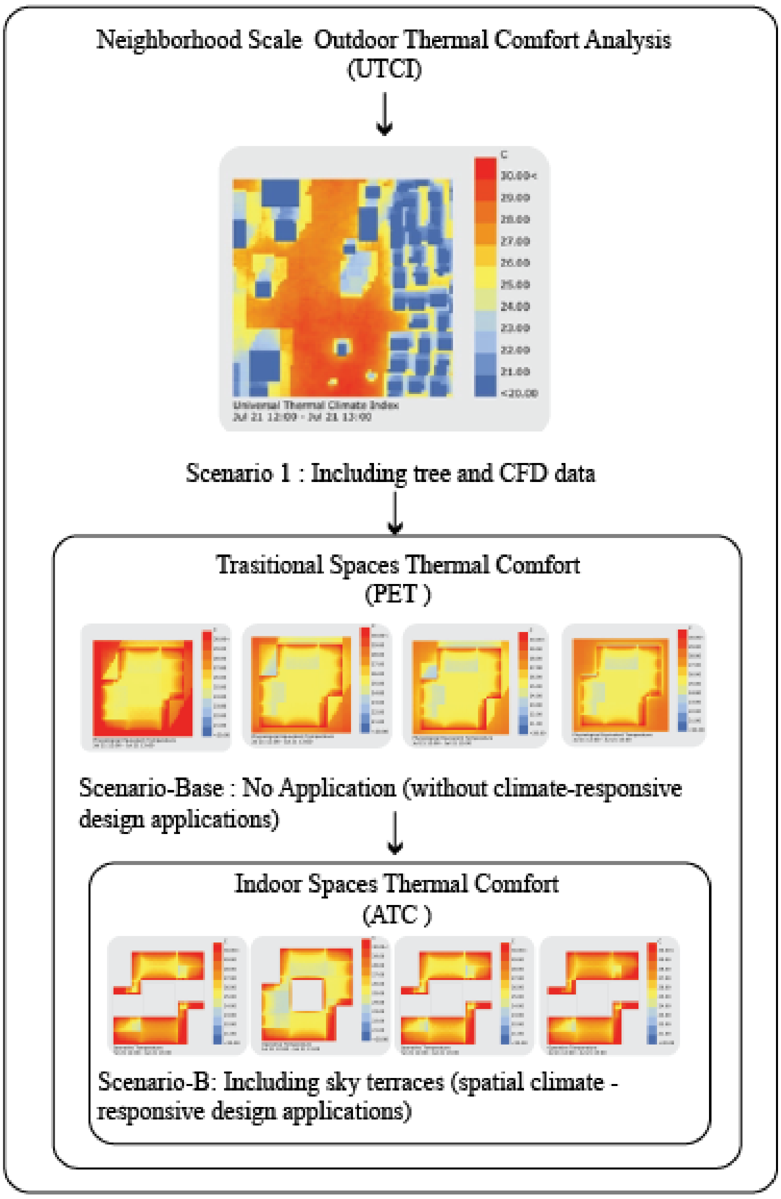



Figure 5.24. The least effective scenarios highlighted and represented above.

As stated above, among the simulation results, the scenario showing the lowest performance in UTCI analysis was determined as scenario -1, where vegetation and region-specific wind data were not integrated. The scenario with the lowest performance in Transitional spaces analysis was determined as the Base scenario, in which no climate-responsive design solution was applied, as a result of PET analysis. Finally, in the indoor comfort analysis, the scenario of the lowest performance in the simulations made in line with the ATC analysis was determined as scenario B, which only includes sky terraces as a spatial intervention.

# CHAPTER 6

# CONCLUSION

As a consequence of the Urban Heat Island effect, which has emerged as a result of rapidly rising urbanization, the demand for energy to produce comfortable indoor environments has grown, while the need for energy to create comfortable outdoor environments has declined. This study, which analyzes the effect of climate-sensitive design solutions on user comfort in interior, exterior and transition spaces, aims to transform neglected semi-outdoor transition spaces into comfortable and effective spaces. On a model of a 15-story structure in the Balgat Region of Ankara, 12 distinct climate-responsible design solutions were evaluated. User comfort analysis was conducted in outdoor, semi-outdoor (transitional spaces), and indoor spaces using the UTCI, PET, and ATC indices, respectively, in the research, which progressed through neighborhood scale to building scale. Within the scope of this study, the following results were reached:

- Climate-responsive facade design promotes user comfort by lowering radiation in transitional and indoor spaces by creating a buffer zone.
- The effect of climate responsive design solutions on the user was examined at multiple scales. In this context, it has been observed that these interventions affect surface temperatures, air temperature and MRT values, and thus affect user comfort to varying degrees.
- The outdoor thermal comfort analysis on the neighborhood scale was analyzed using the UTCI thermal comfort index, and it was observed that both CFD data and vegetation addition caused significant changes in results.
- The use of transitional spaces as a passive cooling strategy was evaluated by performing both outdoor PET analysis and indoor ATC

analysis. In this context, it has been observed that especially the use of atrium-shading device and balcony creates a cooling effect in both indoor and transitional spaces thermal comfort. In addition, these interventions also changed the distribution of air zone air temperature, and air temperature values created a cooling effect, especially in the use of shading and balcony.

- Due to the fact that the climate-responsive design is based on local climatic circumstances, a multi-scale study was conducted. In this context, the impact of plant addition was initially investigated, and it was determined that it increased regional comfort. In addition, the effect of balcony, shading addition and green sky terraces made in the perimeter area of the building on the microclimate was observed by analyzing the MRT and air temperature values. At this point, the use of balcony and shading device decreased the average air temperature. However, in terms of indoor radiant temperature, green sky terraces did not produce as effective results as the use of atrium, balcony and shading device.

In conclusion, neighborhood-scale vegetation generated a cooling impact, and the utilization of vegetated sky terraces, balcony, atrium, and shade mechanisms offered passive cooling by decreasing the felt temperature in transition zones. In the thermal comfort analyses conducted indoors, it was determined that the usage of a balcony and shading provided passive cooling.

**Limitations and Further Studies**

The purpose of this research was to investigate the impact that climate-sensitive design solutions have on the level of user comfort in transition spaces. In this study, building form and layout, building facade, and landscape solutions are the primary areas of focus. Climate-sensitive design and urban heat island mitigation strategies, such as the use of reflective building materials, pavement materials, and water element usage, may be investigated in future studies. In addition, the influence of climate-sensitive design solutions and the use of transitional space on the overall energy consumption of buildings is not analyzed in this particular research project. The impact that these adjustments had on the amount of energy that was used by the high-rise buildings could be investigated in further researches. The research was conducted in consideration of the cold and humid climatic conditions and urban characteristics of the Ankara city. t is possible to study these applications in regions with varying climatic features and to assess the impact of UHI. The technique utilizes the ladybug honeybee and EnergyPlus tools, and the accuracy can be improved by the coupled simulation approach by using various tools for user comfort and monitoring of the urban heat island.

