

MODEL-BASED OUTDOOR THERMAL COMFORT AND URBAN HEAT ISLAND ASSESSMENT IN AN URBAN PARK

A Case Study of Zuidpark Antwerp

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Abstract

The Urban Heat Island and thermal discomfort are growing challenges in European cities as climate change and urbanisation intensify. This thesis investigates the microclimatic and thermal comfort impacts of converting a paved parking lot into a vegetated urban park (Zuidpark, Antwerp). Using a combination of field measurements and ENVI-met modelling, three scenarios were compared: a fully paved parking (before), the current condition with young vegetation (present), and a future scenario with fully developed tree canopies.

Results demonstrate measurable cooling effects, with average daytime air temperature reductions of 0.6 and 1.1 °C and peak hour reductions up to 1.2 °C. Physiological Equivalent Temperature (PET) decreased by 1.2 °C in the present scenario and up to 4.6 °C in the future scenario, delaying and shortening periods of extreme heat stress. The analysis highlights the importance of mature tree canopies and ventilation corridors in maximising cooling, while also showing the limitations of model performance for air temperature accuracy compared to mean radiant temperature.

These findings confirm the value of urban greening as a nature-based solution for mitigating the urban heat island effect and improving thermal comfort. The study provides insights for urban planners, policymakers, and public health agencies in designing climate-resilient cities.

Key words: Urban Heat Island, Outdoor Thermal Comfort, ENVI-met, Computational Fluid Dynamics, Vegetation Modeling, Urban Climate, Heat Mitigation

Abbreviations

UHI = Urban Heat Island

TC = Thermal Comfort

TD = Thermal Discomfort

ORM = Obstacle-resolving Meteorology Models

PMV = Predicted Mean Vote

PPD = Predicted Percentage Dissatisfied

PET = Physiological Equivalent Temperature

UTCI = Universal Thermal Climate Index

WS = Wind Speed

RH = Relative Humidity

LAI = Leaf Area Index

UBL = Urban Boundary Layer

UCL = Urban Canopy Layer

SD = Standard deviation

MRT = Mean Radiant Temperature (used throughout results/discussion)

CFD = Computational Fluid Dynamics

WBGT = Wet Bulb Globe Temperature

ISO = International Organization for Standardization

ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers

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1. Introduction

The world population is growing rapidly, and it is expected that by 2050 up to 70% of people will live in urban areas (United Nations, 2019). This demographic shift is accompanied by transformations in land use and urban morphology (Biney et al., 2024). Paved surfaces, limited vegetation, lack of water bodies, and anthropogenic heat production contribute to higher temperatures in cities. This phenomenon is called the Urban Heat Island (UHI) effect, where urban areas typically exhibit higher temperatures than their surrounding countryside (Tong et al., 2021). Figure 1 shows the number of heatwave days for Flanders and the temperature distribution in Antwerp, clearly visualizing the UHI. Climate change amplifies the UHI by increasing the frequency, intensity, and duration of heatwaves (Amengual et al., 2014). For instance, Antwerp recorded twice as many heatwave days as its rural surroundings the past decade. Under the high-risk RCP8.5 climate scenario, the frequency of such events is expected to increase tenfold by the end of the century (Lauwaet et al., 2020). In Europe, summer mortality rises by approximately 4% due to heat stress (lungman et al., 2023), with cities experiencing disproportionate impacts (Gabriel & Endlicher, 2011). American cities experience a similar increase in mortality rates (Heaviside et al., 2016). Heat stress is a growing concern with an estimated 47,690 heat-related deaths in Europe during the year of 2023 (Gallo et al., 2024). Rising temperatures not only threaten public health but also have significant economic consequences. The International Labour Organization projects that by 2030, heat stress could lead to productivity losses equivalent to 80 million full-time jobs globally, representing 2.2% of total working hours and an economic impact of 2.4 trillion dollars (International Labour Organization, 2019). Additionally, the implications caused by the UHI can have significant effects on the ecosystem as well by for example deteriorating water and air quality.

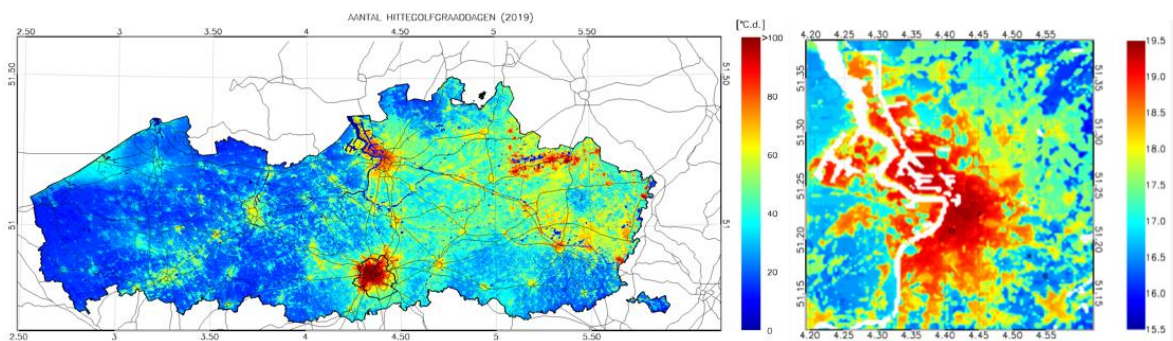


Figure 1: The urban heat island mapped for (left) Flanders including Brussels using the amount of heat wave days, and (right) Antwerp using a temperature indicator (Hitte-eilanden in Steden, n.d.).

Thermal Comfort (TC), defined as the condition of mind that expresses satisfaction with the surrounding thermal environment (ASHRAE et al., 2020), is directly influenced by increased temperatures in urban environments. Not only air temperature, but also other environmental factors like mean radiant temperature (MRT), wind speed, and relative humidity determine how people experience a certain thermal environment (Yılmaz et al., 2024). Additionally, personal factors play a key role. Clothing and metabolic rate are often integrated in formulas calculating TC indices such as the Universal Thermal Climate Index (UTCI) or Physiological Equivalent Temperature (PET). Age, health state, and even economic status can also influence TC and vulnerability. Vulnerable groups, including elderly, children,

people of low socio-economic status, or those with (chronic) health issues, face a higher risk of heat stress (World Health Organization, 2024), as they are often underrepresented in policy frameworks that tend to address average population characteristics (Päivärinne et al., 2025). While indoor thermal comfort is protected by standards and regulations (Motmans, 2017; Mursic, 2024), outdoor thermal comfort remains less defined, lacking binding legislation and largely depending on non-compulsory guidelines. This regulatory gap underscores the need for more robust strategies to enhance outdoor thermal environments.

To mitigate the dual challenges of UHI and thermal discomfort (TD), multiple solutions are available. These range from small-scale measures with limited interference, such as green walls, to large-scale invasive measures, like altering the building morphology (Lai et al., 2019). The effectiveness of these interventions can be very context-specific and requires careful evaluation (Rahman et al., 2019). For example, if trees are used in an area with limited space, they may not reach their full potential due to lack of space. Additionally, the management and convenience of certain measures must be considered. People can complain if prolonged work is carried out or if vegetation is not well maintained. The full implementation of mitigation strategies is often hindered by costs and lack of quantitative observational data on their effectiveness. Computational modelling offers a valuable approach to evaluate and optimize the urban climate by generating quantitative data (Toparlar et al., 2017). Simulations can be used to discover the potential of various solutions. By testing different scenarios, stakeholders can identify optimal solutions and ultimately decide the best possible measures to implement.

Multiple cities are implementing such mitigation strategies on various scales. In Flanders, the UHI is a major topic in their climate adaptation plan (Vlaams Klimaatadaptatieplan, 2023). This plan focusses on short- and long-term solutions to prepare Flanders for the multiple effects of climate change. Often these interventions have multipurpose functions, not only addressing the UHI and TC problems, but also increasing air quality, mental wellbeing, and recreational spots in the city. Urban parks are a great example, providing green social environments for outdoor activities (Li et al., 2024).

Despite the promising potential of urban parks (Bowler et al., 2010; Ghale et al., 2025), evidence confirming their actual effectiveness in reducing local temperatures and improving thermal comfort after implementation remains limited. This thesis aims to address this knowledge gap through two main objectives. On the first hand it evaluates the transformation from a parking lot to an urban park by quantifying changes in temperature and thermal comfort indices. Secondly, it focusses on a future scenario by investigating the influence of developed urban tree canopies. ENVI-met, a microscale climate model, will be used to simulate the site's thermal behaviour. Additional simulations investigate the influence of windspeed, wind direction, radiation settings, grid size, and telescoping on the results. Instead of using models solely to propose ideal design solutions, as is common in much of the existing literature (Morakinyo & Lam, 2016), this thesis takes a reverse approach by simulating already implemented solutions and comparing them to the pre-intervention scenario. The results from these simulations will be validated with field measurements to ensure the model's accuracy and reflection of real-world conditions.

2. Literature Review and Objectives

2.1 The Urban Heat Island

2.1.1 Concept

The Urban Heat Island (UHI) effect is defined as cities having a higher temperature or heat content than its surrounding rural areas, with both minimum and maximum temperatures rising (Tzavali et al., 2015). Quantifiable with the difference in temperature between the urban and rural area and typically showing the highest values in the city centre (Dian et al., 2019). Fundamentally, the UHI effect results from an imbalance in the overarching energy budget of urban environments (Phelan et al., 2015). This budget accounts for all incoming, outgoing, stored, and generated energy in a specific area and can be expressed with the following equation (Oke et al., 2017; Cleugh & Grimmond, 2011; Lemonsu et al., 2009):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S \quad (W\ m^2) \quad (\text{Equation 1})$$

Where

- Q^* is the net all-wave radiation
- Q_F accounts for the anthropogenic heat flux
- Q_H represents the sensible heat flux density
- Q_E is the latent heat flux density
- ΔQ_S is the net heat storage change

The imbalance that causes increased urban temperatures originates in the drastic alteration of geometric, radiative, thermal, moisture, and aerodynamic properties in urban areas (Oke et al., 2017). A key factor is the dominance of built surfaces, often referred to as grey infrastructure. Materials such as concrete and asphalt are widespread in cities and significantly increase heat storage within the urban fabric. Their low albedo means they absorb a large proportion of incoming solar radiation rather than reflecting it, causing them to heat up rapidly under direct sunlight (Cleugh & Grimmond, 2011). In addition, many urban construction materials have a high heat capacity (thermal mass), enabling them to store substantial amounts of heat during the day and release it slowly at night. This delayed release explains why the UHI effect is typically most pronounced during nighttime. Additionally, some materials such as asphalt have a low thermal inertia, meaning they respond very quickly to solar heating and can reach extreme surface temperatures during the day, intensifying daytime heat stress (Oke et al., 2017).

Secondly, the lack of so-called green and blue infrastructure, vegetation and water respectively, also has a significant effect on the UHI. Vegetation cools the air through the process of evapotranspiration, increasing the latent heat flux and decreasing the sensible heat flux, resulting in a cooling effect (Oke et al., 2017). Similarly, water bodies promote evaporative cooling. Surfaces with a high moisture availability tend to heat up less, as they have a higher thermal admittance and facilitate cooling through evaporation. The ratio between sensible heat flux and latent heat flux is represented by the Bowen ratio

(β) (Cleugh & Grimmond, 2011). Typically, vegetated surfaces have a Bowen ratio smaller than one, as latent heat flux is dominant. In contrast, urban surfaces often have a Bowen ratio higher than one, indicating a stronger influence of sensible heat which warms the air directly.

Figure 2 clearly represents the latent and sensible heat flux for different land-use zones. In areas with limited vegetation, such as the Central Business District (CBD) and industrial (IND) zones, sensible heat flux (Q_H) exceeds latent heat flux (Q_E), resulting in a Bowen ratio greater than one. In moderately vegetated areas, such as residential (RES) zones, sensible and latent heat fluxes are of similar magnitude, producing a Bowen ratio close to one. In contrast, highly vegetated rural (RUR) areas exhibit higher latent heat fluxes, leading to a Bowen ratio of less than one. This relationship is further investigated by comparative studies showing that urban environments can have latent heat fluxes as low as half, or even lower, than those in rural vegetated areas, with the Bowen ratio often exceeding two in residential and industrial zones (Cleugh & Oke, 1986; Lemonsu et al., 2008; Offerle et al., 2006; Oke et al., 1999).

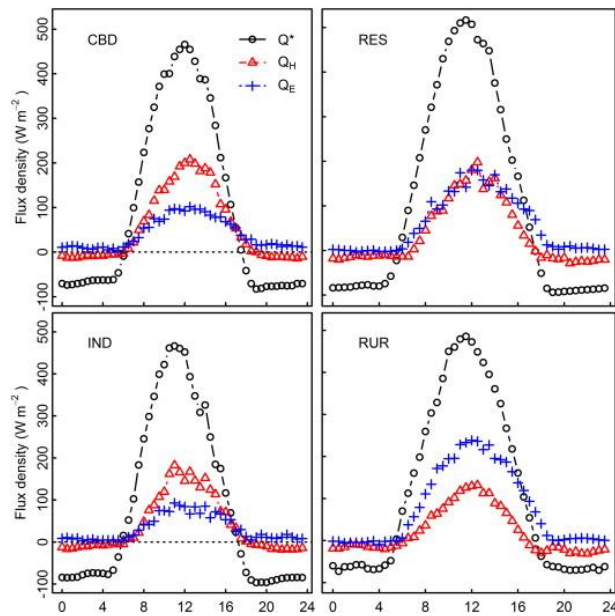


Figure 2: Averages of the surface energy balance (Q^* is total flux density, Q_H is sensible heat flux and Q_E is latent heat flux) for four different land-use zones in a European city (RES: residential, IND: industrial, RUR: rural). The x-axis refers to solar time, in hours (Cleugh & Grimmond, 2011).

Anthropogenic heat production is another important factor (Oke et al., 2017). It results from the conversion of energy into heat through human activities. The main sources include transport, industrial processes, the metabolism of people and animals, and energy use in buildings (e.g., lighting, cooking, appliances, heating, cooling, etc.). This heat flux is characteristic of urban areas and is typically neglected in rural settings, where human-induced heat production is usually minimal. Masson et al. (2008) found that the anthropogenic heat flux in Toulouse during the winter is about two thirds the size of the summertime net all wave radiation, sustaining positive sensible and latent heat fluxes during the winter.

Lastly, the urban morphology also plays a critical role (Oke et al., 2017; Cleugh & Grimmond, 2011). Heat can get trapped in densely built environments, since there is more active surface for energy exchange compared to flat rural surfaces. In addition, urban structures can obstruct airflow, which would otherwise help dissipate heat. As a result, natural cooling by wind is often restricted in urban environments, especially during the night.

Figure 3 visualises the effect of the surrounding landscape on both air and surface temperatures. During the day, suburban areas, industrial zones, urban residential areas, and especially downtown districts exhibit substantially higher surface temperatures than the surrounding rural areas. This is primarily due to the low albedo and high heat storage capacity of urban materials, which absorb large amounts of solar energy. Parks show surface temperatures comparable to rural areas, while ponds are even cooler, reflecting the strong cooling potential of water bodies through evaporation. Air temperatures follow a similar pattern, being highest in industrial and urban residential zones. Interestingly, downtown areas show slightly lower daytime air temperatures than these zones despite elevated surface temperatures. This can be attributed to shading from tall buildings, which reduces direct solar heating at pedestrian level. Vegetated and water areas remain cooler due to shade and enhanced latent heat flux from evapotranspiration. At night, rural and vegetated areas cool rapidly, as their lower thermal inertia allows stored heat to be released quickly. In contrast, downtown and residential areas retain heat for much longer due to the high thermal admittance of building materials, resulting in elevated nighttime air and surface temperatures. This retained heat, in combination with reduced wind flow and longwave radiation trapping by urban structures, contributes to the persistence of the urban heat island effect well into the night.

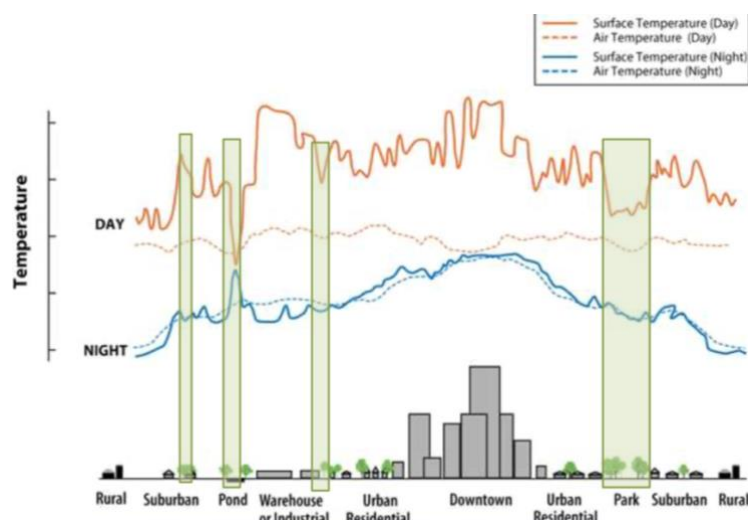


Figure 3: Surface and air temperature profile along different land uses (Hermey, 2016).