# REFERENCES


Abergel, T., Delmastro, C., Monshauer, Y., Lane, K., & Oppermann, M. (2021). Tracking Buildings 2021. In *IEA Publications*.

Addington, M. (2009). Contingent behaviours. *Architectural Design*, *79*(3). https://doi.org/10.1002/ad.882

Albatayneh, A., Alterman, D., Page, A., & Moghtaderi, B. (2019). The significance of the adaptive thermal comfort limits on the air-conditioning loads in a temperate climate. *Sustainability (Switzerland)*, *11*(2). https://doi.org/10.3390/su11020328

Alonso, C., Martín-Consuegra, F., Oteiza, I., Asensio, E., Pérez, G., Martínez, I., & Frutos, B. (2017). Effect of façade surface finish on building energy rehabilitation. *Solar Energy*, *146*. https://doi.org/10.1016/j.solener.2017.03.009

Ashrae. (2004). Thermal Environmental Conditions for Human Occupancy. *ANSI/ASHRAE Standard 55-2004*, *2004*.

ASHRAE. (2017). ANSI/ASHRAE Standard 55-2017 : Thermal Environmental Conditions for Human Occupancy. *ASHRAE Inc.*, *2017*.

Attia, S., & Gobin, C. (2020). Climate change effects on belgian households: A case study of a nearly zero energy building. *Energies*, *13*(20). https://doi.org/10.3390/en13205357

Baiz, W. H., & Fathulla, S. J. (2017). Urban Courtyard Housing Form as a Response to Human Need, Culture and Environment in Hot Climate Regions: Baghdad as a Case Study. *International Journal of Engineering Research and Applications*, *06*(09). https://doi.org/10.9790/9622-0609011019

Baker, N., & Steemers, K. (2000). Energy and Environment in Architecture: A Tehcnical Design Guide. In *Taylor.&.Francis* (Issue Feb).

Battista, G., Evangelisti, L., Guattari, C., Vollaro, E. D. L., Vollaro, R. D. L., & Asdrubali, F. (2020). Urban heat island mitigation strategies: Experimental and numerical analysis of a university campus in Rome (Italy). *Sustainability (Switzerland)*, *12*(19). https://doi.org/10.3390/su12197971

Bekleyen, A., Dalkılıç, N., & Özen, N. (2014). *Geleneksel Mardin Evi'nin mekânsal ve ısısal konfor özellikleri [Spatial and thermal comfort characteristics of the Traditional House of Mardin]*. *7*, 28–44.

Błazejczyk, K., Broede, P., Fiala, D., Havenith, G., Holmér, I., Jendritzky, G., Kampmann, B., & Kunert, A. (2010). Principles of the new universal thermal climate index (UTCI) and its application to bioclimatic research in European scale. *Miscellanea Geographica*, *14*. https://doi.org/10.2478/mgrsd-2010-0009

Bodach, S., Lang, W., & Hamhaber, J. (2014). Climate responsive building design strategies of vernacular architecture in Nepal. *Energy and Buildings*, *81*. https://doi.org/10.1016/j.enbuild.2014.06.022

Boregowda, S. C., Choate, R. E., & Handy, R. (2012). Entropy Generation Analysis of Human Thermal Stress Responses. *ISRN Thermodynamics*, *2012*. https://doi.org/10.5402/2012/830103

Bozdogan, S. (1996). Vernacular Architecture and Identity Politics: The Case of the "Turkish House." *Traditional Dwellings and Settlements Review*, *7*(2).

Brager, G. S., & de Dear, R. J. (1998). Thermal adaptation in the built environment: A literature review. *Energy and Buildings*, *27*(1). https://doi.org/10.1016/s0378-7788(97)00053-4

Budhiraja, B., Agrawal, G., & Pathak, P. (2020). Urban heat island effect of a polynuclear megacity Delhi – Compactness and thermal evaluation of four sub-cities. *Urban Climate*, *32*. https://doi.org/10.1016/j.uclim.2020.100634

Cantón, M. A., Ganem, C., Barea, G., & Llano, J. F. (2014). Courtyards as a passive strategy in semi dry areas. Assessment of summer energy and thermal conditions in a refurbished school building. *Renewable Energy*, *69*. https://doi.org/10.1016/j.renene.2014.03.065

Cezar Mustafa. (1977). *Anadolu Öncesi Türklerde Şehir ve Mimarlık*. Türkiye İş Bankası Kültür Yayınları.

Chatzidimitriou, A., Liveris, P., Bruse, M., & Topli, L. (2013). Urban Redevelopment and Microclimate Improvement : A Design Project in Thessaloniki, Greece. *PLEA 2013, September*.

Choi, J. H., & Loftness, V. (2012). Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. *Building and Environment*, *58*. https://doi.org/10.1016/j.buildenv.2012.07.003

Chun, C., Kwok, A., & Tamura, A. (2004). Thermal comfort in transitional spaces-basic concepts: Literature review and trial measurement. *Building and Environment*, *39*(10). https://doi.org/10.1016/j.buildenv.2004.02.003

Coccolo, S., Kämpf, J., Scartezzini, J. L., & Pearlmutter, D. (2016). Outdoor human comfort and thermal stress: A comprehensive review on models and standards. In *Urban Climate* (Vol. 18). https://doi.org/10.1016/j.uclim.2016.08.004

Cross N. & Design Research Society. (1972). *Design participation : proceedings of the design research society's conference manchester september* .

Dainoff, M. J. (2001). Work Design: Industrial Ergonomics, 5th ed. *Ergonomics in Design: The Quarterly of Human Factors Applications*, *9*(2). https://doi.org/10.1177/106480460100900209

d'Ambrosio Alfano, F. R., Palella, B. I., & Riccio, G. (2011). The role of measurement accuracy on the thermal environment assessment by means of PMV index. *Building and Environment*, *46*(7). https://doi.org/10.1016/j.buildenv.2011.01.001

de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, *104*(Pt 1A).

de Freitas, C. R., & Grigorieva, E. A. (2015). A comprehensive catalogue and classification of human thermal climate indices. *International Journal of Biometeorology*, *59*(1). https://doi.org/10.1007/s00484-014-0819-3

de La Flor, F. S., & Domínguez, S. A. (2004). Modelling microclimate in urban environments and assessing its influence on the performance of surrounding buildings. *Energy and Buildings*, *36*(5). https://doi.org/10.1016/j.enbuild.2004.01.050

Diz-Mellado, E., López-Cabeza, V. P., Rivera-Gómez, C., Galán-Marín, C., Rojas-Fernández, J., & Nikolopoulou, M. (2021). Extending the adaptive thermal comfort models for courtyards. *Building and Environment*, *203*. https://doi.org/10.1016/j.buildenv.2021.108094

Encyclopædia Britannica. (n.d.). atrium with impluvium and compluvium. In *Encyclopædia Britannica*.