2.1.2 UHI Types

Literature mentions multiple types of UHI (Branea et al., 2016; Oke et al., 2017), depending on the scale and/or the observation method. To understand these different UHI types, it is necessary to first define the different atmospheric layers present over urban areas, represented in Figure 4 (Oke et al., 2017; Wang et al., 2014):

- **Atmospheric boundary layer (ABL):** The lowest part of Earth's atmosphere that is directly influenced by the surface, typically extending 1–3 km during the day and shrinking to around 100 m at night. It is characterized by turbulent mixing, rapid changes in temperature, wind, and moisture, and contains the effects of surface heating, roughness, and emissions.
- **Urban boundary layer (UBL):** A specialized form of the ABL over urban areas, where urban features (buildings, streets, pollution, etc.) modify the atmosphere. It forms an urban dome under calm winds or an urban plume when wind is present, with the height increasing downwind. The UBL contains urban-modified air and can transport heat, moisture, and pollutants for tens to hundreds of kilometres.
- **Mixed layer (ML):** The daytime portion of the ABL (or UBL) that becomes well-mixed due to solar heating and convection. Air properties such as temperature, humidity, and wind are nearly uniform with height. It is bounded above by a capping inversion that limits vertical mixing.
- **Surface layer (SL):** The lowest ~10% of the ABL, where the atmosphere is most directly affected by surface heating, cooling, and roughness. Turbulent mixing here is mainly driven by frictional forces. It includes both the roughness sublayer (RSL) and, above it, the inertial sublayer (ISL).
 - **Roughness sublayer (RSL):** A near-surface zone extending from the ground up to approximately 2-5 times the height of urban roughness elements (e.g., buildings or trees). In this layer, airflow is strongly influenced by individual obstacles, leading to complex, small-scale turbulence.
 - **Inertial sublayer (ISL):** The upper portion of the surface layer where the effects of individual buildings are averaged out. In this zone, the flow reflects the bulk characteristics of the urban area, and standard turbulent flow relationships can be used (like the logarithmic wind profile). In dense city centers, this layer may be non-existent.
- **Urban canopy layer (UCL):** The space between the ground and the building tops and trees. It includes pedestrian areas, streets, parks, and building interiors. This layer is the most affected by urban design, and it is where human activity, energy exchange, and climate modification are most intense. Airflow, radiation, and temperature in the UCL are very different from those above roof level due to obstruction, shading, and restricted sky view.

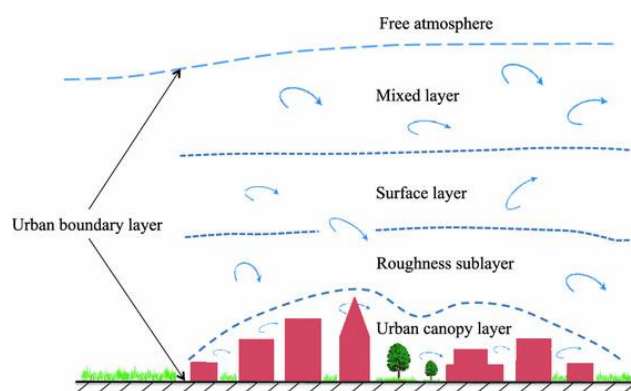


Figure 4: The atmospheric layers present over urban areas (Wang et al., 2014).

The different UHI types are defined as follows (Oke et al., 2017):

- Boundary layer UHI: The difference between the air temperature measured in the UBL, and that at similar elevations in the ABL of the surrounding rural region
- Canopy layer UHI: The difference between the near-surface air temperature measured in the UCL and the corresponding temperature in the near-surface layer of the countryside
- Surface UHI: The temperature differences at the interface of the outdoor atmosphere with the solid materials of the city and equivalent rural air to ground interface.
- Subsurface UHI: The temperature difference beneath the ground under the city, including urban soils and the subterranean built fabric, and beneath the surrounding rural ground.

In this thesis the focus is on the canopy layer UHI, unless stated otherwise. The UCL is the most relevant for urban residents, as it directly affects the thermal environment experienced at pedestrian level.

2.1.3 Evaluation of UHI

The UHI can be measured in different ways (Schmidt, 2024; Huang & Lu, 2017; Mirzaei & Haghighat, 2010; Blocken, 2015). Ground-based measurements with fixed weather stations or mobile temperature sensors are the most straightforward. These ground-based methods measure crucial atmospheric parameters at selected locations, such as air temperature, humidity, wind speed and MRT (Oke & World Meteorological Organization, 2004). They provide high temporal resolution at the cost of limited spatial coverage, frequent maintenance, not being fully controllable due to inherently variable meteorological conditions and being time consuming (Goldblatt et al., 2021; Rodríguez et al., 2023; Blocken, 2015). Citizen science projects such as one performed by Feichtinger et al. in Vienna (2020), or CurieuzeNeuzen in Flanders are also a possibility (CurieuzeNeuzen, n.d.). These can increase spatial data density but require careful data validation, sensor calibration and organisation. Remote sensing provides land surface temperatures (surface UHI) (Goldblatt et al., 2021), which are frequently correlated to air temperature. However, it does not provide enough information to estimate the complex interplay of the different atmospheric parameters at the pedestrian level (Naserikia et al., 2023; Back et al., 2022; Goldblatt et al., 2021). This is with the use of satellites (for example Landsat or MODIS) or airplanes and drones for higher resolution (De Almeida et al., 2021). Wind tunnel measurements are a great option for controlled and predictive evaluation (Blocken, 2015). However, just like the previously mentioned techniques, they only provide point measurements, and the smaller scale can influence results for multiphase flow problems and buoyant flows (e.g. transport of sand, dust, rain, snow, and hail), buoyancy driven natural ventilation and pollutant dispersion studies.

To overcome constraints like meteorological variability, computational or numerical modelling is a final option. It can accurately simulate temperature distributions in urban areas while providing whole flow field data under controlled and reproducible conditions (Blocken, 2015). Various types of models can be employed, ranging from simpler energy balance models to more complex numerical approaches such as Computational Fluid Dynamics (CFD) (Back et al., 2022; Toparlar et al., 2017; Blocken, 2015; Mirzaei & Haghighat, 2010). The advantage is that it requires limited measurement equipment and physical labour for large-scale or scenario-based assessments, hence it is becoming increasingly popular. By providing accurate input data, modelling can serve as the ideal tool for parametric studies,

process understanding and future design studies. However, CFD simulations also face challenges, especially due to high computational cost and need for careful turbulence modelling (Mirzaei & Haghighat, 2010). Additionally, the accuracy of CFD is highly dependent on the boundary conditions provided and surface property assumptions. Ideally, they are combined with ground-based measurements or remote sensing to provide the essential data for model input, calibration, and validation (Toparlar et al., 2017).

2.2 Thermal Comfort

Thermal comfort (TC) is closely linked temperatures in the canopy layer, but air temperature alone is not sufficient to represent TC accurately (Yilmaz et al., 2024). Additional environmental factors that influence TC include windspeed, relative humidity and MRT. Personal factors such as metabolic rate and clothing insulation also play a significant role.

2.2.1 Concept

The original definition of TC according to ASHRAE 55 is stated as “*That condition of mind which expresses satisfaction with the thermal environment*” (ASHRAE et al., 2020). It is influenced not only by the physical condition but also by psychological and behavioural factors (Aljawabra & Nikolopoulou, 2011; Potchter et al., 2018). Important to note is that TC is inherently subjective, some people may feel comfortable in a certain thermal environment, whilst others may feel uncomfortable under the same conditions.

Indoor thermal comfort has been studied extensively, whereas outdoor thermal comfort is a relatively new and evolving research field. With increasing urban temperatures and less direct solutions like air conditioning in outdoor areas, outdoor TC has become increasingly relevant. In recent years, the number of studies focussing on outdoor TC has increased exponentially. However, it is still considerably less compared to indoor thermal comfort studies, see Figure 5 from Aghamolaei et al. (2022). A possible explanation could be the complexity involved in assessing outdoor thermal comfort, since it introduces a variety of complex and confounding parameters. These include fluctuating solar radiation, unpredictable air movement, diverse surface materials, variable relative humidity and the varied behaviour of people outdoors. In contrast, the variables influencing indoor thermal comfort tend to remain more constant, making indoor environments easier to study and model. Outdoor TC studies typically focus on climate conditions, building energy demand, mitigation strategies, and evaluation of thermal comfort indices.

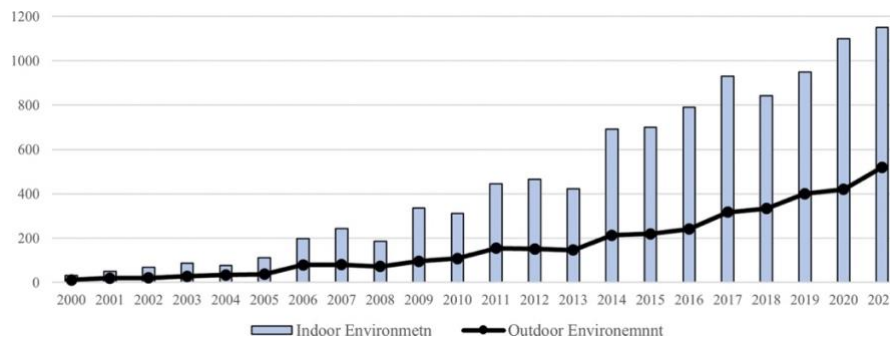


Figure 5: Comparison of indoor and outdoor thermal comfort studies between 2000 and 2021. Figure taken from Aghamolaei et al. (2022).

2.2.2 PMV/PPD Index

There are numerous ways to quantify thermal comfort through an index. A study by De Freitas and Grigorieva (2016) identified more than 165 thermal comfort indices. Each one is specialized in different environments, climates or purposes. One of the most widely used indices, particularly for indoor settings, is the PMV/PPD model. Originally founded by Fanger in his book: *Thermal comfort: Analysis and applications in environmental engineering* (1970), it discusses the predicted mean value (PMV) and the predicted percentage dissatisfied (PPD).

The PMV is an index that predicts the mean value of thermal satisfaction of a large group of people on the 7-point ASHRAE 55 (Figure 6) thermal sensation scale, based on the heat balance of the human body (Fabbri, 2024; Motmans, 2017). This simplistic scale, ranging from -3 (very cold) to +3 (very hot), was formalized in ASHRAE Standard 55 (ASHRAE et al., 2020) and developed in conjunction with the PMV model introduced by Fanger in 1966 (Humphreys & Hancock, 2007; Jenkins, 2025). Thermal balance, corresponding to the score 0, is achieved when internal heat production equals the heat loss to the environment. This scale is prone to regional differences and thermal expectations. For instance, people in cold countries prefer slightly warm thermal conditions (Humphreys & Hancock, 2007).

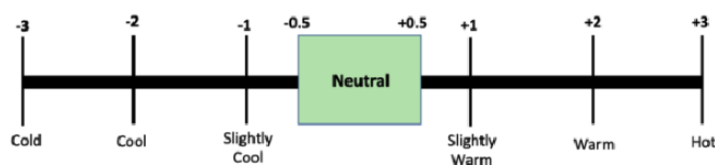


Figure 6: Thermal sensation scale of ASHRAE Standard 55 (Hossain et al., 2022).

The PMV model is based on a steady-state human heat budget equation that estimates thermal sensation by evaluating the balance between internal heat production and heat loss to the environment under given climatic and personal conditions. The model incorporates the following parameters to account for convective and radiative heat exchange, as well as latent heat losses through evaporation:

- Metabolic rate (W/m^2)
- Effective mechanical power (W/m^2), often 0 in passive activities
- Air temperature ($^{\circ}\text{C}$)

- MRT (°C)
- Air velocity relative to the person's movement (m/s)
- Water vapor pressure (Pa)
- Clothing insulation (m² K/W)
- Clothing surface area factor (-)

For a detailed calculation of the PMV index, I refer to the chapter “The Indoor Thermal Comfort Indexes PMV and PPD” in Thermal Comfort Perception by K. Fabbri (Fabbri, 2024).

While the PMV represents a mean value across a population, the PPD is a percentage quantifying the number of individuals feeling dissatisfied with the thermal environment, feeling either too cold or too hot (Fabbri, 2024). Even at a PMV of 0, a minimum of approximately 5% dissatisfaction is expected due to natural variability in individual preferences. As a result, the PPD is a nonlinear U-shaped function with a minimum value of 5%, see Figure 7. The PPD increases rapidly the further the PMV moves from thermal neutrality. The only variable in the formula of PPD is the PMV value (Equation 2).

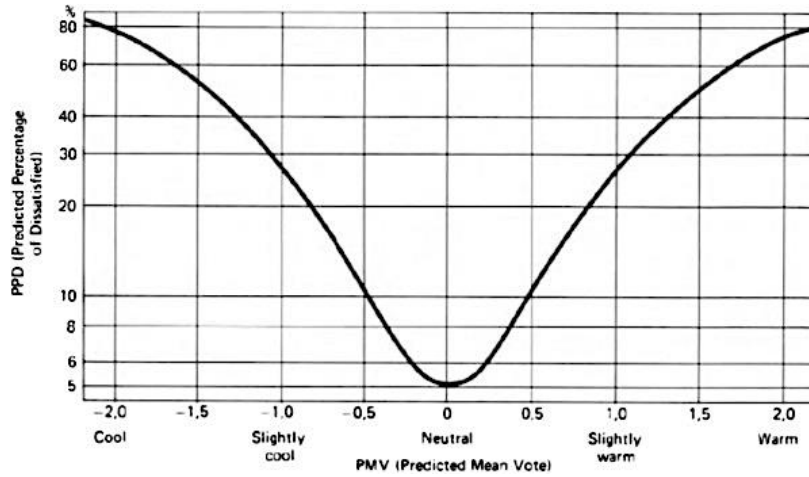


Figure 7: The relationship between PPD and PMV (Ekici & Atilgan, 2013).

$$PPD = 100 - 95e^{(-0.3353 PMV^4 - 0.2179 PMV^2)} \quad (\text{Equation 2})$$

- PPD = Predicted Percentage Dissatisfied
- PMV = Predicted Mean Vote (ranging from -3 to +3)

Krüger et al. (2017) adjusted the PPD calculation in their research for outdoor applications by increasing the minimum value to 12% (Equation 3), as they found that even under optimal outdoor conditions, this level of dissatisfaction was the baseline. This higher baseline reflects the greater variability of outdoor environments and the wider tolerance range of thermal perception outdoors. Higher minimum values may also occur in different settings, as each population has its own specific tolerance to heat and cold.

$$PPD_{(adjusted)} = 100 - 88 e^{(-0.3353 PMV^4 - 0.2179 PMV^2)} \quad (\text{Equation 3})$$

The PMV/PPD model forms the basis for international thermal comfort standards like ISO 7730 (ISO = International Organization for Standardization) and ASHRAE Standard 55. PMV values between -0.5

to +0.5 are deemed acceptable, corresponding to a maximum PPD of 10%. An additional 10% net increase in PPD has been added due to potential local discomfort, resulting in a thermal acceptability threshold of at least 80% as a guideline (Olesen & Parsons, 2002). Nonetheless, it is important to recognise the limitations of the PMV/PPD model. It assumes steady-state conditions and limited personal or behavioural adaptation, making it less suitable for outdoor environments where thermal conditions fluctuate rapidly, and individuals tend to frequently engage in adaptive behaviours. As a result, alternative models are often preferred for assessing outdoor TC, as will be discussed in the following sections after the Wet-bulb-globe Temperature.

2.2.3 Wet-bulb-globe Temperature

An additional index, more focussed on heat stress risk, is the wet-bulb-globe temperature (WBGT). Developed in the 1950s, WBGT is a simplified index easily calculated with the use of three thermometers, a natural wet-bulb, a globe and a dry-bulb (Budd, 2007). This combination accounts for the main factors of the thermal environment (air temperature, humidity, radiant heat and air movement). However, it does not simulate the full thermoregulation of the human body. It is also expressed in °C, but this is not the perceived temperature of people as it is with PET or UTCI.

Some studies have stated that WBGT can be estimated using only air temperature and humidity alone (Budd, 2007). Radiant temperature and air movement show inadequate responses, and it underestimates the stress of restricted evaporation. As a result, heat stress is often underestimated by WBGT (Alfano et al., 2014). The basic empirical formula does not accurately reflect the complex interactions between environmental conditions and human thermoregulation. Consequently, it is often considered to be too simplistic for thermal comfort or heat stress assessments, resulting in a growing consensus to move on to more complex indices like PMV and UTCI (Brocherie & Millet, 2015; Parsons, 1995; Steeneveld et al., 2011).

2.2.4 Physiological Equivalent Temperature

To address the challenges associated with quantifying outdoor TC, multiple other indices have been developed. Among the most widely used are PET and UTCI. The Physiological Equivalent Temperature (PET) is a commonly applied index designed to assess the human thermal perception in outdoor settings. Developed based on the Munich Energy Balance Model for Individuals (MEMI), PET is grounded in a full human energy balance approach (Höppe, 1999). It expresses the complex interaction of climatic parameters such as air temperature, humidity, wind speed, and MRT as a single equivalent temperature value that corresponds to the conditions of a typical indoor environment. This value corresponds to the air temperature at which, under standard indoor settings (no wind, no solar radiation), the heat balance of the human body would be maintained with the same core and skin temperatures as under the actual outdoor conditions.

A key advantage of PET is that it is expressed in degrees Celsius (°C) (Matzarakis et al., 1999), which makes it easily understandable and directly comparable to common weather reports and indoor thermal experiences. This interpretability supports its broad application in urban climatology, public health, and the design of outdoor spaces.

PET has become particularly useful for evaluating the thermal impacts of urban design features, such as tree canopies, surface materials, and building orientation. It is also widely used to evaluate the effectiveness of climate adaptation strategies in urban environments. It is especially relevant for studying the urban heat island effect, as it captures both meteorological and physiological factors influencing outdoor thermal comfort. Additionally, it is applicable across different climates (Matzarakis et al., 1999), when properly calibrated to the respective region (Krüger et al., 2017; Ribeiro et al., 2022). For instance, Matzarakis et al. (1999) found that the difference in thermal neutrality was different at different PET values for Glasgow (14.2 °C) and Curitiba (19.2 °C), indicating regional variability in thermal adaption. Table 1 represents a PET classification for physiological stress level for western and central Europe.

Table 1: Physiologically equivalent temperature (PET) for different grades of thermal sensation and physiological stress on human beings for western and central Europe (Basarin et al., 2020).

PET (°C)	Thermal sensation	Physiological stress level
<4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
>41.1	Very hot	Extreme heat stress

The calculation of PET requires both meteorological input parameters and physiological constants. Key inputs include air temperature, MRT, wind speed, and relative humidity. These are combined with standard assumptions for a reference individual: typically a 35-year-old male, weighing 75 kg, 1.75 m in height, with a clothing insulation of 0.9 clo and performing light activity at a metabolic rate of 80 W. Due to the complexity of human energy balance modelling, PET is typically calculated using specialized software such as RayMan or the BIO-met module integrated in ENVI-met, which simulate the physiological responses of the body under varying environmental conditions (Matzarakis et al., 2006; Matzarakis et al., 2009).

2.2.5 Universal Thermal Climate Index

The Universal Thermal Climate Index (UTCI) was developed in 2009 through an international scientific collaboration under COST Action 730 (Błażejczyk et al., 2010), in response to the limitations of earlier thermal indices. Many of these older indices relied on simplified assumptions and lacked consistency across climates and populations (Jendritzky et al., 2011). UTCI was specifically designed to provide a standardized, physiologically meaningful, and globally applicable index for assessing outdoor TC and

heat stress. It expresses complex microclimatic conditions, including air temperature, wind speed, humidity, and MRT, as a single value of equivalent temperature. It is defined as the temperature of a reference environment that would induce the same physiological response as the actual conditions.

Unlike traditional indices, UTCI is grounded in an advanced thermophysiological model known as the UTCI-Fiala model (Błażejczyk et al., 2013), which simulates the dynamic interaction between the human body and its thermal environment. This model separates human thermoregulation into two interacting systems: a passive system and an active system. The passive system consists of a detailed, multi-layered, and multi-segmental representation of the human body. It includes 12 body elements and 187 tissue nodes, allowing for heat exchange modelling across different tissue layers and simulating the anatomical and physiological properties of an average person (73.5 kg, 14% body fat, and a Dubois surface area of 1.86 m²). The active system models thermoregulatory responses governed by the central nervous system, including vasoconstriction, vasodilation, shivering, and sweating. These responses are based on physiological experiments that cover a wide range of environmental exposures, from cold to hot conditions and from rest to intense levels of physical activity. The calculation of UTCI is based on a sixth order polynomial regression function, integrating the four environmental TC parameters (ENVI-met, n.d.; UTCI Homepage, n.d.). Another key feature of UTCI is the inclusion of a state-of-the-art dynamic clothing model that reflects behavioural adaptation by adjusting clothing insulation based on ambient temperature (Havenith et al., 2011; Havenith et al., 2015). This component further enhances the applicability of UTCI across various climates.

UTCI provides a continuous scale of thermal stress categories, ranging from extreme cold stress to extreme heat stress (Pecelj et al. 2018). It is expressed in degrees Celsius (°C), making it intuitive just like PET. Table 2 represents the UTCI classification. Due to its sensitivity to small changes in environmental parameters, especially wind and radiation (Błażejczyk et al., 2011; Bröde et al., 2011), UTCI is particularly effective for outdoor TC analysis. Its strong physiological basis standardized operational procedure, and broad applicability have led to its use in biometeorology, urban climate studies, public health, and climate-responsive urban design (Jendritzky et al., 2011). UTCI allows for meaningful comparisons between different geographic locations (Błażejczyk et al., 2011), making it a powerful tool for evaluating heat stress, guiding urban planning, and informing climate adaptation strategies.

Table 2: UTCI classification based on Pecelj et al. (2018).

UTCI (°C)	Thermal sensation	Physiological stress level
<-40	Extremely cold	Extreme cold stress
[-40,-27]	Very cold	Very strong cold stress
[-27,-13]	Cold	Strong cold stress
[-13,0]	Cool	Moderate cold stress
[0,9]	Slightly cool	Slight cold stress
[9,26]	Comfortable	No thermal stress

[26,32]	Slightly warm	Moderate heat stress
[32,38]	Warm	Strong heat stress
[39,46]	Hot	Very strong heat stress
>46	Very hot	Extreme heat stress

2.2.6 Comparison of Different Indices

A study by Błażejczyk et al. (2011) evaluated the performance of UTCI against a range of other established thermal indices. The results showed that all indices derived from the human heat budget, such as PET and UTCI, correlated strongly to the other indices. Indices based on simple formulas showed weaker relationships. UTCI proved to be highly adaptable, accurately representing various climates, weather conditions and geographic locations. Furthermore, in terms of the microclimatic scale, UTCI was found to capture the variability of thermal conditions more effectively than the other indices. UTCI is very sensitive to changes in environmental parameters: temperature, solar radiation, humidity and especially wind speed. In contrast, PET and other discussed indices are more closely related to air temperature, especially as their assumptions on clothing insulation differ strongly from the state-of-the-art clothing model used in UTCI.

Fischereit & Schlünzen (2018) deemed both PET and UTCI suitable for use in obstacle-resolving meteorology models (ORMs). ORMs are high-resolution atmospheric simulation tools designed to explicitly represent urban elements such as buildings, trees, and other surface features. Unlike traditional models that approximate these obstacles, ORMs simulate airflow, temperature, and radiation at fine spatial and temporal scales (Blocken, 2015). This allows for detailed analysis of microclimatic conditions, particularly at pedestrian level, making them highly suitable for evaluating urban heat, thermal comfort, and the effectiveness of local climate adaptation strategies. Despite the development of UTCI in 2012, PET remains the most widely used index for assessing outdoor TC in these ORMs (Fischereit & Schlünzen, 2018). This preference is largely due to the flexibility and practicality of PET: it is easier to modify and apply across different climates, and there is a well-established presence in literature, which facilitates comparability of study results (Potchter et al., 2018; Fischereit & Schlünzen).

2.3 Heat Stress Consequences

As stated in the introduction, the UHI effect has multiple consequences for public health, environmental quality, energy demand and urban biodiversity (Santamouris, 2019; Oke et al., 2017). One of the most notable impacts is on outdoor TC (Qaid et al., 2016). Elevated urban temperatures can directly contribute to increased TD, heat stress, and the worsening of pre-existing medical conditions, especially among vulnerable groups such as elderly, children, and individuals with chronic illnesses (Arifwidodo et al., 2019; Campbell et al., 2018). More broadly, the health effects of UHI can be categorized as both direct, such as an increased rate of mortality and morbidity as well as lower life satisfaction, and indirect, through the aggravation of cardiopulmonary and respiratory diseases, including ischemic heart disease, cerebrovascular disease, and sleep disturbances (Vujovic et al., 2021). TD can significantly influence

residents' outdoor activities (Li et al., 2024). Prolonged exposure to urban heat can lead to reduced physical activity, compounding physical and mental health issues (Vujovic et al., 2021). Evidence suggests that even marginal increases in temperature can have visible effects on health outcomes. For example, Goggins et al. (2012) stated that each 1 °C rise above 29 °C corresponds to an increase in mortality by 4.1%. During the summer of 2003, more than 70 000 additional deaths occurred in Europe (Robine et al., 2007).

Apart from public health, the UHI effect contributes to enhanced pressure on energy systems, primarily due to rising demand for air conditioning. In Athens the UHI caused a doubling of the buildings cooling loads and a tripling of peak electricity loads (Santamouris et al., 2001). Similarly, other cities like Hong Kong (Chan, 2011), London (Kolokotroni et al., 2011; Kolokotroni et al., 2006), Boston (Street et al., 2012), and Beijing (C. Li et al., 2014) show an increased cooling load, although the impact of UHI is often smaller compared to Athens. The impact of UHI shows significant inter-city variations, but also intra-city variations with the strongest impacts in the urban centre (X. Li et al., 2019). This increased electricity demand indirectly increases greenhouse gas emissions and air pollution by electricity generation in power plants, with primary pollutants including sulphur dioxide (SO₂), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and mercury (Hg) (United States Environmental Pollution Agency, n.d.). More directly, UHI worsens air quality by its role in the formation of ground-level ozone and urban smog. Elevated temperatures accelerate photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs), enhancing the production of tropospheric ozone (Vujovic et al., 2021; Oke et al., 2017). For instance, in Los Angeles, it has been observed that for every 1 °C increase above 22 °C, smog incidents rise by approximately 5% (Akbari, 2005). Additionally, limited atmospheric mixing and reduced nocturnal cooling in urban areas can trap pollutants near the surface, further degrading air quality and increasing health risks (Oke et al., 2017). This contributes to the so-called Urban Pollution Island as cities already have an increased level of air pollution (Cichowicz & Bochenek, 2024).

Lastly, the UHI can also degrade biodiversity by disrupting species composition and habitat suitability (Esperon-Rodriguez et al., 2021). In general, urban biodiversity is lower compared to rural biodiversity with the UHI as a contributing factor, combined with human activity and lack of space (Jogan et al., 2021). It affects species richness by filtering species according to their thermal affinity (Caban et al., 2024). Increased temperatures deteriorate water quality by disrupting chemical and biological processes (Phelan et al., 2015).

2.4 Heat-related Legislation

Air quality is governed by well-established, legally binding regulations in contrast to UHI mitigation and TC regards. The European Union has implemented strict directives, such as the Ambient Air Quality Directive ("Directive 2008/50/EC of the European Parliament and of the Council," 2008), which sets limit values for various pollutants like PM₁₀, PM_{2.5}, NO₂, and O₃ to protect public health. The aim of this directive is to meet the air quality guidelines provided by the World Health Organization (EU Adopts Pioneering Air Pollution Law for Europe - Clean Air Fund, 2024). These standards are enforced through

national legislation and monitored via standardized air quality networks. By comparison, UHI and thermal comfort policies are less formal and often addressed through voluntary urban planning strategies, local greening initiatives, or integrated climate adaptation plans. These incentivised actions have no binding temperature or comfort thresholds, so they are often voluntary. This contrast illustrates a regulatory gap, despite the growing evidence that heat stress, like air pollution, poses serious public health risks in urban environments.

In the context of occupational heat exposure, more structured standards exist (Alfano et al., 2014). The Wet Bulb Globe Temperature (WBGT) index is internationally recognized and frequently applied in practice. According to ISO 7243, WBGT serves as a guideline to assess workplace heat stress and define appropriate work-rest cycles and protective measures, particularly in outdoor or high-heat settings (Wilde, 2023). Additional standards like ISO 7730 (which uses the PMV/PPD model) and ASHRAE Standard 55 are widely used in indoor workplace assessments, especially for office environments and controlled industrial settings as technical guidelines for good practice in building design (Motmans, 2017; Mursic, 2024). These are voluntary international standards, only legally enforceable when adopted or referenced by national legislation, building codes or regulatory frameworks (ASHRAE et al., 2020).

While Belgium currently lacks a national law specifically targeting the UHI effect or outdoor TC, various regional and local policies have emerged to address these growing challenges. For example, in the climate plan of the city of Antwerp urban heat is a major topic (Stad Antwerpen, 2020). It includes green roof mandates, requirements for permeable surfaces, and heat-conscious renovation guidelines for its inhabitants (Gemeentelijke Stedenbouwkundige Verordening - Bouwcode, n.d.; Antwerpen Voor Klimaat, n.d.). Similarly, Liège's "Plan Canopée" focuses on expanding urban tree canopy to mitigate local temperature increases and improve thermal comfort (Plan Canopée — Liège, n.d.).

At the European level, several major frameworks support and encourage UHI and TD mitigation through urban greening, spatial planning, and climate adaptation. The EU Strategy on Adaptation to Climate Change emphasizes the importance of making cities more resilient to heat stress through nature-based solutions (European commission, 2021), while the European Green Deal and the proposed Nature Restoration Regulation reinforce the expansion of urban green spaces to combat overheating and biodiversity loss (The European Green Deal: A Growth Strategy That Protects the Climate, 2019; The EU #NatureRestoration Law, 2024). Although not enforceable as strict legal mandates, these frameworks can influence national and local planning strategies across Europe.

2.5 Heat Mitigation Measures

Solutions to mitigate the UHI effect have a direct impact on the urban energy balance (Formula 1). To effectively address both UHI and TC challenges, a combination of long-term urban planning and short-term adaptive strategies is required. Long-term strategies involve structural changes to the urban fabric, while short-term measures are more flexible and can be implemented with minimal intervention.

For instance, urban parks have been shown to be 1-2 °C cooler compared to non-vegetated urban areas with temperature differences of up to 7 °C (Ghale et al., 2025). This is because an urban park typically integrates multiple mitigation measures simultaneously, such as vegetation, trees and permeable surfaces. In the following section, the effectiveness of multiple individual measures are discussed. These include both infrastructural interventions and nature-based solutions (Lai et al., 2019).

2.5.1 Trees

Planting trees is one of the most widely implemented and effective strategies to improve TC and mitigate UHI (Lauwaet et al., 2020). They provide shade, drastically reducing MRT in the shaded areas due to decreased solar radiation exposure (Coutts et al., 2015; Rahman et al., 2019). Additionally, they enhance latent heat flux through evapotranspiration, causing the sensible heat flux to decrease. Numerous studies have examined the thermal and co-benefits of (urban) trees, as they contribute to improved air quality, aesthetic value, and mental well-being as well (Bolund & Hunhammar, 1999; Cimburova & Pont, 2021). Coutts et al. (2015) measured the effect of street trees in Melbourne, Australia during a heatwave and found a maximal UTCI reduction of 6°C and a maximal air temperature reduction of 1.5 °C. The provided shade can reduce surface temperature of concrete by up to 19 °C and globe temperatures (the temperature measured by a grey/black globe thermometer to estimate MRT temperature ; Thorsson et al., 2007) by 5 – 7 °C (Armson et al., 2012). Other studies assessing the impact of urban trees on UHI and TC show similar results (Shahidan et al., 2012; Lauwaet et al., 2020; Herath et al., 2017; Kim et al., 2018; Bande et al., 2019; Razzaghmanesh et al., 2021; Coutts et al., 2015).

Studies regarding different tree species have also been extensively studied. According to Rahman et al. (2019) the foliage and canopy density are the most important factors for cooling capacity. Hence, tree species with a high leaf area index (LAI) will be preferred. The higher LAI provides more surface area for transpiration and more shading. As an example, *Tilia cordata* with a LAI 35% higher than *Robinia pseudoacacia*, prevented more incoming radiation (Rahman et al., 2020). Additionally, trees with diffuse-porous wood, like *Tilia cordata*, can maintain a more reliable water flow, than ring-porous wood, like *Robinia pseudoacacia*, enabling more consistent evaporative cooling of the air. Diffuse-porous wood has relatively uniform pores distributed evenly across the growth ring. In contrast, ring-porous wood has large pores concentrated in the earlywood portion of each growth ring, which is formed at the beginning of the growing season, and smaller pores in the latewood portion. However, ring-porous wood is more drought resilient and has a higher water efficiency during peak times (Bader et al., 2022; Hafner, 2023). The maximal air temperature reduction of *Tilia cordata* was 2.8 °C, while the maximal reduction of the *Robinia pseudoacacia* was 1.9 °C. Surface temperatures of asphalt were more drastically reduced due to shade and radiation blocking, with 12.9 °C for *Robinia pseudoacacia* and 23 °C for *Tilia cordata*. This resulted in a PET difference of 4 °C and 11 °C respectively for *Robinia pseudoacacia* and *Tilia cordata* under their canopies (Rahman et al., 2020).