Enescu, D. (2017). A review of thermal comfort models and indicators for indoor environments. In *Renewable and Sustainable Energy Reviews* (Vol. 79). https://doi.org/10.1016/j.rser.2017.05.175

Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban Microclimate*. Routledge. https://doi.org/10.4324/9781849775397

Fabbri, K., Pretelli, M., & Bonora, A. (2019). The study of historical indoor microclimate (Him) to contribute towards heritage buildings preservation. *Heritage*, *2*(3). https://doi.org/10.3390/heritage2030140

Fathy, H. (1986). Natural energy and vernacular architecture : principles and examples with reference to hot arid climates / Hassan Fathy / edited by Walter Shearer and Abd-el-rahman Ahmed Sultan. *Proceedings of Conference: Air Conditioning and the Low Carbon Cooling Challenge*.

Fiala, D., Lomas, K. J., & Stohrer, M. (1999). A computer model of human thermoregulation for a wide range of environmental conditions: The passive system. *Journal of Applied Physiology*, *87*(5). https://doi.org/10.1152/jappl.1999.87.5.1957

Fox, J., Osmond, P., & Peters, A. (2018). The effect of building facades on outdoor microclimate-Reflectance recovery from terrestrial multispectral images using a robust empirical line method. *Climate*, *6*(3). https://doi.org/10.3390/cli6030056

Gamero-Salinas, J., Kishnani, N., Monge-Barrio, A., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021a). Evaluation of thermal comfort and building form attributes in different semi-outdoor environments in a high-density tropical setting. *Building and Environment, 205*. https://doi.org/10.1016/j.buildenv.2021.108255

Gamero-Salinas, J., Kishnani, N., Monge-Barrio, A., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021b). The influence of building form variables on the environmental performance of semi-outdoor spaces. A study in mid-rise and high-rise buildings of Singapore. *Energy and Buildings, 230*. https://doi.org/10.1016/j.enbuild.2020.110544

Gamero-Salinas, J., Kishnani, N., Sánchez-Ostiz, A., Monge-Barrio, A., & Benitez, E. (2022). Porosity, openness, and exposure: Identification of underlying factors associated with semi-outdoor spaces' thermal performance and clustering in tropical high-density Singapore. *Energy and Buildings, 272*, 112339. https://doi.org/10.1016/J.ENBUILD.2022.112339

García, S. (2014). *Teresianas School, Bercelona Spain* . Https://Archello.Com/Project/Teresianas-Ganduxer-School.

García-Luna Romero, A. C., & Flores Leal, J. A. (2022). Responsive Architecture: New paradigms of urban relations. *SHS Web of Conferences*, *139*, 01005. https://doi.org/10.1051/shsconf/202213901005

Ghisi, E., & Felipe Massignani, R. (2007). Thermal performance of bedrooms in a multi-storey residential building in southern Brazil. *Building and Environment*, *42*(2). https://doi.org/10.1016/j.buildenv.2005.10.026

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007a). Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, *33*(1), 115–133. https://doi.org/10.2148/benv.33.1.115

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007b). Adapting Cities for Climate Change: The Failure of Modern Buildings. *Built Environment*, *33*(1), 205–236. https://doi.org/10.2148/benv.33.1.115

Givoni, B. (1998). Climate considerations in building and urban design. *Building*.

Golasz-Szolomicka, H., & Szolomicki, J. (2019). Vertical Gardens in High-Rise Buildings - Modern Form of Green Building Technology. *IOP Conference Series: Materials Science and Engineering*, *603*(2). https://doi.org/10.1088/1757-899X/603/2/022067

Grifoni, R. C., Tascini, S., Cesario, E., & Marchesani, G. E. (2017). Cool façade optimization: A new parametric methodology for the urban heat island phenomenon (UHI). *Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2017*. https://doi.org/10.1109/EEEIC.2017.7977677

Grimmond, S. (2007). Urbanization and global environmental change: Local effects of urban warming. *Geographical Journal*, *173*(1). https://doi.org/10.1111/j.1475-4959.2007.232_3.x

Grobman, Y. J., Capeluto, I. G., & Austern, G. (2017). External shading in buildings: comparative analysis of daylighting performance in static and kinetic operation scenarios. *Architectural Science Review*, *60*(2). https://doi.org/10.1080/00038628.2016.1266991

Guo, H., Aviv, D., Loyola, M., Teitelbaum, E., Houchois, N., & Meggers, F. (2020). On the understanding of the mean radiant temperature within both the indoor and outdoor environment, a critical review. In *Renewable and Sustainable Energy Reviews* (Vol. 117). https://doi.org/10.1016/j.rser.2019.06.014

Hastings, S. R. (1989). Computer design tools for climate-responsive architecture. *Solar and Wind Technology*, *6*(4). https://doi.org/10.1016/0741-983X(89)90054-4

Havenith, G. (2005). Temperature regulation, Heat balance and climatic stress. In *Extreme Weather Events and Public Health Responses*. https://doi.org/10.1007/3-540-28862-7_7

Heidari Matin, N., & Eydgahi, A. (2020). Factors affecting the design and development of responsive facades: a historical evolution. In *Intelligent Buildings International* (Vol. 12, Issue 4). https://doi.org/10.1080/17508975.2018.1562414

Höppe, P. (1999). The physiological equivalent temperature - A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *43*(2). https://doi.org/10.1007/s004840050118

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings*, *34*(6). https://doi.org/10.1016/S0378-7788(02)00017-8

Hosseini, S. M., Mohammadi, M., & Guerra-Santin, O. (2019). Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes. *Building and Environment*, *165*. https://doi.org/10.1016/j.buildenv.2019.106396

Howard, L. (1833). The Climate of London, vol I. *Harvey and Darton*.

*https://www.ladybug.tools/ladybug-comfort/docs/ladybug_comfort.collection.pet.html?highlight=pet#module-ladybug_comfort.collection.pet*. (n.d.).

Hu, X. M., Huang, J., Fuentes, J. D., Forkel, R., & Zhang, N. (2016). Advances in Boundary-Layer/Air Pollution Meteorology. In *Advances in Meteorology* (Vol. 2016). https://doi.org/10.1155/2016/2825019

Humphreys, M. (1978). OUTDOOR TEMPERATURES AND COMFORT INDOORS. *Batim Int Build Res Pract*, *6*(2). https://doi.org/10.1080/09613217808550656

Humphreys, M. A., & Fergus Nicol, J. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings*, *34*(6). https://doi.org/10.1016/S0378-7788(02)00018-X

IEA. (2019). 2019 Global Status report for Buildings and Construction. Towards a zero-emissions, efficient and resilient buildings and construction sector. In *Global Status Report*.