Multiple studies stress the positive effect of older, bigger trees (Park et al., 2021; Rahman et al., 2019; Z. Li et al., 2022). They provide more ecosystem services compared to newly planted trees. Sun et al. (2017) demonstrated that the presence of taller trees (20 m) significantly reduced PET. Specifically, a

10% increase in tree-covered area was associated with a 0.77 °C decrease in PET compared to areas with no trees. Trees of 10 m had a weaker and no significant effect in this case. Although lower trees (10 m) can improve thermal comfort through similar shading effects as taller trees (20 m), they may also reflect more sunlight and reduce ventilation, as their lower canopies leave less open space for air circulation beneath them. However, in urban areas, hollow-bearing trees, which are often older and bigger trees, are in steep decline due to short management cycles and safety concerns, leading to long-term ecological and ecosystem service losses that cannot be easily offset by new plantings. 87% decline in hollow-bearing trees over 300 years in urban greenspaces is expected under current management practices (Roux et al., 2014). In a worst-case scenario, these trees could be completely lost within 115 years. Urban trees have a mean life expectancy of 19 to 28 years, which is considerably lower than rural or forest trees (Roman & Scatena, 2011). Mortality in the first 5 to 10 years within planting brings down the average drastically (Hilbert et al., 2019). Additionally, the UHI effect contributes to the accelerated growth rates observed in urban trees by creating warmer microclimates that extend the growing season (Moser et al., 2017; Singh et al., 2018), especially in moderate to cool climates. Smith et al. (2019) discovered that urban trees in Boston exhibited mean diameter growth rates nearly four times higher (0.78 ± 0.02 cm/year) than those in nearby rural forests (0.21 ± 0.02 cm/year). Despite accelerated growth, the urban trees experienced more than double the mortality rates (3.06 ± 0.25 % per year) compared to rural trees (1.41 ± 0.04 % per year), leading to higher costs for tree management and a reduction in long-term ecosystem services.

Urban trees must be carefully selected as not all trees are suitable to grow in the harsh conditions urban areas provide (Augustinus et al., 2024). Limited space, increased temperatures, drought, vandalism, soil degradation are challenges urban trees must undergo (Czaja et al., 2020). Additionally, it is advised to plant a wide arrange of tree species to increase biodiversity and pest resilience (Jactel et al., 2020; Augustinus et al., 2024). Tree groups show greater cooling effects than individual urban trees (Terrani et al., 2024). On the other hand, trees can be hard to implement, especially in urban areas. In street canyons with low wind speed, they can increase air pollution by trapping the pollutants and decreasing wind speeds or space can be too constrained. Other options must be considered when these problems arise.

2.5.2 Low Vegetation

In this thesis, the focus on low vegetation is mainly on grass, bushes, and hedges. This type of vegetation contributes to evapotranspiration but provides limited shading. Although less effective than trees in mitigating UHI and improving TC, it can help reduce surface temperatures (Z. Wang et al., 2015; Liu et al., 2023; Wei et al., 2024; J. Li et al., 2020; Rahman et al., 2020). Combining trees with grass can have an added positive effect, compared to trees or grass alone (Shashua-Bar et al., 2010; Armson et al., 2012), but it also requires the highest water demand. So, in water-scarce areas, it should be evaluated whether the extra water usage is worth it.

Healthy vegetation typically has equal or lower temperatures to its surrounding atmosphere during hot periods, while manmade urban materials often exhibit higher temperatures (Boujelbene et al., 2023; Armson et al., 2012). As illustrated in Figure 8, asphalt can reach temperatures of nearly 20 °C, while

grass in full sun had peak temperatures 0 °C to 3 °C lower than the air temperature. As such, low vegetation has a major effect on surface temperatures and to a lesser extent on the surrounding air temperature.

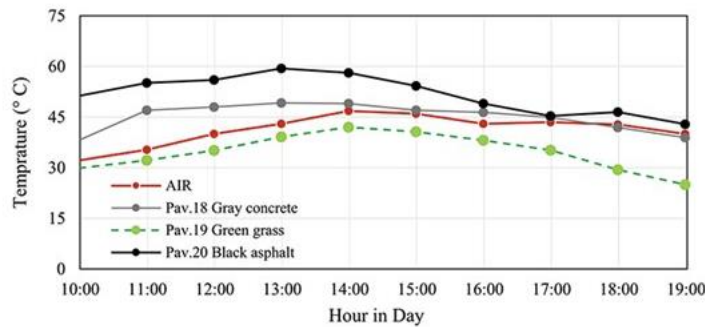


Figure 8: Comparison between concrete, grass, asphalt and surface air temperature (Boujelbene et al., 2023).

Increased evapotranspiration from vegetation contributes to higher local relative humidity by releasing additional water vapor into the air through both evaporation from surfaces and transpiration from plant leaves. Sensible heat flux is reduced by the increase in latent heat flux. While this process is beneficial for mitigating urban heat, it can also have mixed effects on human thermal comfort (Meili et al., 2021). In hot-humid climates or during heatwave periods elevated relative humidity can impair the body's ability to regulate temperature through sweat evaporation, potentially leading to increased TD. Thus, while evapotranspiration is a key component of cooling in urban microclimates, its influence on perceived comfort must be carefully considered, particularly in climates where high humidity levels are already a concern. Due to its maritime climate, Belgium experiences year-round relatively high humidity, which can amplify TD during warm periods by inhibiting sweat evaporation and reducing the body's natural cooling efficiency (Oke et al., 2017; World Bank Climate Change Knowledge Portal, n.d.).

2.5.3 Depaving & Surface Materials

In Antwerp, the impervious surface ratio is 41.3% (Departement Omgeving Vlaanderen, 2024), which contributes tremendously to the UHI. Not only does paving introduce materials with unsuited thermal properties, it takes up space that could be used for low vegetation. Additionally, it compacts the soil, making the growing conditions of trees even worse (Czaja et al., 2020).

One of the key findings of the study by Azodo et al. (2020) is the significant influence of land cover materials on outdoor thermal comfort, as measured by the Physiological Equivalent Temperature (PET). They compared microclimatic conditions over four common surface types: tarmac, grass, soil, and concrete, and found clear differences in PET values based on surface material properties. Hard, impervious surfaces such as tarmac and concrete tended to exhibit higher PET values, especially during the afternoon hours. This is attributed to their low albedo (reflectivity) and high thermal mass, which cause them to absorb and store more solar radiation during the day and release it slowly, resulting in higher surface and air temperatures near the ground. These materials also lack the capacity for evaporative cooling, further intensifying heat stress conditions in the surrounding area. Sun et al. observed a significant increase of 0.57 °C in PET when paved ground was increased by 10%. In

contrast, grass and soil surfaces demonstrated significantly lower PET values, particularly during peak heat hours. These surfaces have higher albedo and support evapotranspiration, which contributes to local cooling. The vegetative cover provided by grass also creates a buffering effect by shading the soil and reducing the intensity of direct solar radiation reaching the surface. To minimize surface temperatures, shaded permeable are preferred (Park et al., 2021).

Although high-albedo pavements are effective in reducing surface and air temperatures, they can worsen thermal comfort by increasing the MRT due to reflected solar radiation. In contrast, low-albedo pavements absorb more radiation but reduce the amount reflected onto pedestrians, resulting in lower MRT and improved thermal comfort as measured by PET. Karimi et al. (2020) found that despite their higher surface temperatures, low-albedo pavements performed better in terms of outdoor thermal comfort in a park environment.

Permeable pavements are another ideal solution for still providing paved surfaces while reducing temperature compared to impermeable pavements. Unlike conventional impervious surfaces such as asphalt or concrete, permeable materials (e.g., porous asphalt, permeable concrete, or interlocking pavers) enable rainwater and runoff to pass through, which reduces surface water accumulation and supports evaporative cooling from the sublayers. This process helps lower surface temperatures, especially during hot days when traditional pavements tend to store and re-radiate large amounts of heat. Moreover, permeable pavements typically have higher albedo and lower heat storage capacity, which further limits surface heating. By mitigating excessive surface temperatures and enhancing local latent heat fluxes, these pavements help to reduce thermal discomfort for pedestrians, particularly in urban areas with limited vegetation (Vujovic et al., 2021).

2.5.4 Extra Mitigation Strategies

This section briefly discusses some other commonly used strategies, which are not specifically applied in this thesis.

2.5.4.1 *Water Bodies*

Water can cool the air through evaporation. Furthermore, it has a high thermal capacity resulting in lower temperatures than its surrounding buildings and grounds (Lai et al., 2019). Measurements by Chatzidimitriou and Yannas (2015) showed a 20 °C difference between water (26.2 °C) and asphalt (46.2 °C) surface temperatures. Additionally, the MRT was 4 °C lower. The lower temperatures of the water bodies provide higher temperature gradients for convective heat transfer between air and water (Lai et al., 2019). Nearby water bodies can cool the air by 1 to 2 °C (Manteghi et al., 2015).

2.5.4.2 *Cool Roofs & Green Walls*

Traditional roofs heat up very quickly during the day, because of low albedo and direct solar radiation. During the night they cool down quicker than enclosed streets, because the longwave radiation does not get blocked by ground objects. Green roofs have the potential to mitigate the UHI by, once again, evapotranspiration and a higher albedo compared to traditional roofs. The peak surface temperatures are reduced when a green roof is installed. Figure 9 compares a temperature profile during the day of

a traditional roof with gravel with a green roof. Traditional roofs vary highly in temperature during the day, reaching peak surface temperatures up to around 80 °C in summer (Hermy, 2016). Green roofs have a more consistent temperature, not reaching higher temperatures than around 35 °C. During winter, the green roof also shows more consistent, but slightly higher surface temperatures. For air temperature the effect all depends on the implemented scale. On urban scale the potential of green roofs is higher than on a single roof, showing temperature reductions to up to 3 °C (Santamouris, 2012; Smith & Roebber, 2010). Pedestrian-level air temperature often shows no change, only when considering low-rise buildings, a decrease of 0.4 °C to 1.7 °C is feasible (Jamei et al., 2023). Roof-top level TC is also enhanced, but for TC of pedestrians, green roofs can often be neglected (Chen et al., 2009; Taleghani et al., 2016). The difference in height is too big to have a significant influence on the TC of outdoor people. Green roofs can, however, improve indoor TC more effectively (Taleghani et al., 2014).

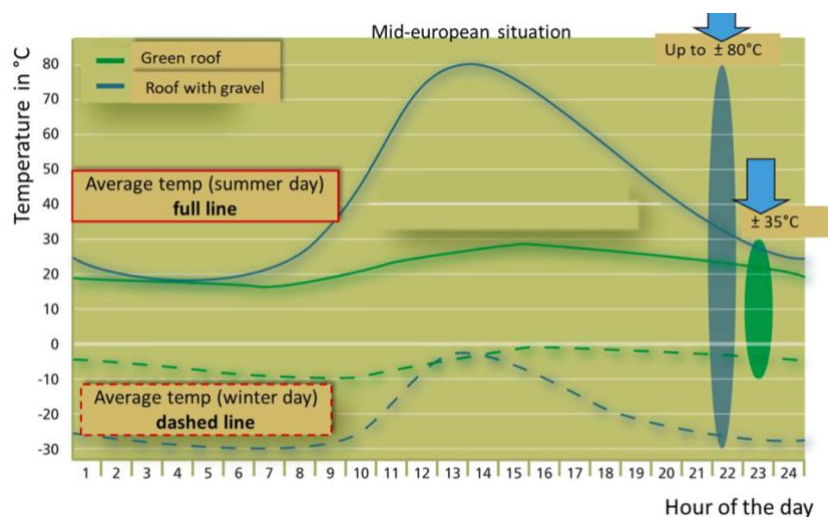


Figure 9: Surface temperatures of a green roof vs a roof with gravel during both the winter and summer (Hermy, 2016).

Looking at the most used roofing materials, like bitumen membrane, concrete tiles and ceramic tiles, they show rather low albedo values, with bitumen reflecting the least solar radiation (Wyrd et al., 2023; Parker et al., 2000; Pisello, 2015). Similarly to green roofs, there is potential in increasing the albedo to increase, not only indoor thermal environments (Taleghani et al., 2014; Wang et al., 2023), but also outdoor temperatures. Several tactics like coatings or using white paint increase the albedo. An example of this in practise is the NYC CoolRoofs program launched in 2009 in New York, where over half a million square meters of rooftop were covered with a white, reflective coating (NYC CoolRoofs - C40 Cities, 2015). White (and green) roofs have a cooling effect of 20 °C to 30 °C on surface temperatures when compared to black roofs (Frei, 2023).

As green walls are fundamentally composed of low vegetation, the same principles apply to them as to low vegetation or grass-covered pavements, as discussed earlier in this thesis. The surface temperature will be drastically reduced for green walls compared to bare walls (reduction up to 18.9 °C based on a literature review by Koch et al. in 2020), with a limited effect on the ambient temperature (Wong et al., 2009), especially further away from the wall. Models showed that green walls outperformed green roofs

for street-level cooling in street canyons across various climates (Koch et al., 2020). Evapotranspiration, higher albedo and shade on the wall are the most important factors causing the temperature reductions.

2.5.4.3 *Urban Morphology and Planning*

Zhou & Chen (2018) investigated how different urban development patterns influence the UHI. They looked into 2 potential future urban morphology scenarios, one being a high-rise scenario characterized by tall buildings with lower density and two being a high-density scenario characterized by shorter buildings with higher density. The high-rise scenario provided more shading, especially at pedestrian level. At peak summer hours (midday), the solar elevation angle is high making the shading effect of high buildings more significant. This resulted in lower observed temperatures up to 1 °C during the day, further confirmed by other studies (Liu et al., 2023). The high-density case had lower temperatures before dawn, assumingly because there is a higher nighttime cooling effect in this scenario. The high buildings in the high-rise scenario obstruct air flow, disrupting the cooling of the urban area. Still the high-rise scenario has lower critical wind speed values (7.1 - 10.7 m/s compared to 7.7 - 16.9 m/s), meaning lower windspeeds are needed to mitigate the UHI. Notably, a high-rise scenario provides additional surface space for other mitigation measures like low vegetation and trees, potentially further decreasing the UHI effect and increasing the TC of pedestrians. Conversely Xiang et al. (2023) found that high-rise buildings exhibited higher outdoor temperatures compared to low-rise buildings. So general rules of thumb are difficult to obtain, since urban morphology influence is often very case-specific (Schmidt, 2024). Additionally, street orientation can drastically influence the effect of different metrics on thermal comfort (Ma et al., 2022).

The sky view factor (SVF), a measure of the openness of a location (0 = completely obstructed, 1 = completely unobstructed; Miao et al., 2019), also plays an important role in the context of the UHI effect and TC. A non-linear relationship is observed since low and high SVF tend to mitigate the UHI, while a moderate SVF tends to increase the UHI (Liu et al., 2023). Low SVF reduces solar radiation during the day, due to enhanced shade (Tong et al., 2017). High SVF allows for more longwave radiation escape at night but increased solar radiation during the day leading to higher daytime temperatures. Moderate SVF can trap heat during the day since there is less shade, causing materials to heat up during the day, and restrict nighttime cooling. It should be noted however that the SVF alone is often not a reliable predictor for TC (Karimi et al., 2020).

2.6 Computational Fluid Dynamics

As discussed before, multiple approaches exist for studying the UHI effect, including field measurements, thermal remote sensing, and small-scale modelling using wind tunnels. In this thesis numerical three-dimensional modelling or more specifically, computational fluid dynamics (CFD) will be used (Blocken, 2015). The primary strength of CFD lies in its predictive methodology, enabling the simulation of complex physical interactions that are difficult to capture through measurements alone (Huo et al., 2021; Toparlar et al., 2017).

The yearly number of studies regarding CFD analysis of the urban microclimate has increased rapidly (Toparlar et al., 2017). Mainly because CFD provides detailed spatial and temporal insight beyond what

measurements alone can provide and the improvement of computers and calculation methods (Blocken, 2018). Accurately assessing urban mitigation strategies requires advanced modelling of urban airflow and pollutant dispersion, as these processes are shaped by complex urban geometries and highly turbulent flows.

The basis of CFD modelling relies on solving the Navier-Stokes equations to accurately represent the fundamental physical laws, specifically conservation of mass, momentum and energy (Blocken, 2015). As these are analytically unsolvable, approximate forms are solved. Two main options are common in literature, Large Eddy Simulations (LES) and Reynolds-Averaged Navier-Stokes (RANS). While LES explicitly resolves the large turbulent structures in the flow (eddies), they are computationally demanding. RANS is a more practical alternative (Blocken et al., 2016; 2018), where the effects of turbulence are averaged over time, reducing computational costs. More specifically, in RANS the flow variables are decomposed into a mean (time-averaged) and fluctuating (turbulent) part. This introduces new unknowns called Reynolds stresses, representing the effects of turbulence on the mean flow. These Reynolds stresses cause the RANS equations to not form a closed set as there are more unknowns than equations. Turbulence modelling is required to obtain closure, typically through models like $k-\epsilon$ or $k-\omega$ which introduce additional equations to complement the set.