Iken, O., Fertahi, S. ed D., Dlimi, M., Agounoun, R., Kadiri, I., & Sbai, K. (2019). Thermal and energy performance investigation of a smart double skin facade integrating vanadium dioxide through CFD simulations. *Energy Conversion and Management*, *195*. https://doi.org/10.1016/j.enconman.2019.04.070

ISO. (2005). ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. *Management*, *3*.

James, D. (2006). Building adaptation, second edition. In *Building Adaptation, Second Edition*. https://doi.org/10.4324/9780080458519

Jendritzky, G., & Nübler, W. (1981). A model analysing the urban thermal environment in physiologically significant terms. *Archives for Meteorology, Geophysics, and Bioclimatology Series B*, *29*(4). https://doi.org/10.1007/BF02263308

Johansson, E., Thorsson, S., Emmanuel, R., & Krüger, E. (2014). Instruments and methods in outdoor thermal comfort studies - The need for standardization. *Urban Climate*, *10*(P2). https://doi.org/10.1016/j.uclim.2013.12.002

Johnsen, K., & Winther, F. v. (2015). Dynamic facades, the smart way of meeting the energy requirements. *Energy Procedia*, *78*. https://doi.org/10.1016/j.egypro.2015.11.210

Kaihoul, A., Sriti, L., Amraoui, K., di Turi, S., & Ruggiero, F. (2021). The effect of climate-responsive design on thermal and energy performance: A simulation based study in the hot-dry Algerian South region. *Journal of Building Engineering*, *43*. https://doi.org/10.1016/j.jobe.2021.103023

Karanouh, A., & Kerber, E. (2015). Innovations in dynamic architecture. *Journal of Facade Design and Engineering*, *3*(2). https://doi.org/10.3233/fde-150040

Katić, K., Li, R., & Zeiler, W. (2016). Thermophysiological models and their applications: A review. In *Building and Environment* (Vol. 106). https://doi.org/10.1016/j.buildenv.2016.06.031

Kirwan, C., & Zhiyong, F. (2020). Chapter 2 - City as living organism. In *Smart Cities and Artificial Intelligence*.

Klemm, W. (2018). *Clever and cool : generating design guidelines for climate-responsive urban green infrastructure* [Wageningen University]. https://doi.org/10.18174/453958

Kolarevic, B., & Parlac, V. (2015). Building dynamics: Exploring architecture of change. In *Building Dynamics: Exploring Architecture of Change*. https://doi.org/10.4324/9781315763279

Kolokotroni, M., Giannitsaris, I., & Watkins, R. (2006). The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. *Solar Energy*, *80*(4). https://doi.org/10.1016/j.solener.2005.03.010

Kopter, K., & Bingham Hall, P. (2016). Oasia Hotel Downtown / WOHA. In *https://www.archdaily.com/800878/oasia-hotel-downtown-woha*.

Kwong, Q. J., & Ali, Y. (2011). A review of energy efficiency potentials in tropical buildings - Perspective of enclosed common areas. In *Renewable and*

*Sustainable Energy Reviews* (Vol. 15, Issue 9). https://doi.org/10.1016/j.rser.2011.07.097

Lee, D. H. K., & Givoni, B. (1971). Man, Climate, and Architecture. *Geographical Review*, *61*(2). https://doi.org/10.2307/214009

Lenzholzer, S., & Brown, R. D. (2013). Climate-responsive landscape architecture design education. *Journal of Cleaner Production*, *61*. https://doi.org/10.1016/j.jclepro.2012.12.038

(Leon) Wang, L., & Shu, C. (2021). Assessment of the Effects of Urban Heat Island on Buildings. In *Advances in 21st Century Human Settlements*. https://doi.org/10.1007/978-981-33-4050-3_2

Li, R. (2007). *Natural ventilation of atrium spaces*. University of Sheffield.

Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., & Li, W. (2019). Urban heat island impacts on building energy consumption: A review of approaches and findings. In *Energy* (Vol. 174). https://doi.org/10.1016/j.energy.2019.02.183

Lim, T., Yim, W. S., & Kim, D. D. (2022). Analysis of the Thermal and Cooling Energy Performance of the Perimeter Zones in an Office Building. *Buildings*, *12*(2). https://doi.org/10.3390/buildings12020141

Lima, L. J. B., & Hamzagic, M. (2022). Strategies for the energy transition: literature review. *Revista Científica Multidisciplinar Núcleo Do Conhecimento*, 96–120. https://doi.org/10.32749/nucleodoconhecimento.com.br/uncategorized/energy-transition

Lin, H., Xiao, Y., Musso, F., & Lu, Y. (n.d.). *Green Façade Effects on Thermal Environment in Transitional Space: Field Measurement Studies and Computational Fluid Dynamics Simulations*. https://doi.org/10.3390/su11205691

Liu, M., Wittchen, K. B., & Heiselberg, P. K. (2015). Control strategies for intelligent glazed façade and their influence on energy and comfort performance of office buildings in Denmark. *Applied Energy*, *145*. https://doi.org/10.1016/j.apenergy.2015.02.003

Loh, N., & Bhiwapurkar, P. (2022). Urban heat-mitigating building form and façade framework. *Architectural Science Review*, *65*(1). https://doi.org/10.1080/00038628.2021.1924610

Looman, R. (2017a). Climate-responsive design: A framework for an energy concept design-decision support tool for architects using principles of climate-responsive design. *A+BE Architecture and the Built Environment*, *1*, 1–282.

Looman, R. (2017b). Climate-responsive design: A framework for an energy concept design-decision support tool for architects using principles of climate-responsive design. *A+BE Architecture and the Built Environment*, *1*, 1–282.

Matin, N. H., Eydgahi, A., & Shyu, S. (2017). Comparative analysis of technologies used in responsive building facades. *ASEE Annual Conference and Exposition, Conference Proceedings*, *2017-June*. https://doi.org/10.18260/1-2--28052

Menges, A., Reichert, S., & Krieg, O. D. (2021). Meteorosensitive Architectures. In *ALIVE*. https://doi.org/10.1515/9783990436684.39

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. In *Journal of Environmental Management* (Vol. 197). https://doi.org/10.1016/j.jenvman.2017.03.095

Mohammadi, A., Saghafi, M. R., Tahbaz, M., & Nasrollahi, F. (2018). The study of climate-responsive solutions in traditional dwellings of Bushehr City in Southern Iran. *Journal of Building Engineering*, *16*. https://doi.org/10.1016/j.jobe.2017.12.014

Mohammed, A., Pignatta, G., Topriska, E., & Santamouris, M. (2020). Canopy urban heat island and its association with climate conditions in Dubai, UAE. *Climate*, *8*(6). https://doi.org/10.3390/CLI8060081

Mui, K. W., Tsang, T. W., & Wong, L. T. (2020). Bayesian updates for indoor thermal comfort models. *Journal of Building Engineering*, *29*. https://doi.org/10.1016/j.jobe.2019.101117

Natanian, J., & Auer, T. (2020). Beyond nearly zero energy urban design: A holistic microclimatic energy and environmental quality evaluation workflow. *Sustainable Cities and Society*, *56*. https://doi.org/10.1016/j.scs.2020.102094

Negroponte, N. (2021). Soft Architecture Machines. In *Soft Architecture Machines*. https://doi.org/10.7551/mitpress/6317.001.0001

Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, *45*(1). https://doi.org/10.1016/j.buildenv.2008.12.013

Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and Buildings*, *11*(1–3). https://doi.org/10.1016/0378-7788(88)90026-6

Oke, T. R. (1989). The micrometeorology of the urban forest. *Philosophical Transactions - Royal Society of London, B*, *324*(1223). https://doi.org/10.1098/rstb.1989.0051

Olgyay, V. (2015). Design with climate: Bioclimatic approach to architectural regionalism: New and expanded edition. In *Design with Climate: Bioclimatic Approach to Architectural Regionalism: New and Expanded Edition*.

Oral, G. K., & Yilmaz, Z. (2002). The limit U values for building envelope related to building form in temperate and cold climatic zones. *Building and Environment*, *37*(11). https://doi.org/10.1016/S0360-1323(01)00102-0

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. a., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-

Echeverri, L., Hallegatte, S., … van Ypersele, J.-P. (2014). IPCC, 2014. *CLIMATE CHANGE 2014 Synthesis Report Summary for Policymakers*.

Padmaperuma, D. I., Buddhinie, U. A., & Senadeera, J. (2020). Architectural Responsiveness of Entry Threshold Spaces of Public Buildings: Physical Attributes and People's Perceptions. *Cities People Places : An International Journal on Urban Environments*, *4*(2). https://doi.org/10.4038/cpp.v4i2.49

Parry, M., & Chandler, T. J. (1966). The Climate of London By Luke Howard. *The Geographical Journal*, *132*(1).

Perera, K., Donn, M., & Schnabel, M. A. (2020). Outdoor thermal comfort: A model based on thermal adaptation in New Zealand. *Proceedings of the International Conference of Architectural Science Association*, *2020-November*.

Perino, M., & Serra, V. (2015). Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings. *Journal of Facade Design and Engineering*, *3*(2). https://doi.org/10.3233/fde-150039

Pitts, A. (2013). Thermal comfort in transition spaces. *Buildings*, *3*(1). https://doi.org/10.3390/buildings3010122

Pitts, A., & Saleh, J. bin. (2006). Transition spaces and thermal comfort - Opportunities for optimising energy use. *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*.

Pitts, A., & Saleh, J. bin. (2007). Potential for energy saving in building transition spaces. *Energy and Buildings*, *39*(7). https://doi.org/10.1016/j.enbuild.2007.02.006

Potchter, O., Cohen, P., Lin, T. P., & Matzarakis, A. (2018). Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. In *Science of the Total Environment* (Vols. 631–632). https://doi.org/10.1016/j.scitotenv.2018.02.276

Prianto, E., & Depecker, P. (2002). Characteristic of airflow as the effect of balcony, opening design and internal division on indoor velocity: A case study of traditional dwelling in urban living quarter in tropical humid region. *Energy and Buildings*, *34*(4). https://doi.org/10.1016/S0378-7788(01)00124-4

Prihatmanti, R., & Taib, N. (2017). Improving Thermal Comfort through Vertical Greeneries in Transitional Spaces for the Tropical Climate : A Review. *GSTF Journal of Engineering Technology*, *4*(3).

Raji, B., Tenpierik, M. J., & van den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. In *Renewable and Sustainable Energy Reviews* (Vol. 45). https://doi.org/10.1016/j.rser.2015.02.011

Reinke, S. C. (2020). The future of workplace in vertical cities:Hanging gardens, roof terraces and vertical plazas. *International Journal of High-Rise Buildings*, *9*(1). https://doi.org/10.21022/IJHRB.2020.9.1.71

Ribeiro, C., Ramos, N. M. M., & Flores-Colen, I. (2020). A review of balcony impacts on the indoor environmental quality of dwellings. In *Sustainability (Switzerland)* (Vol. 12, Issue 16). https://doi.org/10.3390/su12166453

Rodríguez Álvarez, J. (2021). *35th PLEA Conference on Passive and Low Energy Architecture (PLEA 2020).* (J. C. Soares Gonçalves, Ed.). University of A Coruña; Asoc. PLEA2020 Planning Post Carbon Cities. https://doi.org/10.17979/spudc.9788497497947

Rotach, M. W., & Calanca, P. (2015). Boundary Layer (Atmospheric) and Air Pollution: Microclimate. In *Encyclopedia of Atmospheric Sciences: Second Edition*. https://doi.org/10.1016/B978-0-12-382225-3.00225-5

Roudsari, M. S., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, 3128–3135. https://doi.org/10.26868/25222708.2013.2499

Ruefenacht, L. A., & Acero, J. A. (2017). Strategies for Cooling Singapore: A catalogue of 80+ measures to mitigate urban heat island and improve outdoor thermal comfort. In *Str*. https://doi.org/10.3929/ethz-b-000258216

Sadeghipour Roudsari, M., & Mackey, C. (2018). *Ladybug Tools*. Ladybug Tools Website.

Sala Lizarraga, J. M. P., & Picallo-Perez, A. (2019). Exergy analysis and thermoeconomics of buildings: Design and analysis for sustainable energy systems. In *Exergy Analysis and Thermoeconomics of Buildings: Design and Analysis for Sustainable Energy Systems*. https://doi.org/10.1016/C2018-0-01196-2

Schellen, L., Loomans, M. G. L. C., Kingma, B. R. M., de Wit, M. H., Frijns, A. J. H., & van Marken Lichtenbelt, W. D. (2013). The use of a thermophysiological model in the built environment to predict thermal sensation: Coupling with the indoor environment and thermal sensation. *Building and Environment*, *59*. https://doi.org/10.1016/j.buildenv.2012.07.010

Schoenauer, N. (2000). 6,000 years of housing. *6,000 Years of Housing.*

Sezen, S. (2014). Balgat:  Modernleşme Kuramının “Örnek” Köyünden Postmodern Karmaşaya. In *İDEALKENT* (Vol. 5, Issue 11, pp. 300–324). İdeal Kent Yayınları.

Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street. An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings*, *31*(3). https://doi.org/10.1016/S0378-7788(99)00018-3

Sher, F., Kawai, A., Güleç, F., & Sadiq, H. (2019). Sustainable energy saving alternatives in small buildings. *Sustainable Energy Technologies and Assessments*, *32*. https://doi.org/10.1016/j.seta.2019.02.003

Shooshtarian, S., Lam, C. K. C., & Kenawy, I. (2020). Outdoor thermal comfort assessment: A review on thermal comfort research in Australia. In *Building and Environment* (Vol. 177). https://doi.org/10.1016/j.buildenv.2020.106917

Soflaei, F., Shokouhian, M., & Mofidi Shemirani, S. M. (2016). Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment*, *5*(1). https://doi.org/10.1016/j.ijsbe.2015.12.001

Soflaei, F., Shokouhian, M., Tabadkani, A., Moslehi, H., & Berardi, U. (2020). A simulation-based model for courtyard housing design based on adaptive thermal comfort. *Journal of Building Engineering*, *31*. https://doi.org/10.1016/j.jobe.2020.101335

Soudian, S., & Berardi, U. (2021). Development of a performance-based design framework for multifunctional climate-responsive façades. *Energy and Buildings*, *231*. https://doi.org/10.1016/j.enbuild.2020.110589

Spagnolo, J., & de Dear, R. (2003). A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment*, *38*(5). https://doi.org/10.1016/S0360-1323(02)00209-3

Stewart, I. D., & Mills, G. (2021). Introduction. In *The Urban Heat Island*. https://doi.org/10.1016/b978-0-12-815017-7.00001-1

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, *93*(12). https://doi.org/10.1175/BAMS-D-11-00019.1

Stewart, I. D., Oke, T. R., & Krayenhoff, E. S. (2014). Evaluation of the “local climate zone” scheme using temperature observations and model simulations. *International Journal of Climatology, 34*(4). https://doi.org/10.1002/joc.3746

Tabadkani, A., Tsangrassoulis, A., Roetzel, A., & Li, H. X. (2020). Innovative control approaches to assess energy implications of adaptive facades based on simulation using EnergyPlus. *Solar Energy*, *206*. https://doi.org/10.1016/j.solener.2020.05.087

Taib, N., Abdullah, A., Ali, Z., Fadzil, S. F. S., & Yeok, F. S. (2014). Trends in the air temperature of transitional spaces of a high-rise office building: The effects of season and location. *Indoor and Built Environment*, *23*(8). https://doi.org/10.1177/1420326X13499361

Taib, N., & Ali, Z. (2016). Assessment of Physiological Equivalent Temperature (PET) in Transitional Spaces of a High-Rise Building. *Environment-Behaviour Proceedings Journal*, *1*(1). https://doi.org/10.21834/e-bpj.v1i1.231

Taleghani, M., Tenpierik, M., & van den Dobbelsteen, A. (2014). Energy performance and thermal comfort of courtyard/atrium dwellings in the Netherlands in the light of climate change. *Renewable Energy*, *63*. https://doi.org/10.1016/j.renene.2013.09.028

Taveres-Cachat, E., Grynning, S., Thomsen, J., & Selkowitz, S. (2019). Responsive building envelope concepts in zero emission neighborhoods and smart cities - A roadmap to implementation. *Building and Environment*, *149*. https://doi.org/10.1016/j.buildenv.2018.12.045

Thermal comfort: Analysis and applications in environmental engineering. (1972). *Fanger, P.O.*, *3*(3). https://doi.org/10.1016/s0003-6870(72)80074-7

Tools., L. (2022). *ladybug_comfort.utci module — ladybug comfort documentation*. https://www.ladybug.tools/ladybug-comfort/docs/ladybug_comfort.utci.html

Tzikopoulos, A. F., Karatza, M. C., & Paravantis, J. A. (2005). Modeling energy efficiency of bioclimatic buildings. *Energy and Buildings*, *37*(5). https://doi.org/10.1016/j.enbuild.2004.09.002

UN Department of Economic and Social Affairs. (2018). 68% of the world population projected to live in urban areas by 2050, says UN. *United Nations News*.

U.S. Department of Energy. (2020). EnergyPlus | EnergyPlus. In *U.S. Department of Energy's*. https://energyplus.net/

U.S. Energy Information Agency. (2019). Annual Energy Outlook 2020 with projections to 2050. *Annual Energy Outlook 2019 with Projections to 2050*, *44*(8).

Voogt, J. A., & Oke, T. R. (1997). Complete urban surface temperatures. *Journal of Applied Meteorology*, *36*(9). https://doi.org/10.1175/1520-0450(1997)036<1117:CUST>2.0.CO;2

Walther, E., & Goestchel, Q. (2018). The P.E.T. comfort index: Questioning the model. *Building and Environment*, *137*. https://doi.org/10.1016/j.buildenv.2018.03.054

Wurnig, S. (2009). Caldor Hotel . In *https://www.archdaily.com/69015/caldor-hotel-so%25cc%2588hne-partner*.

Xiang, C., & Matusiak, B. S. (2022). Façade Integrated Photovoltaics design for high-rise buildings with balconies, balancing daylight, aesthetic and energy productivity performance. *Journal of Building Engineering*, *57*, 104950. https://doi.org/10.1016/J.JOBE.2022.104950

Yamamoto, Y. (2005). Measures to Mitigate Urban Heat Islands. *Environmental and Energy Research Unit. Quaterly Review*, *18*.

Yang, L., Fu, R., He, W., He, Q., & Liu, Y. (2020). Adaptive thermal comfort and climate responsive building design strategies in dry–hot and dry–cold areas: Case study in Turpan, China. *Energy and Buildings*, *209*. https://doi.org/10.1016/j.enbuild.2019.109678

Yi, C. Y., & Peng, C. (2014). Microclimate change outdoor and indoor coupled simulation for passive building adaptation design. *Procedia Computer Science*, *32*. https://doi.org/10.1016/j.procs.2014.05.478

Zhang, Y., Liu, J., Zheng, Z., Fang, Z., Zhang, X., Gao, Y., & Xie, Y. (2020). Analysis of thermal comfort during movement in a semi-open transition space. *Energy and Buildings*, *225*. https://doi.org/10.1016/j.enbuild.2020.110312

Zhao, Q., Lian, Z., & Lai, D. (2021). Thermal comfort models and their developments: A review. In *Energy and Built Environment* (Vol. 2, Issue 1). https://doi.org/10.1016/j.enbenv.2020.05.007