The most common approach is RANS in steady form (SRANS), assuming the flow does not change over time (Franke et al., 2007). To retain time-dependent variations, one can employ unsteady RANS (URANS) or hybrid models, combining LES and RANS. The latter employs LES in the whole domain, except for near wall regions where URANS is used. Turbulent eddies near walls are very small, leading to possible high computational cost when using LES there. To solve the equations, the simulation domain is discretized into a three-dimensional grid, called a mesh with physical variables calculated at the centre points of each grid cell. The resolution of this grid, that is, the spacing between grid points, directly influences the accuracy and stability of the simulation results. In this study, the best practice guidelines of COST Action 732 (Franke et al., 2007) were taken into account wherever possible to ensure appropriate mesh quality and numerical reliability.

2.7 Previous Studies and Research Gaps

Originally the first publications around the topic of urban heat appeared in the 1970s, with limited studies for the next 40 years (Schmidt, 2024). Due to the more frequent occurrence of heat waves, evidence of climate change and rapid urbanization this topic is showing a positive trend. Starting from 2010 the publications were growing exponentially, with around 50% of literature on this topic being published between 2020 and 2023. Other relevant topics like urban morphology + thermal comfort and UHI show similar trends (Y. Chen et al., 2021; Huang & Lu, 2017). Appendix 1 gives a non-extensive overview of several relevant papers in the field of thermal comfort. Still Elnabawi and Hamza (2024) concluded that more studies on outdoor TC are needed, particularly those integrating industry 4.0 principles, such as smart sensing, data integration and computational modelling.

In general, the effects of urban morphology and vegetation are highly context-specific and should be evaluated with care. Comprehensive site assessments to implement the right trees and discover the

trade-offs with other measures are required (Rahman et al., 2019). Specific CFD simulations to predict the local microclimate are a great way to investigate how certain measures perform.

Numerous studies have evaluated UHI mitigation and TC improvement strategies, using both field measurements and microclimate simulations. However, most research has focused on urban areas in arid or tropical climates where dynamics and vegetation responses differ from those in temperate, maritime environments. Additionally, while simulation tools like ENVI-met are well-established, many studies lack (proper) validation (Toparlar et al., 2017). Studies with no validation are often comparative studies where multiple scenarios are evaluated to discover the best-case scenario. Park et al. (2021) outlined the need for studies integrating all site-level thermal variables with the use of CFD models such as ENVI-met. Especially for thermal comfort, there is a lack of numerical studies with validation of multiple thermal variables. Often, the only validated variable is air temperature, while windspeed, MRT and relative humidity are overlooked. As these variables are significant for thermal comfort (Lai et al., 2019), validation of not only air temperature is desired (Elraouf et al., 2022). Finally, CFD is often used to design predictive scenarios (Toparlar et al., 2017), fewer studies have focused on comparing present data to the past before the transformation.

In contrast, this thesis provides a site-specific analysis of Zuidpark in Antwerp. The basis is microclimate modelling, with field measurements used for validation. The park exists now, making it possible to assess not just simulated conditions, but the actual effects of its transformation on UHI and TC with full detail of the implemented design. This will provide locally grounded insights into the cooling performance of the urban park and the enhancement of pedestrian thermal comfort. Aiming to support evidence-based design strategies for climate-adaptive public space planning in temperate urban contexts

2.8 Research Questions and Hypotheses

This thesis investigates the role of urban park development in mitigating heat stress and improving thermal comfort, using Zuidpark in Antwerp as a case study. The study addresses the following research questions:

- 1) Transformation effects
 - a) What is the influence of the transformation from a parking area into an urban park on:
 - i) air temperature / UHI effect?
 - ii) the thermal comfort of city dwellers?
 - (1) Specifically, what percentage of the park space remains within acceptable thermal comfort levels (during peak summer hours), compared to pre-transformation scenario?
- 2) Effect of tree maturity
 - a) What is the difference in UHI and TD mitigation between a recently developed park and a fully grown park with mature tree canopies?
- 3) Park vs. surrounding urban area
 - a) How do air temperature and TD levels within the park compare to those in the surrounding-built-up environment?

- 4) Optimal activity
 - a) Which Park zones offer the most favourable microclimatic conditions for different activities (resting, sports, walking), and do these locations align with the current park design?

Based on the literature review the following hypotheses are proposed:

- 1) Transforming a fully paved parking area into an urban park will reduce average air temperatures and mitigate the UHI effect.
- 2) Thermal comfort will improve after the park's implementation, with a greater share of the area remaining within acceptable PET thresholds during peak summer hours compared to pre-park conditions.
- 3) A fully grown park with mature tree canopies will provide significantly greater cooling and comfort benefits than a recently developed park.
- 4) Air temperature and thermal discomfort levels will be lower within the park than in the surrounding built-up urban area.
- 5) Vegetated zones, particularly grass fields and tree-covered areas, will be the most suitable locations for resting, sports, and walking.

3. Material & methods

3.1 Case Study Area

During the 20th century, three docks in the heart of Antwerp, Belgium, were closed and an uninspiring, grey square remained, serving as a parking lot. In the past couple of years, this area was transformed into Zuidpark (51° 12.63' N, 4° 23.43' E), and the parking lots moved underground, see Figure 10. The new park integrates green infrastructure to improve liveability in the dense city environment and contains playgrounds, sport grounds, grass fields, wadis, flower beds and many seating areas. In May 2025 it received both the public space award and the audience award, illustrating its public success. This transformation makes Zuidpark an ideal case study for this thesis to investigate whether the redevelopment has had a positive effect on the thermal environment.



Figure 10: The evolution of the “Gedempte Zuiderdokken” in Antwerp. In the 1950s, 2013 and 2025 respectively (Zuidpark, Antwerpen, 2025).

3.2 Microclimate model (ENVI-met)

For this thesis, the ENVI-met software (version 5.7.1) was used. It is a widely recognized three-dimensional microclimate model specifically developed for urban environments (Crank et al., 2018). The software is particularly suited for evaluating thermal comfort, urban heat island (UHI) mitigation, and vegetation-climate interactions on a microscale, with high spatial and temporal resolution. ENVI-met has been found to be the most used software for model numerical simulation for UHI, microclimates and heat studies (Schmidt, 2024). Additionally, ENVI-met is well known for being more user-friendly than other modelling software, while still providing validated results.

The ENVI-met modelling process begins with creating a detailed three-dimensional model domain, which includes the geometry and physical characteristics of urban elements such as buildings, streets, pavement materials, vegetation types and sizes, and soil conditions. This is complemented by the input of relevant meteorological boundary conditions, including initial air temperature, wind speed and direction, relative humidity, and solar radiation. ENVI-met’s physical core is based on a CFD approach, where non-hydrostatic, incompressible Navier–Stokes equations are solved using the Boussinesq approximation in a structured grid. This enables the simulation of three-dimensional wind flow and turbulent air movement around urban structures and vegetation. The effects of vegetation specifically are included as drag forces in the wind field (ENVI-met Model Architecture, n.d.). Turbulence is modelled using a 1.5-order closure scheme ($E-\epsilon$ or $k-\epsilon$ model), which incorporates turbulent kinetic energy and

its dissipation rate (ϵ) as additional prognostic variables (Karimi et al., 2020). In addition to airflow, ENVI-met simulates heat and moisture transport in the air, soil, and surfaces using combined advection and diffusion equations. The model accounts for radiative exchanges, both shortwave and longwave, as well as evapotranspiration and shading effects from vegetation, which are critical for assessing thermal comfort. Vegetation is fully modelled, including leaf area density, transpiration rate, shading behaviour, and radiative properties, enabling detailed analysis of green infrastructure impacts. Once the model domain and inputs are prepared, ENVI-met simulations are typically run over a 24-hour period to capture diurnal changes in microclimatic conditions. The outputs include high-resolution spatial and temporal data on air temperature, relative humidity, wind speed and direction, surface temperature, and MRT. These variables are essential for calculating outdoor thermal comfort indices such as the PET or the UTCI, using the BIO-met post-processing tool.

In CFD practise, trees are often replaced with simple shapes as they have a complicated geometry that is difficult to simulate (Mirzaei & Haghighat, 2010). They are represented as porous media, simplifying their impact on airflow by introducing resistance and affecting wind speed and turbulence. In contrast, ENVI-met treats trees as individual species with detailed water balance, heat and water stress reactions and a model for stomata behavior (ENVI-met Model Architecture, n.d.). All vegetation is represented as volumetric 3D blocks with spatially distributed properties. They interact with the microclimate through radiation, evapotranspiration and airflow resistance.

3.3 Model Setup

The ENVI-met model of Zuidpark was constructed using a QGIS-to-ENVI-met workflow rather than building the model entirely from scratch within ENVI-met. This approach reduced manual input effort and allowed integration of geospatial datasets from public sources. Using QGIS and the ENVI-met plugin, a 3D model was generated that accurately reflects the physical and biological characteristics of Zuidpark and its immediate surroundings. The model was organised into thematic layers representing specific components of the urban environment, as outlined below.

3.3.1 Study Area

The domain was delineated to include the park and the first block of surrounding buildings, sufficient to capture interactions between park and buildings while keeping computational demands manageable. Buildings on the northeast and southwest sides were excluded to reduce model size, while a portion of the Schelde River to the northwest was included. The total study area is represented in Figure 11.



Figure 11: Chosen study area around Zuidpark.

3.3.2 Surface Layer

The surface layer was derived from the soil map of Flanders (Bodembedekkingskaart (BBK), 1m Resolutie, Opname 2018, n.d.). For the parking scenario, this map was modified in ENVI-met's Spaces module to assume a uniform surface of single stone granite. For the present and future scenarios, the original raster data were converted to vector format and edited based on the master plan provided by the City of Antwerp. For a detailed overview of all materials used, see Appendix 3. Areas outside the park remained as defined in the original soil map.

3.3.3 Buildings and Geometry

Building footprints and heights were obtained from a digital twin model derived from LiDAR data (Stad Antwerpen, n.d.). Minor adjustments were made, including the removal of four small structures no longer present and the correction of height values for three buildings that contained null entries in the dataset. Building heights were estimated by multiplying the number of floors by 4 m, following a standard assumption. The historical "Waterpoort" monument, which was absent from the dataset, was manually added with an estimated height of 17.8 m, based on the height of neighbouring buildings.

3.3.4 3D Vegetation (Trees)

Tree data were taken from the City of Antwerp's tree database, which includes all public trees taller than 3 m. This dataset only covered trees present before the park's transformation, so missing trees were added manually using the city's tree map, increasing the number of trees from 82 to 557. Species were matched to entries in the ENVI-met database where possible; for missing species, similar alternatives were selected based on size, canopy structure, leaf area index (LAI) and leaf type, in consultation with biologist Arne Ven, from the department of bioscience engineering University of Antwerp (Appendix 4). Many tree species in ENVI-met have multiple options representing different sizes or ages. Where these different options were unavailable, custom trees were created using the L-system (Lindenmayer system) editor (Liu et al., 2023). This rule-based tool allowed adjustment of the proportional scale of the tree and the iteration depth of branching, thereby controlling height, crown spread, and structural

complexity. These adjustments ensured that the vegetation structure in the model closely matched real-world conditions, providing more realistic shading, evapotranspiration, and aerodynamic effects.

3.3.5 2D Vegetation (Low Plants)

Low vegetation was implemented manually based on field observations, aerial photographs, and a city-provided map (Appendix 2). Given the limitations of the ENVI-met database, higher bushes were represented as dense hedges with a height of 1 m, grass was set to 25 cm, and flowers were represented by luzerne at 18 cm. Raingardens and wadi areas were modelled as tall grass with a height of 50 cm. In addition, a buffer of 3.5 m of luzerne was added around trees located in the outer rows of the park, while trees in the park centre were assumed to have no flowers at their base.

3.4 Model details

3.4.1 Scenarios

The parking scenario was assumed to be fully paved with single stone granite for the parking area and dark asphalt for the roads. The only trees present in the area of interest were a row of *Platanus* (plane trees) surrounding the parking lot, and no low vegetation was included.

The present scenario incorporated a significant increase in both trees and low vegetation. Only the existing plane trees were assumed to be middle-aged (not yet fully grown), while all newly planted trees were modelled as young and therefore smaller in height and crown spread. Paved surface coverage was reduced, and multiple surface materials were represented according to the actual site layout.

The future scenario was identical to the present scenario except for fully developed tree canopies. Based on the tree plan and species information, tree heights and crown sizes were increased to represent maturity. In particular, the outer rows of *Platanus*, *Tilia*, *Quercus*, *Ulmus*, and *Alnus* were assumed to reach heights of at least 20 m.

3.4.2 Gridding & Simulation details

The mesh of the base model is visible in Figure 12. With a x and y resolution of 3 m, and a z resolution of 2.1 m, the total model size is 176 x 277 x 26 grids or 528 m x 831 m x 112.52 m. A horizontal resolution of 3 m captures enough detail for temperature effects, while the vertical resolution of 2.1 m is a bit finer and close to frequently used values of 2 m (Ouyang et al., 2021; Elraouf et al., 2022; Rui et al., 2018). The first cell is divided in 5 subcells, resulting in the centre of the third subcell being at 1.47 m. All the results are taken from this height. A height of 1.5 m is representative for humans and often taken as guideline for thermal comfort measurements and overall air temperature measurements. An additional detail to decrease computational demand is telescoping while still reaching desired model heights. This is a grid refinement technique where cell sizes gradually increase toward the model boundaries, typically only done for the vertical (z) resolution. ENVI-met guidelines state that telescoping should only start at the height of the highest building or above to ensure buildings are gridded correctly. However, the telescoping process is chosen to start at a height of 30 m with a percentage of 20% as only a few

buildings in the model are higher than 30 m. For thermal effects the first grids are the most important ones, but a too low starting height might influence the results since certain factors can be stretched out.

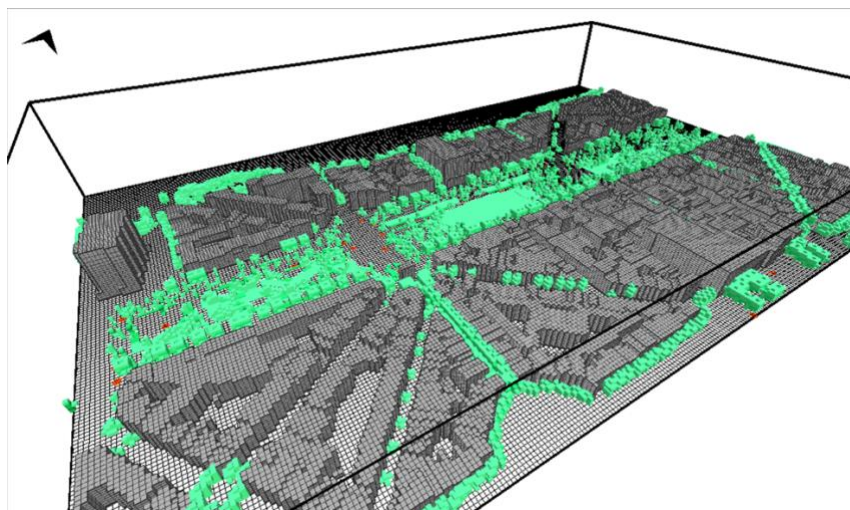


Figure 12: The computational mesh.

The boundary conditions for the simulation were based on weather station data recorded during the hottest day of 2024 in Belgium (Meteo België, 2024; Windy, n.d.; Humidity Forecast Antwerp, n.d.). They are given in Table 3.

Table 3: The simulation and meteorology data for the models. The varied parameters are the ones implemented in the additional models.

	INPUT PARAMETERS	VALUE/DESCRIPTION	VARIED PARAMETERS
S I M U L A T I O N	Domain size	528 m x 831 m x 112.5 m	
	x,y resolution	3 m	2 m & 4 m
	z resolution	2.1 m	
	Telescoping	20% starting at 30 m	Starting at 15 m & 45 m
	Simulation time	24 h starting at 05:00	48 h
M E T E O R O L O G Y	Wind velocity at 10 m	2 m/s	5 m/s
	Wind direction	SW, 225°	SE, 135°
	Temperature	Min: 20 °C Max: 34 °C	
	Clouds	none	
	Humidity	Specific humidity in 2500m: 8.00 g/kg Min RH: 35 % Max RH: 85 %	
	Radiation modelling	Low (30°)	Medium (15°)
	Microscale roughness length	0.1 m	
	Building wall surface	Concrete	Brick to glass ratio 70/30

3.5 Additional models

Following up the base models, some variations were implemented to investigate the effect of different parameters. The varied parameters discussed in Table 3 represent the additional models discussed in this section. For all but the first additional model, the results were run for only the present scenario and analysed at 04:00, 10:00 and 16:00.

3.5.1 Increased Simulation Time

Each scenario was run for an additional 24 hours, making the total simulated time 2 days. The average temperature and PET over the whole days were analysed to see the impact of heat remaining in the city.

3.5.2 Wind Direction

For the present and parking scenario, the wind direction was changed from southwest (SW) to southeast (SE; 135°). A wind coming from the SE is instantly blocked by an array of buildings, potentially affecting the thermal environment of the park.

3.5.3 Wind Speed

The windspeed is increased from 2 to 5 m/s. This is a windspeed which often occurred in 2024 in Antwerp (Weather Spark, 2025). Additionally, this increase is based on the scale of Beaufort. Where the original windspeed was scaled a one and the increased windspeed a three.