## APPENDICES

### A. Physiological Equivalent Temperature Formula

***Calculation of Radiant Heat Exchange (R):***

$$R = f_{cl} h_r (T_{cl} - T_{mrt}) \quad (1)$$

*R: Radiant heat transfer, W/m2 fcl: Clothing area coefficient ,*

*hr: Radiation heat transfer coefficient, W/(m2. °C), Tcl:Clothing surface temperature, °C, Tmrt:Mean radiant temperature, °C,*

$$f_{cl} = \frac{1}{(1 + 0.155 \times (h_c + h_r) \times I_{cl})} \quad (1.1)$$

*fcl: Clothing area coefficient , hc:Convective heat transfer coefficient, W/(m2 °C), hr.Radiation heat transfer coefficient, W/(m2. °C), Iclo Total clothing insulation, clo*

$$h_r = f_{rad} \varepsilon [(T_{cl} + 273.15)^2 + (T_{mrt} + 273.15)^2] \times [(T_{cl} + 273.15) + (T_{mrt} + 273.15)] \times 5.67 \times 10^{-8} \quad (1.2)$$

$$T_{cl} = 35.7 - 0.032M - 0.18 I_{cl} \left\{ -3.4 \times 10^{-8} f_{cl} [(T_{cl} + 273.15)^4 - (T_{mrt} + 273.15)^4)] + f_{cl} h_c (T_{cl} - T_a) \right\} \quad (1.3)$$

*R: Radiant heat transfer, W/m2 fcl: Clothing area coefficient , frad: Correction coefficient of the effective surface area , hr: Radiation heat transfer coefficient, W/(m2. °C), Tcl:Clothing surface temperature, °C, Tmrt: Mean radiant temperature, °C, Ta: Air temperature, °C*

***Calculation of Convective Heat Exchange (C):***

$$C = f_{cl} h_c (T_{cl} - T_a) \quad \textit{(2)}$$

*u:Average wind velocity, m/s, TI: Turbulence intensity,*

***Calculation of Evaporating Heat Exchange (E):***

$$E = E_{sk} + (C_{res} + E_{res}) \quad (3)$$

*Esk Total rate of evaporative heat loss from skin, W/m, Eres:Rate evaporative heat loss from respiration, W/m2, Cres: Dry respiratory heat loss per unit area, W/m2,*

$$E_{sk} = \omega (p_{sk} - p_a) R_{ecl} h_e \quad (3.1)$$

$$T_{sk} = 33.876 - 0.641M \quad (3.3)$$

$$C_{res} + E_{res} = 0.0014M(34 - T_a) + 0.0173M(5.87 - p_a) \quad (3.4)$$

$\omega$ : Moisture index of skin, $p_{sk}$ : Vapor pressure of water on the skin surface, $k_{Pa}$, $p_a$: Vapor pressure of water in air, $k_{Pa}$, $R_{ecl}$:Wet permeability coefficient of the clothing, $h_e$ : Coefficient of evaporating heat transfer, W/(m$^2$ . $k_{Pa}$), $h_c$ : Convective heat transfer coefficient, W/(m$^2$ . °C),

***Calculation Heat Storage (S):***

$$S = M - E + R + C - W$$

*S = rate of heating (+) or cooling (-) by the body, M = net rate of metabolic heat production, E =total evaporative heat loss, R = heat gained (+) or lost (-) by radiation, C = heat gained (+) or lost (-) by convection, and W=work accomplished.*

MRT Calculation in PET Thermal Comfort Model

```
def calculatePointMRT(srfTempDict, testPtsViewFactor, hour, originalHour, outdoorClac, outSrfTempDict, outdoorNonSrf
ViewFac, prevailingOutdoorTemp):
    #Calculate the MRT for each point.
    pointMRTValues = []v
    for zoneCount, pointList in enumerate(testPtsViewFactor):
        if outdoorClac == False or zoneCount != len(testPtsViewFactor)-1:
            pointMRTValues.append([])
            for pointViewFactor in pointList:
                pointMRT = 0
                for srfCount, srfView in enumerate(pointViewFactor):
                    path  = str([zoneCount,srfCount])
                    weightedSrfTemp = srfView*(math.pow((srfTempDict[path]["srfTemp"][hour] + 273.15),4))
                    pointMRT = pointMRT+weightedSrfTemp
                pointMRT = math.pow(pointMRT,0.25) - 273.15
                pointMRTValues[zoneCount].append(round(pointMRT, 3))
        else:
            pointMRTValues.append([])
            for ptCount, pointViewFactor in enumerate(pointList):
                pointMRT = 0
                for srfCount, srfView in enumerate(pointViewFactor):
                    path  = str([zoneCount,srfCount])
                    weightedSrfTemp = srfView*(math.pow((outSrfTempDict[path]["srfTemp"][hour]+273.15),4))
                    pointMRT = pointMRT+weightedSrfTemp

                weightedSrfTemp = outdoorNonSrfViewFac[ptCount]*(math.pow((prevailingOutdoorTem
p[originalHour]+273.15),4))
                pointMRT = pointMRT+weightedSrfTemp
                pointMRT = pointMRT / (sum(pointViewFactor) + outdoorNonSrfViewFac[ptCount])
                pointMRT = math.pow(pointMRT,0.25) - 273.15
                pointMRTValues[zoneCount].append(round(pointMRT, 3))

    return pointMRTValues
```

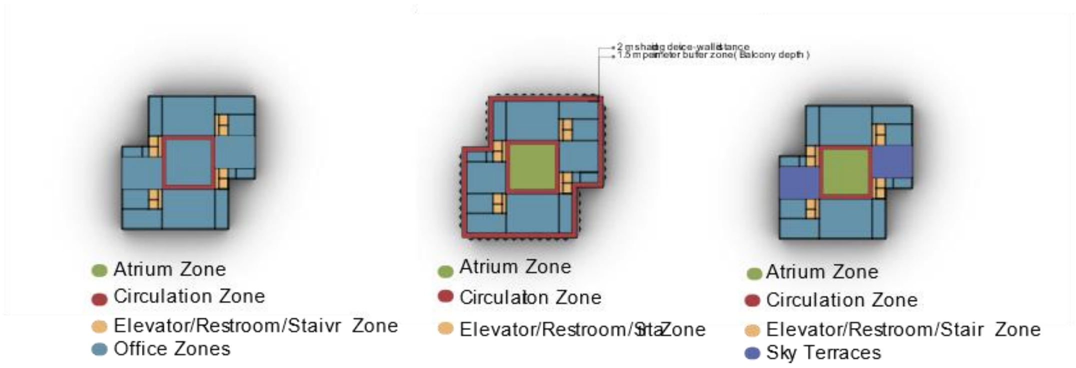
MRT calculation method in microclimate map analysis component

```
     petObj = lb_comfortModels.physiologicalEquivalentTemperature
 - airTemp,
 - pointMRTValues[ptCount],
 - pointRelHumidValues[ptCount],
 - pointWindSpeedValues[ptCount],
 - bodyCharacteristics['age'],
 - bodyCharacteristics['sex'],
 - bodyCharacteristics['heightM'],
 - bodyCharacteristics['weight'],
 - bodyCharacteristics['bodyPosition'],
 - bodyCharacteristics['Mmets'],
 -bodyCharacteristics['Icl']
```