3.5.4 Radiation Settings

In ENVI-met there is the custom option to choose for higher radiation modelling, based on the indexed view sphere algorithm. A higher level of detail is possible regarding the calculation of reflected short- and longwave radiation fluxes. As the angle size decreases, accuracy of received radiation and the number of segments calculated for each view sphere increases at the cost of higher RAM demand. To investigate the impact of this setting, a model of the present scenario was run with a medium (15°) radiation setting instead of a low (30°) radiation setting.

3.5.5 Grid Size

Crank et al. (2018) performed grid-sensitivity testing in a simplified ENVI-met domain, showing that differences in average temperature were small compared to the effects of the tested interventions, even when strict grid independence was not achieved. Similarly, other studies (e.g. Ayyad & Sharples, 2019) have relied on domain-averaged results to support their resolution choices. Following this methodology, this thesis compared area-averaged air temperature, MRT, RH, WS, and PET across two alternative grid configurations at the representative times. The alternative configurations consisted of a finer grid (2 × 2 m) and a coarser grid (4 × 4 m), which were evaluated against the baseline grid (3 × 3 m) used in the base simulations.

3.5.6 Telescoping (Grid Stretching)

Telescoping in context of thermal simulations is discussed limitedly in literature, although it potentially has significant effects. ENVI-met recommends only starting at a height higher than the highest building (ENVI-met Model Architecture, n.d.). Two additional models were run, one with telescoping starting at 15 m (lower than most of the buildings) and one at 45 m (higher than the highest building), to discover a good balance between accuracy and computational demand. The telescoping factor of 20% was kept the same. This telescoping process resulted in a model height of 20 and 32 blocks respectively, instead of the 26 blocks in the base model.

3.5.7 Advanced Wall Detail

Originally the building materials remained default concrete. A more advanced model was run with a different material for the walls. Most buildings situated around the park are made out of bricks, but around 30% of their walls contain windows. A brick to glass ratio of 70/30 was chosen as the wall material for all buildings. The roofs remained concrete, as most roofs are made out of concrete or bitumen membrane which has similar thermal properties.

3.6 Post Processing and Data Analysis

The ENVI-met model is classified as an ORM itself and mentions that the use of PET is preferred over the other options (ENVI-met, n.d.) and the combination PET is frequently used in ENVI-met literature (Schmidt, 2024). The average male integrated in ENVI-met was used to calculate PET for every scenario. Table 4 represents the individual person settings for a default male with average clothing.

Table 4: Default male with average clothing settings for the calculation of PET in BIO-met.

Age of person	35 years	Height	175 cm
Weight	75 kg	Static insulation	0.90 clo
Body position	Standing	Basal Rate	84.49 W
Walking speed	1.21 m/s	Work Metabolism	80.00 W
Gender	Male	Metabolic rate	1.48 met

Data was analysed using a combination of ENVI-met's Leonardo and statistical software R (version 4.4.0). Limitations in the ENVI-met software 5.7.1 made it labour intensive to export data from ENVI-met. A selection was made to ensure only the park area was used to obtain results, areas outside the park were left out (X grid 65 to X grid 113, see vertical lines in Figure 13a). This also ensured that the river was not included in the analysis. Building values were filtered out as they have no valid parameter values. The base scenarios were analysed and compared by looking at the average hourly temperature and PET distribution (for Western Europe; Table 1) across the whole day. Additionally, three hours were chosen to further analyse the simulation (10:00, 16:00 and 04:00). Three different cross sections along the y-axis were made to identify the temperature and PET trend along the park. These cross sections

were situated at grid 84, 135, and 206 representing the paved walkway, grass field and general park area respectively (Figure 13b).

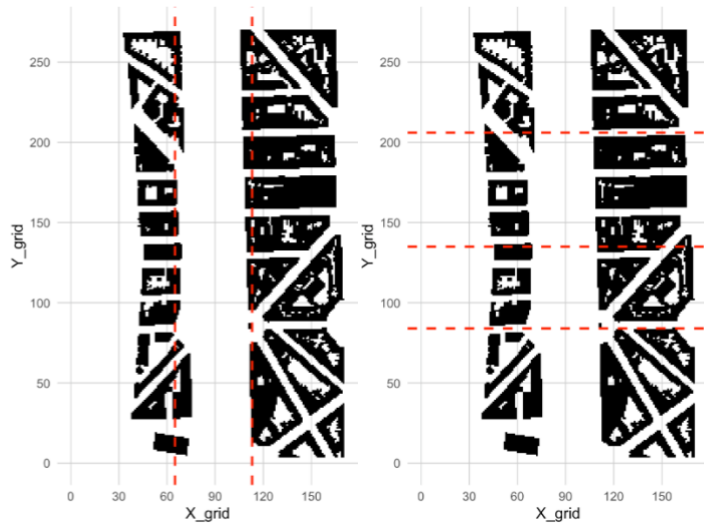


Figure 13: 2D view of the model. (a) Visualizes the chosen park area, (b) visualizes the cross sections.

Four zones were identified that correspond to their use today: the stone walkway to cross the park, the grass field, a tree row and a sport field (Figure 14). These zones were analysed specifically to discover whether their intended use fits their design and place. The metabolic rate was calculated based on the walking speed of the individual. In the base scenario the walking speed was 1.21 m/s. This was increased to 3 m/s to stimulate jogging and sport activities and 0 m/s representing people resting in the park.

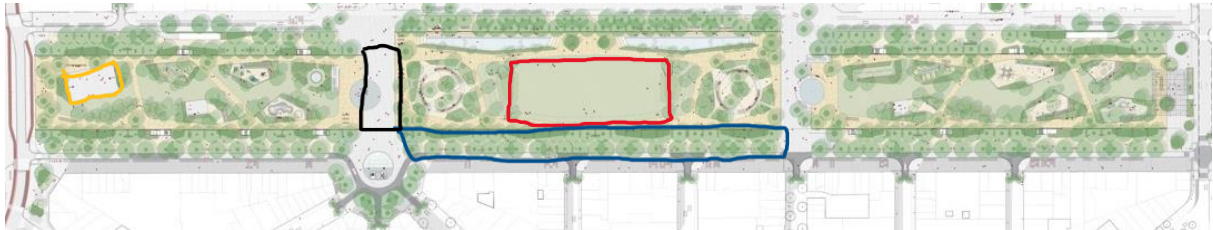


Figure 14: Masterplan of Zuidpark, pointing out the four selected zones. The grass field in red, tree row in blue, stone crosswalk in black and the sport area in yellow.

3.7 Field Measurements

Field measurements were conducted using the Testo 400 comfort set, a multifunctional device capable of recording all key environmental parameters relevant to thermal comfort assessments. Specifically, air temperature, relative humidity, globe temperature and windspeed were measured using the CO₂ probe, turbulence probe and 150 mm black globe thermometer. The setup is visible in Figure 15a. MRT was calculated based on Equation 4 (Alfano et al., 2021).

$$MRT = \left[(t_g + 273)^4 + \frac{h_{c,g}}{\epsilon_g \sigma} (t_g - t_a) \right]^{1/4} - 273 \quad (\text{Equation 4})$$

Where: t_g = globe temperature (°C), t_a = air temperature (°C), ε_g = emissivity of the globe surface (~0.95 for black paint), σ = Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$) and $h_{c,g}$ = convective heat transfer coefficient ($\text{W/m}^2\text{K}$) = $6.3 \frac{v_a^{0.6}}{D^{0.4}}$ (under forced conditions) with v_a = air velocity (m/s) and D = globe diameter (m).

Measurements were carried out over a two-day period, from 13:00 to 18:00, corresponding with peak daytime heat exposure. Only cloud-free days with stable, dry weather were selected to ensure consistent solar radiation input and minimize atmospheric variability. Three distinct measurement locations were chosen, each representing a different urban microclimatic condition (Figure 15b): (1) beneath a tree canopy in the shadow, (2) on an open grass area, (3) on a paved crossing in the park. There was only one thermal comfort kit available, and it was not feasible to leave the measurement equipment without supervision due to potential vandalism or theft. Hence, each point was measured for a duration of 20 minutes, allowing sufficient time for the black globe thermometer to equilibrate with its surroundings and capture realistic values. This way, each location had measurements for every hour. All sensors were mounted at standard pedestrian level (1.5 m) to reflect human thermal experience.

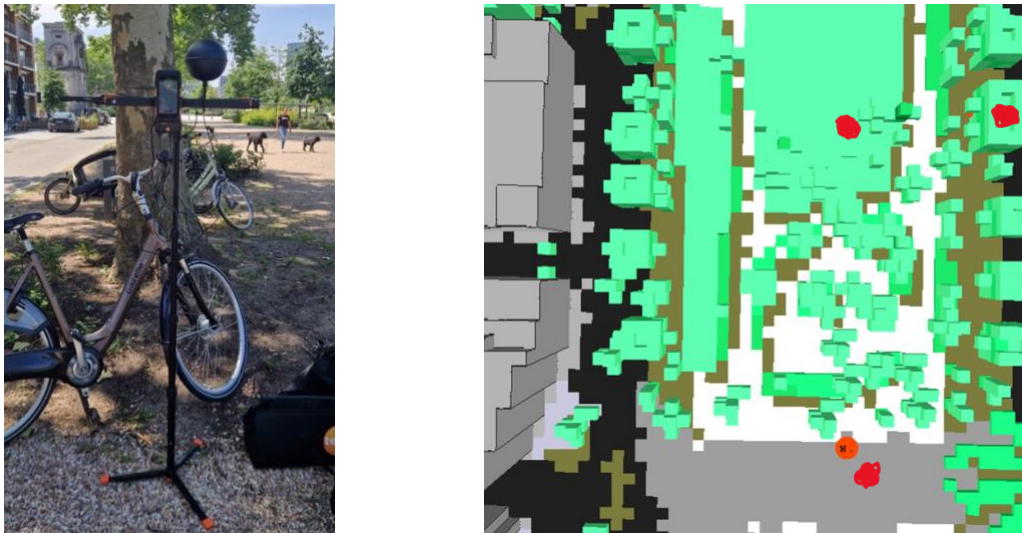


Figure 15: (a) The field measurement setup with the Testo 400 comfort kit including a black globe (150mm) a turbulence meter and a CO₂ meter that captures air temperature and RH. (b) The locations of the field measurements in the model.

A descriptive and statistical analysis of the field data was conducted to identify differences between the three locations. A generalised linear mixed model was used, with day being a random effect and time was nested in day. Location was a fixed effect to identify whether temperature is different in the different locations. Time was rounded down to hours. To support the validation of the ENVI-met model, a set of simulations were run replicating the same two days. Data from the KMI and Meteoblue were used to obtain minimal and maximal temperature and relative humidity, average windspeed and wind direction (KMI – België, n.d.; Weer Archief Antwerpen – Meteoblue, n.d.), a similar approach as for the three base models. The modelled and measured data were then compared using the coefficient of determination (R^2) to assess the model's accuracy in reproducing two key thermal comfort variables, local temperature and MRT. The cells that matched with the field measurements were assumed to be (104, 117), (91, 117), and (93, 87) for the tree, grass and stone location respectively.

4. Results and Discussion

4.1 Field Measurements & Validation

4.1.1 Field Results

The average air temperature varied noticeably between the three locations. The tree-covered site recorded the lowest mean temperature at 29.2 °C, followed by grass at 32.1 °C and stone at 33.2 °C. Maximum temperatures reached 39.4 °C at the stone location, compared to 36.9 °C for grass and 33.3 °C for the tree site. The temperature distribution across locations is presented in Figure 16.

As the day progressed, temperature rose, especially for the tree location. For the first measurement day for example, air temperatures started at around 27 °C at 13:00 and ended up being almost 33 °C at 17:00. Stone and grass peaked at 15:00.

Additionally, Figure 17 shows the boxplots for air temperature and MRT at each location, clearly illustrating the observed differences.

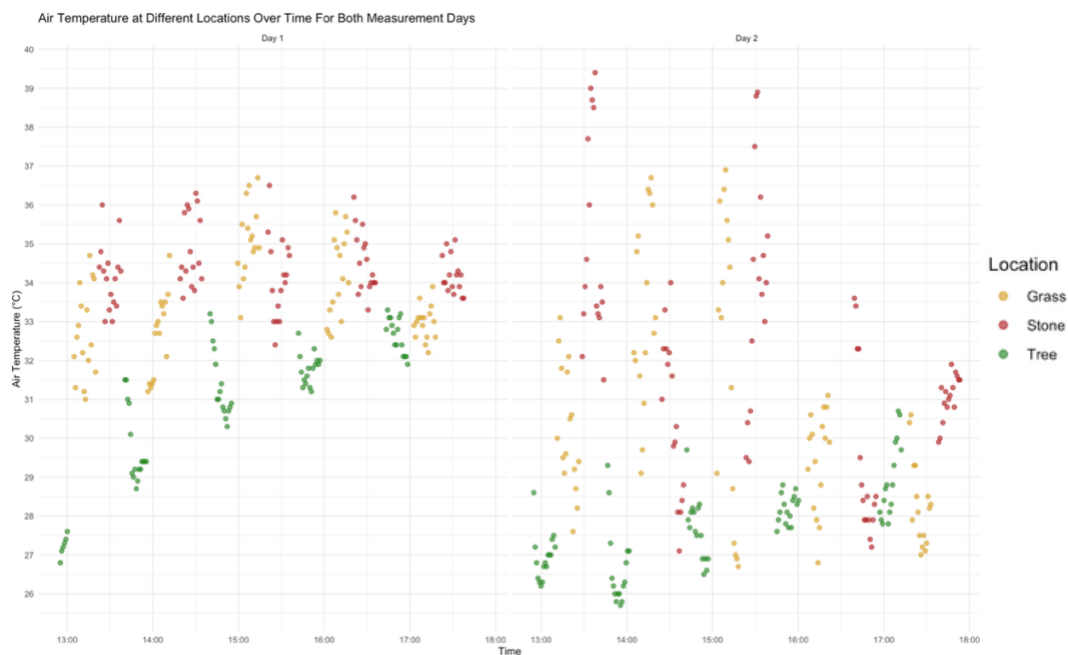


Figure 16: Air temperature measurements for both measurement days.

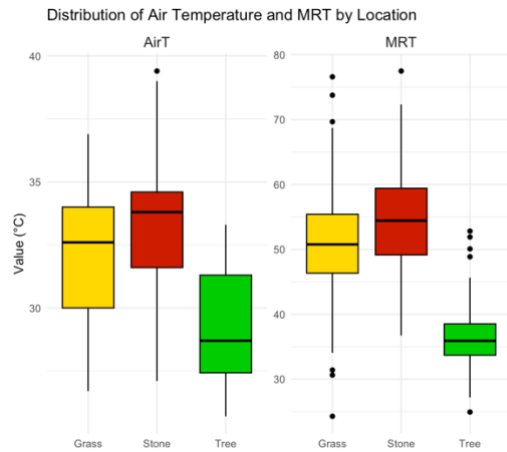


Figure 17: Boxplots representing the differences between measurement location for both air temperature and MRT.

A linear mixed-effects model with *day* and *hour* nested within *day* as random effects revealed a significant effect of location on air temperature ($p < 0.001$). The adjusted mean air temperature for the grass location was 32.08 °C. The tree location was on average 2.80 °C cooler than grass, whereas the stone location was on average 1.11 °C hotter than grass. All pairwise differences were highly significant ($p < 0.001$). The random effects accounted for additional variability, particularly due to the variable *day*. Model assumptions for normality and homoscedasticity were visually assessed and found to be reasonably met.

There was a significant difference in MRT between the three locations ($p < 0.001$). The adjusted mean MRT for the grass location was 50.80 °C. The tree location was on average 14.89 °C lower than grass, while the stone location was on average 3.64 °C higher than grass. All pairwise differences were highly significant ($p < 0.001$). The variance component for *day* was estimated as zero, indicating that day-to-day variation was negligible compared to within-day differences. The random effect for *hour* nested within *day* captured some of the residual variability. Model assumptions for normality and homoscedasticity were visually checked and found to be reasonably met.

4.1.2 Model Validation

The R^2 for the fit between field and model air temperature was 0.25, indicating that the model did not accurately reproduce temperature differences between locations. Within-location performance varied (Figure 18a): the tree location showed relatively strong agreement ($R^2 = 0.87$), grass showed moderate agreement ($R^2 = 0.24$), and stone showed almost no agreement ($R^2 = 0.01$). Additionally, the model consistently underestimated air temperature at all locations.

For MRT, the overall R^2 was 0.87, indicating strong agreement between model and field data and suggesting that the model accurately predicted MRT differences between locations. However, the model tended to overestimate MRT for most points, except for certain measurements at the tree location (Figure 18b). Since the overall spatial pattern is well reproduced but absolute values are often biased, the results may be more reliable for qualitative assessments (e.g., ranking locations) than for precise quantitative predictions.

The contrasting performance for MRT and air temperature may reflect differences in how these variables respond to surface heat storage and radiative exchange in the model. MRT is driven primarily by radiation balance, which may be better represented, while air temperature depends more on turbulent heat exchange, surface conduction, and model boundary conditions. The relatively strong performance for the tree location suggests that the thermal properties of surface materials may be misrepresented while shading effects are well represented. If the modelled materials store less heat than they should, this effect would be most pronounced in locations with higher heat storage (grass and stone), while shaded areas (tree) would be less affected. Improving the parameterisation of material thermal properties and boundary temperatures could therefore enhance air temperature predictions without compromising the strong MRT fit.

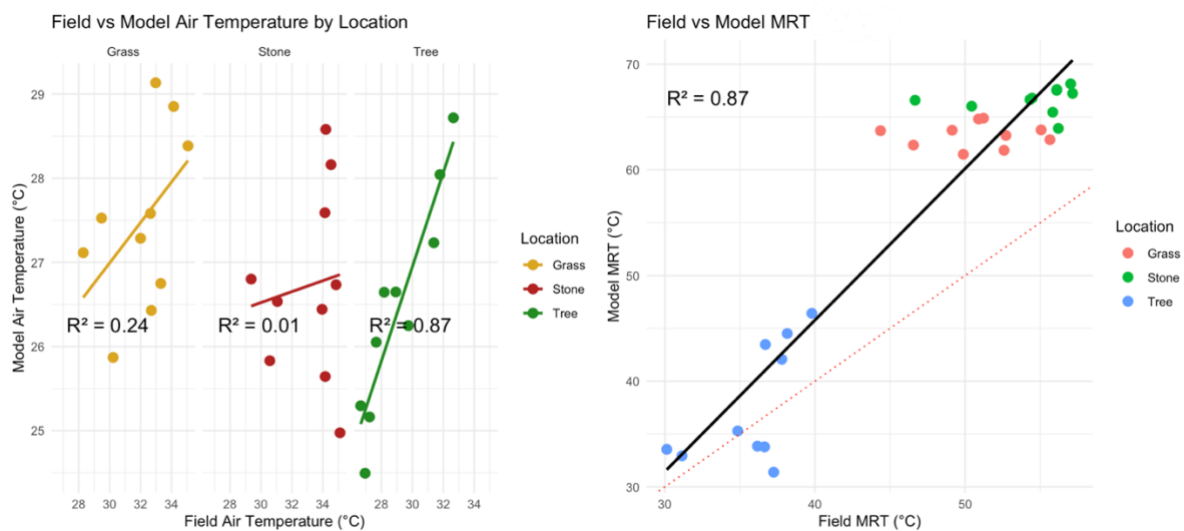


Figure 18: Comparison of modelled and measured values for air temperature (left) and MRT (right). The left panel shows within-location performance, with separate regressions for each location. R^2 values indicate how well the model reproduces temporal variation at each site, with strong agreement for the tree location, moderate agreement for grass, and almost no agreement for stone. The right panel shows between-location performance for MRT across all sites and times. Solid black line shows least-squares regression fit; dotted red line represents the 1:1 line (perfect agreement). The high R^2 (0.87) indicates that the model captures the overall spatial pattern of MRT differences between locations.

The optimal approach for conducting this validation would involve field measurements taken both before and after the park's implementation. This would allow for the validation of both the pre-park (parking) and post-park scenarios within the model. Furthermore, continuous measurements over an extended period would be preferable to capture the full diurnal cycle and account for temporal variability.

4.2 Base Models

4.2.1 Day Profiles

The three different models are visible in Figure 19. The parking scenario depicts a completely paved area with only a few plane trees located along the sides of the parking. The present illustrates a substantial increase in greenery and a greater diversity of surface materials compared to the parking scenario. The future scenario represents the present park configuration with all factors remaining constant except for the selection of trees that has grown.

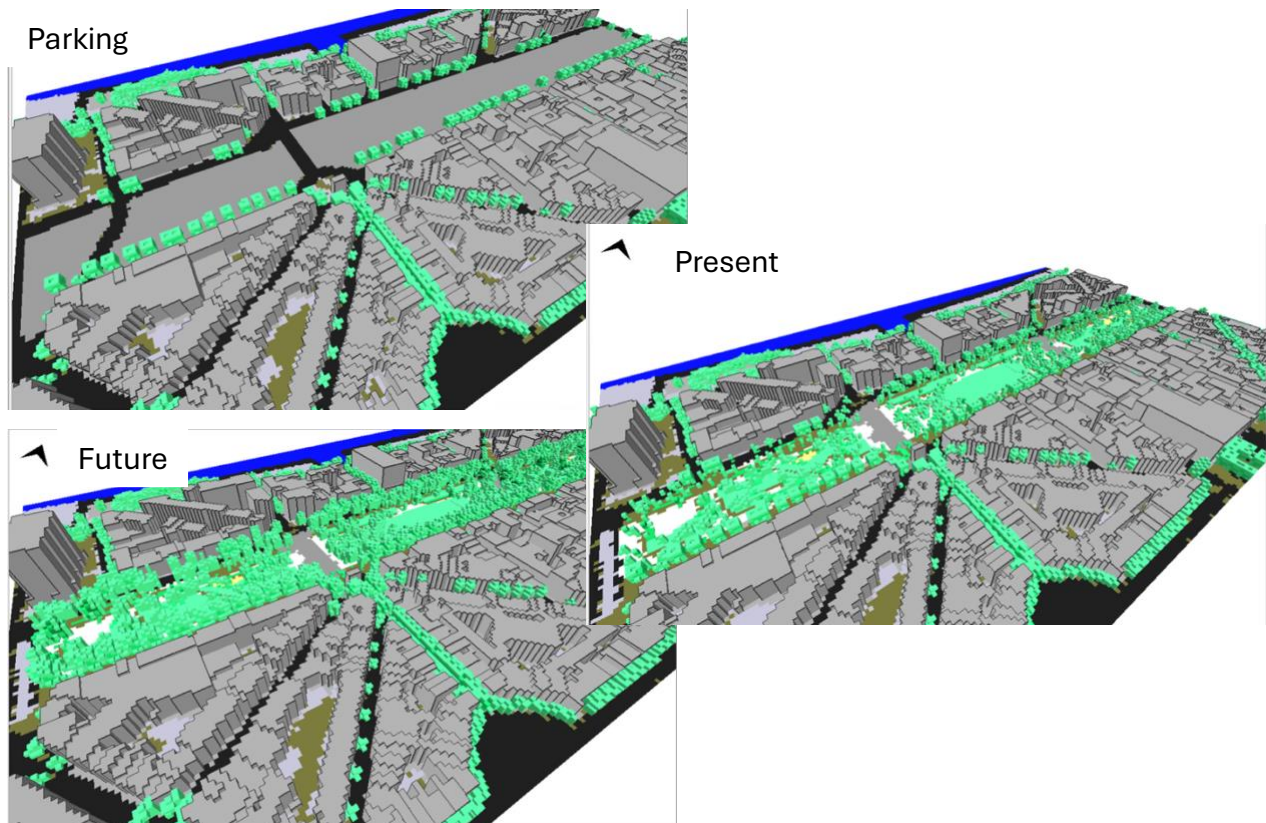


Figure 19: The base models (parking, present and future).

Figure 20 presents the average hourly air temperature and PET across the parking throughout the day. The mean air temperature in this scenario was 28.1 °C, with a minimum of 20.3 °C and a maximum of 35.6 °C. The lowest values occurred near the wind inflow boundary, while the highest were recorded adjacent to a sun-exposed building façade. This hotspot was unshaded and composed of materials exposed to continuous solar radiation, which contributed to progressive heat accumulation during the day. PET ranged from 19.0 °C to 58.5 °C, with an average of 34.0 °C. Higher PET values were consistently observed in sunlit zones in front of buildings, whereas shaded areas behind buildings exhibited lower values. Thermal variability, assessed through the standard deviation (SD) across grid cells, was markedly higher during the day than at night. For air temperature, daytime SD averaged 0.79 °C compared to 0.39 °C during evening and night hours. PET variability was more pronounced, with an average daytime SD of 4.02 °C versus only 0.81 °C at night. This indicates that spatial contrasts in thermal conditions were stronger under daytime heating and shading differences, while nocturnal cooling produced a more uniform thermal environment. From a comfort perspective, this means that during the day individuals may experience highly heterogeneous microclimatic conditions depending on their exact location (e.g., shaded vs. sunlit areas), whereas at night thermal conditions are more homogeneous across the park.

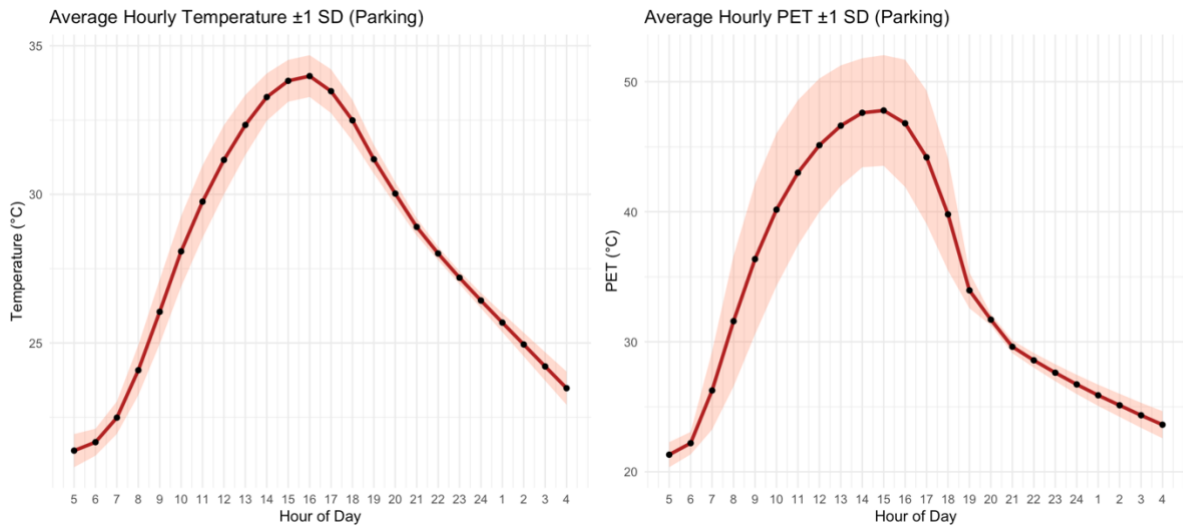


Figure 20: Hourly averaged temperature and PET with the standard deviation in the parking scenario.

For the present scenario the minimum air temperature was 20.0 °C, while the maximum reached 35.7 °C, slightly higher than the parking scenario's maximum of 35.6 °C. The mean temperature across the park was 27.5 °C, representing a 0.6 °C reduction compared to the parking scenario. The location of the highest temperature was the same as for the parking scenario, but the coolest areas shifted to the park's open central zone. This indicates a nighttime cooling effect of the open vegetated area. PET values ranged from 19.0 °C to 58.6 °C, with an average of 33.0 °C, marking a 1.0 °C decrease compared to the parking scenario. Similar to the parking scenario, both air temperature and PET displayed greater variability during the day. The mean SD of daytime air temperature was 0.768 °C, compared to 0.491 °C at night. PET variability was again more pronounced, with an average daytime standard deviation of 3.97 °C versus 0.927 °C during the evening and night. These results are visualised in Figure 21.

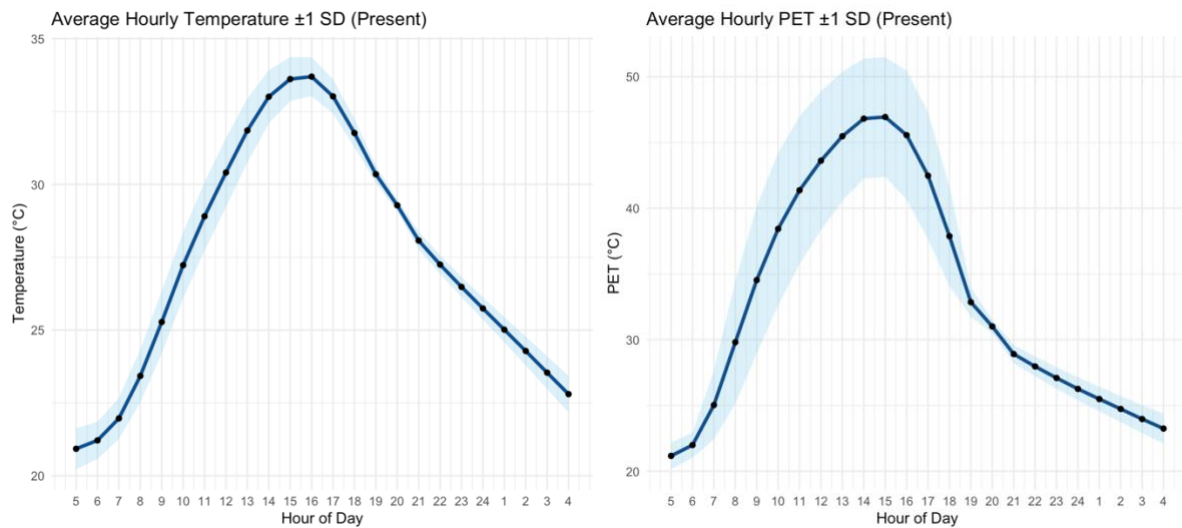


Figure 21: Average hourly temperature and PET with standard deviation in the present scenario.

Figure 22 presents simulation results for future scenario. The minimum air temperature was 19.6 °C, occurring once again in the central part of the park. Hence, mature trees contribute to a distribution of cold airflow. Similarly low values were recorded across large portions of this central park zone. The

maximum air temperature reached 35.6 °C, consistent with the peak locations observed in both the parking and present scenarios. The mean temperature across the park was 27.0 °C, a further decrease of 0.5 °C compared to the present scenario. PET values ranged from 19.0 °C to 58.6 °C, with an average PET of 31.6 °C (representing a 1.4 °C reduction compared to the present scenario and a 2.4 °C reduction compared to the parking scenario). As in the previous models, both air temperature and PET exhibited greater variability during the day than during the evening and night. The average daytime SD of air temperature was 0.783 °C, compared to 0.501 °C at night. PET variability again showed a more pronounced contrast, averaging 3.90 °C during the day and 0.886 °C during the evening and night.

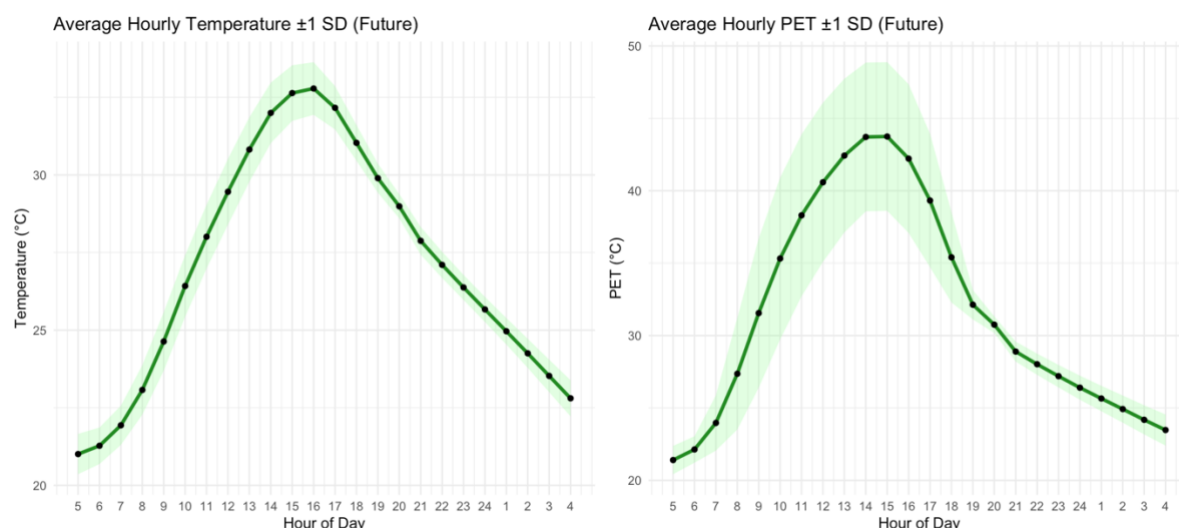


Figure 22: Average hourly temperature and PET with standard deviation for the future scenario.

Figure 23 compares the diurnal variation in average air temperature for the parking, present, and future scenarios in one graph. During most of the day, the future scenario recorded the lowest average temperatures, except for three hours during the night when the present scenario was marginally cooler. This nighttime cooling in the present scenario is likely due to the larger proportion of open space, which facilitates the emission of longwave radiation without obstruction. In contrast, the increased tree cover in the future scenario may partially block longwave radiation, leading to some heat retention. Temperature differences between scenarios were smaller during nighttime than daytime. As expected, the parking scenario exhibited the highest average temperatures throughout the 24-hour period. This aligns with established urban climate theory: the absence of shade and evapotranspiration, combined with the high heat capacity and low albedo of asphalt and granite surfaces, leads to rapid heating during the day and slower cooling at night.