Calculation of PET using Microclimate Map Analysis component from Honeybee tool.

```python
def computeFloorReflect(testPts, testPtViewFactor, zoneSrfTypes, flrRefList):
    # Set defaults and a list to be filled.
    defaultRef = 0.2
    zoneFlrReflects = []
    includeOutdoor = False
       if len(testPts) == len(flrRefList): includeOutdoor = True
```

Calculation of MRT ground surface albedo assumption




Office Floor Area:1064 $m^2$

Figure 4.1. Case study building plan

## B. Simulation Results

| Out MRT | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 50.2 | 48.3 | 45.0 | 45.5 | 41.7 | 44.6 | 44.0 | 41.2 | 40.8 | 38.3 | 40.9 | 38.2 |
| Level 5 | 50.6 | 47.3 | 45.3 | 45.9 | 46.1 | 44.0 | 43.2 | 41.5 | 44.0 | 41.8 | 40.5 | 41.0 |
| Level 10 | 51.6 | 47.1 | 46.4 | 47.7 | 43.8 | 43.9 | 44.1 | 43.5 | 41.4 | 40.3 | 41.5 | 38.9 |
| Level 15 | 59.6 | 56.1 | 59.5 | 58.3 | 62.2 | 56.0 | 55.4 | 58.2 | 60.3 | 62.0 | 55.4 | 60.2 |
| Avreage | 53.0 | 49.7 | 49.0 | 49.3 | 48.4 | 47.1 | 46.7 | 46.1 | 46.6 | 45.6 | 44.6 | 44.6 |
| Ind. MRT | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 27.6 | 26.7 | 25.5 | 29.2 | 32.2 | 25.4 | 28.0 | 26.5 | 30.6 | 29.0 | 26.4 | 28.5 |
| Level 5 | 27.6 | 26.0 | 25.6 | 28.9 | 28.7 | 24.9 | 27.1 | 26.6 | 27.3 | 26.5 | 25.8 | 25.9 |
| Level 10 | 27.4 | 25.7 | 25.6 | 29.0 | 31.8 | 24.6 | 26.9226 | 26.8 | 29.6 | 29.2 | 25.6 | 28.0 |
| Level 15 | 27.4 | 26.7 | 27.5 | 29.7 | 34.4 | 26.7 | 28.6 | 29.6 | 33.3 | 34.1 | 28.7 | 33.3 |
| Avreage | 27.5 | 26.3 | 26.0 | 29.2 | 31.8 | 25.4 | 27.7 | 27.4 | 30.2 | 29.7 | 26.6 | 28.9 |
| PET | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 29.3 | 28.7 | 27.8 | 28.0 | 27.0 | 27.6 | 27.5 | 26.8 | 26.7 | 26.7 | 26.0 | 25.9 |
| Level 5 | 26.6 | 25.9 | 25.5 | 25.7 | 25.7 | 25.3 | 25.2 | 25.2 | 24.7 | 25.3 | 24.9 | 24.8 |
| Level 10 | 26.0 | 25.3 | 25.1 | 25.4 | 24.7 | 24.7 | 24.8 | 24.7 | 24.3 | 24.3 | 24.1 | 23.9 |
| Level 15 | 27.1 | 26.5 | 27.0 | 26.8 | 27.5 | 26.4 | 26.3 | 26.8 | 26.3 | 27.2 | 27.5 | 27.2 |
| Avreage | 27.3 | 26.6 | 26.4 | 26.5 | 26.2 | 26.0 | 26.0 | 25.9 | 25.5 | 25.9 | 25.6 | 25.4 |
| OPT | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 25.3 | 25.0 | 24.5 | 25.9 | 27.3 | 24.4 | 25.3 | 24.6 | 26.5 | 25.7 | 24.6 | 25.5 |
| Level 5 | 25.2 | 24.6 | 24.4 | 25.7 | 25.6 | 24.1 | 24.8 | 24.6 | 24.9 | 24.5 | 24.2 | 24.2 |
| Level 10 | 25.1 | 24.5 | 24.4 | 25.7 | 27.0 | 23.9 | 24.7 | 24.6 | 25.9 | 25.7 | 24.0 | 25.0 |
| Level 15 | 25.2 | 25.0 | 25.4 | 25.8 | 27.9 | 24.9 | 25.3 | 25.8 | 27.4 | 27.8 | 25.4 | 27.4 |
| Avreage | 25.2 | 24.8 | 24.7 | 25.8 | 27.0 | 24.3 | 25.0 | 24.9 | 26.2 | 25.9 | 24.5 | 25.5 |
| ATC | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 0.7 | 0.7 | 0.0 | 1.6 | 3.0 | 0.0 | 1.0 | 0.2 | 1.3 | 0.1 | 2.9 | 1.0 |
| Level 5 | 0.5 | 0.2 | 0.0 | 1.4 | 1.3 | -0.3 | 0.4 | 0.2 | 0.1 | -0.3 | 0.5 | -0.2 |
| Level 10 | 0.5 | 0.0 | 0.0 | 1.3 | 2.6 | -0.5 | 0.2 | 0.2 | 1.2 | -0.4 | 1.4 | 0.5 |
| Level 15 | 0.5 | 0.6 | 1.0 | 1.5 | 3.5 | 0.5 | 0.9 | 1.5 | 3.3 | 1.0 | 2.9 | 2.9 |
| Avreage | 0.5 | 0.4 | 0.3 | 1.4 | 2.6 | -0.1 | 0.6 | 0.5 | 1.5 | 0.1 | 1.9 | 1.1 |
| Tcomf | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 23 | 24 | 24 |
| Level 1 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Level 5 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Level 10 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 |
| Level 15 | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Avreage | 25 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 25 | 24 | 24 | 24 |
| Air T | scBase | P | B | S | | P+B | P+S | | | | P+S+B | |
| Levels | Sc0 | Sc1 | Sc2 | ScA | ScB | Sc3 | ScA1 | ScA2 | ScB1 | ScB2 | ScA3 | ScB3 |
| Level 1 | 23.5 | 23.5 | 23.4 | 23.3 | 23.0 | 23.4 | 23.3 | 23.3 | 22.9 | 22.9 | 23.3 | 22.9 |
| Level 5 | 23.3 | 23.3 | 23.3 | 23.2 | 23.2 | 23.3 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 | 23.1 |
| Level 10 | 23.3 | 23.3 | 23.3 | 23.1 | 22.7 | 23.3 | 23.1 | 23.1 | 22.6 | 22.6 | 23.1 | 22.6 |
| Level 15 | 23.3 | 23.3 | 23.3 | 23.1 | 22.7 | 23.3 | 23.1 | 23.1 | 22.7 | 22.7 | 23.1 | 22.7 |
| Avreage | 23.3 | 23.3 | 23.3 | 23.2 | 22.9 | 23.3 | 23.2 | 23.1 | 22.9 | 22.8 | 23.1 | 22.8 |