The PET results followed a similar pattern. The future scenario consistently yielded PET values closer to thermally comfortable conditions, particularly during daytime hours. However, from approximately 22:00 to 06:00, the present scenario recorded the lowest PET values. In the future scenario, mature trees appear to block a portion of emitted longwave radiation and reduce wind speed, which may elevate

PET slightly during nighttime. Nevertheless, as with air temperature, the differences in PET between scenarios were more pronounced during the day than during the evening and night.

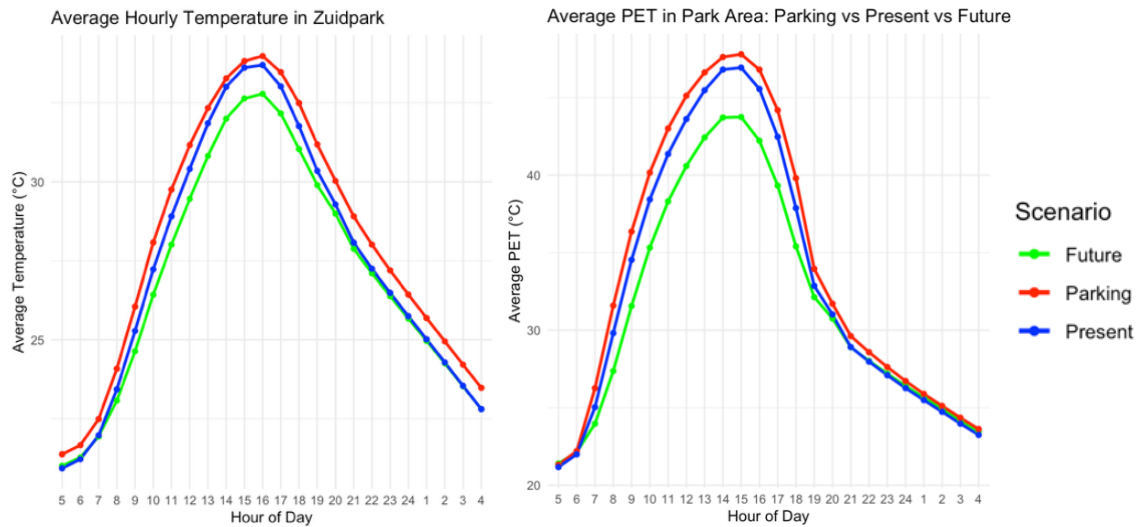


Figure 23: Average hourly temperature (left) and PET (right) for parking, present and future scenario.

4.2.2 PET Classification for the Whole Day

The PET distribution for each scenario is shown in Figure 24. PET categories were classified according to the PET classification for Central and Western Europe proposed by Basarin et al. (2020) (Table 1). In the parking scenario, slight heat stress dominated during the nighttime hours (22:00 to 04:00), with a brief period of comfortable conditions between 05:00 and 06:00. From 08:00 onward, strong heat stress became the dominant category, shifting to extreme heat stress by 10:00. This extreme category persisted until 18:00, after which conditions transitioned to moderate heat stress, and then to slight heat stress by 22:00.

In the present scenario, nighttime patterns were similar, with slight heat stress prevailing and a short interval of comfortable conditions between 04:00 and 06:00. However, the timing of changes in dominant PET category shifted: strong heat stress began at 09:00, followed by extreme heat stress from 10:00 to 17:00. This was succeeded by three hours of moderate heat stress, before returning to slight heat stress. The one-hour delay in the onset of strong heat stress compared to the parking scenario indicates a slower morning increase in PET. Furthermore, the absence of extreme heat stress as the dominant category at 18:00 suggests a more rapid decrease in PET during the evening hours.

The future scenario displayed a broadly similar nighttime pattern to the present scenario, though with slightly reduced comfort at 04:00, likely due to partial heat retention from increased canopy cover. At 12:00, over 50% of the park experienced extreme heat stress, marking a one-hour delay compared to the present scenario and a two-hour delay compared to the parking scenario. This extreme category persisted for five hours, before shifting to strong heat stress at 17:00 and moderate heat stress at 18:00. These results highlight the positive effect of larger, mature trees in reducing the duration and delaying the onset of peak heat stress, particularly during midday and afternoon hours.

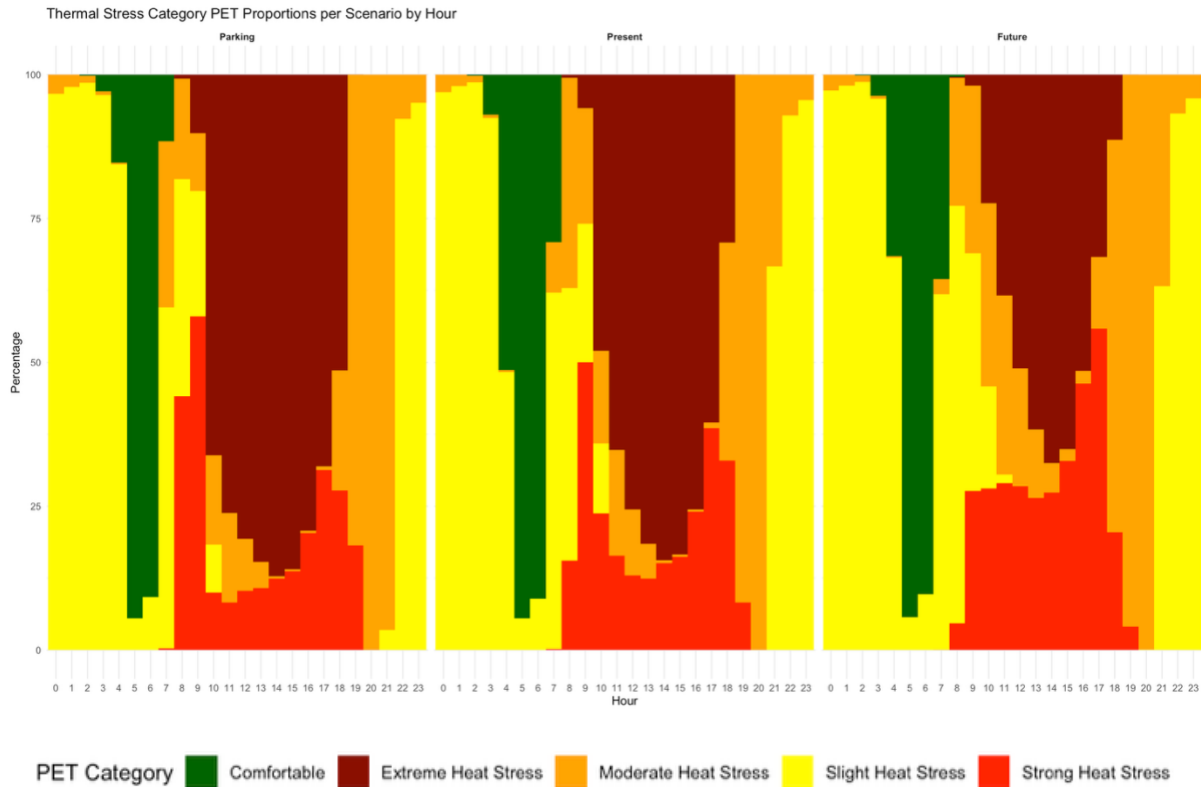


Figure 24: PET classification over the whole park for the parking, present and future scenario.

4.2.3 Specific Hour Analysis

At 16:00, corresponding to the warmest period, the average air temperature for the parking scenario reached 34.0 °C. Figure 25a indicates that parking has a uniform temperature distribution, with lower temperature values for the tree rows. The streets next to the parking enclosed by buildings are colder than the parking itself due to the limited solar exposure. The mean PET at this time was 46.8 °C. The present scenario showed a 0.3 °C lower air temperature (33.7 °C). Figure 25b reveals a less uniform spatial distribution of air temperature in the park compared to the parking scenario. The presence of vegetation and tree cover introduced localized cooling effects, resulting in greater micro-scale temperature variability across the site. PET at this time averaged 45.6 °C, a 1.2 °C reduction compared to the parking scenario. The future scenario showed a further decrease of 0.9 °C compared to the present scenario, resulting in an average temperature of 32.8 °C. Figure 25c illustrates the cooling influence of mature tree cover. Notably, lower temperatures are observed at the downwind end of the park, suggesting that the trees form a cooling breezeway contributing to additional cooling in this area. PET at this time averaged 42.2 °C, a 3.4 °C reduction compared to the present scenario. This substantial decrease highlights the significant cooling effect of fully developed tree canopies on human thermal comfort.

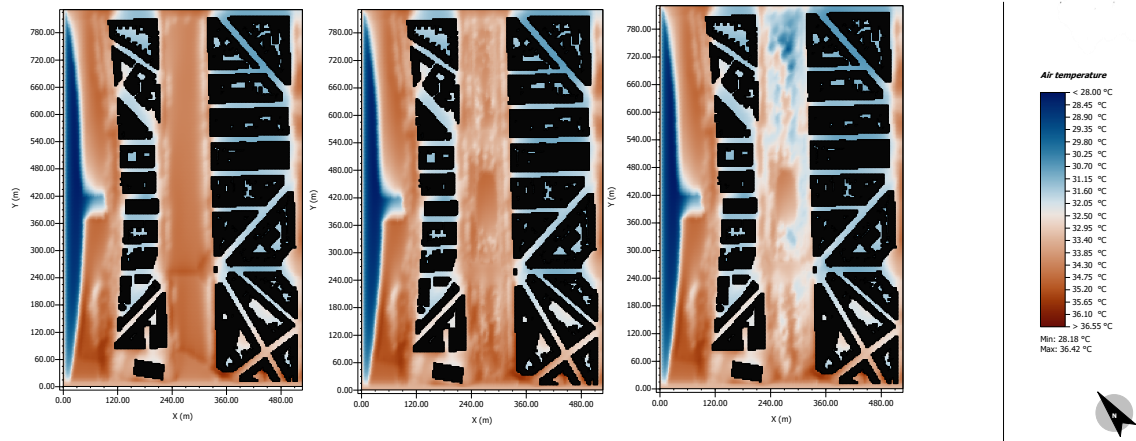


Figure 25: The air temperature in the whole model area at 16:00 for all three scenarios ((a)parking, (b) present and (c) future).

Table 5 summarises the PET classification for 16:00, 10:00, and 04:00 in the parking scenario, and Figure 26 visualises the spatial distribution of these categories. Almost 80% of the parking experienced extreme heat stress and $\approx 20\%$ strong heat stress. In the morning (10:00), extreme heat stress remained the dominant category (66.1%). At night (04:00), $\approx 15\%$ of the park classified as comfortable while the remaining 85% experienced slight heat stress. The 0.3% moderate heat stress in Table 5 was located in an area between buildings with low windspeed where the heat was trapped. The ability of the parking area to cool during nighttime is likely due to its openness and minimal obstruction to wind flow. However, during the day, the lack of vegetation and shading elements leads to rapid heating and consistently uncomfortable thermal conditions.

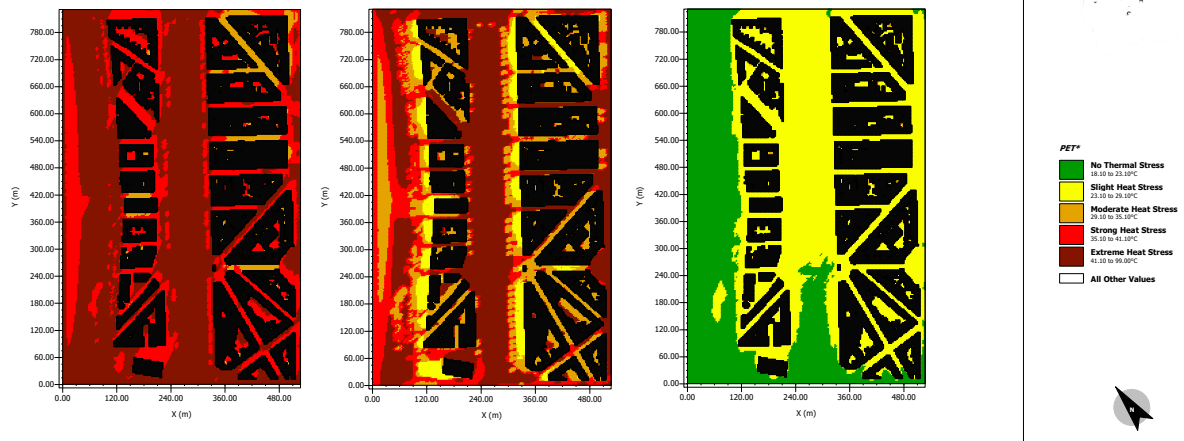


Figure 26: PET classification at 16:00 (left), 10:00 (middle) and 04:00 (right) for the parking scenario.

Table 5: The PET classification at 16:00, 10:00 and 04:00 in the parking scenario.

	At 16:00	At 10:00	At 04:00
Extreme heat stress	79.3%	66.1%	0.0%
Strong heat stress	20.3%	10%	0.0%
Moderate heat stress	0.4%	15.5%	0.3%
Slight heat stress	0.0%	8.3%	84.4%

Comfortable	0.0%	0.0%	15.3%
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The PET classification for the present scenario at the three chosen hours is visible in Figure 27 and Table 6. The PET distribution at 16:00 showed that extreme heat stress and strong heat stress still prevailed with only a decrease of $\approx 4\%$ in extreme heat stress. In the morning (10:00), extreme heat stress affected almost half of the park (48%), a higher reduction compared to the peak hour. At night (04:00), comfortable conditions prevailed in over 50% of the park area.

These findings highlight the enhanced nighttime cooling capacity of an open, vegetated environment. Additionally, they further indicate lower thermal stress levels compared to the parking scenario, reflecting more thermally tolerable conditions. Although differences at the peak hour remain limited, there is a slower build-up of heat stress during the day. At 10:00 there was a clear difference visible for different zones. Most of the extreme heat stress was situated over the paved walkway and grass field (at 240 m and 420 m on the y-axis), so in areas with no trees.

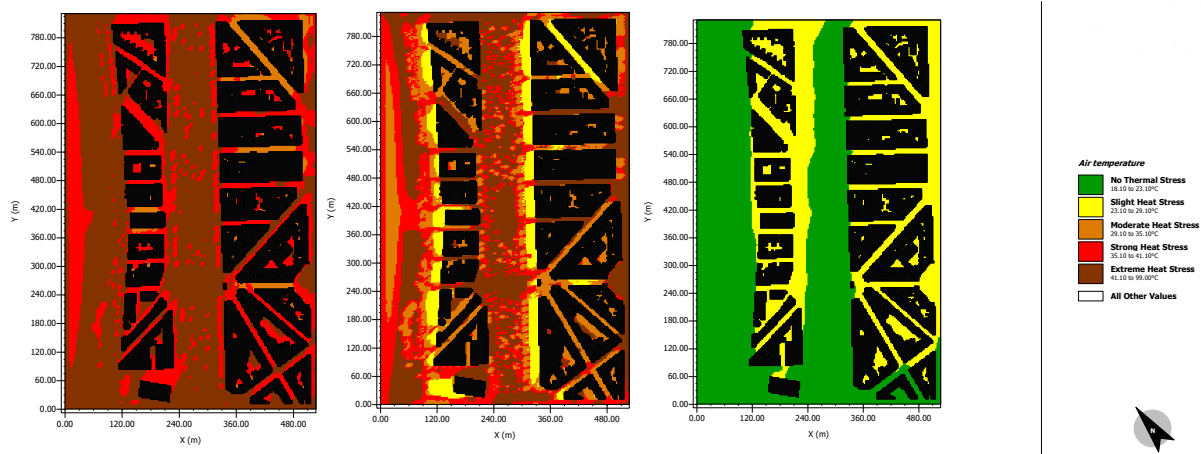


Figure 27: PET classification at 16:00 (left), 10:00 (middle) and 04:00 (right) for the present scenario.

Table 6: The PET classification at 16:00, 10:00 and 04:00 in the present scenario.

	At 16:00	At 10:00	At 04:00
Extreme heat stress	75.6%	48.0%	0.0%
Strong heat stress	24.0%	23.7%	0.0%
Moderate heat stress	0.4%	16.1%	0.3%
Slight heat stress	0.0%	12.2%	48.3%
Comfortable	0.0%	0.0%	51.4%

For the future scenario Table 7 summarises the PET classification at 16:00, 10:00 and 04:00, while Figure 28 visualises the spatial distribution of heat stress categories. At 16:00, extreme heat stress affected just over half of the park, representing a reduction of almost 28% compared to the present scenario. Additionally, some areas in the park now classified as moderate heat stress (2.2%). Instead of extreme heat stress, moderate heat stress was the dominant category in the morning (10:00). At

night (04:00), the park experienced less areas of thermal comfort compared to the present scenario. However, it was still more comfortable than the parking scenario.

These results once again indicate the effect of mature tree canopies. Peak hour thermal comfort is drastically increased and there is a slower build-up of heat stress during the day. The small percentage of moderate heat stress at 16:00 represents the effect of an urban breezeway and blocking of solar radiation of trees on TC levels. The grass field and paved walkway were again clearly visible at 10:00, but also at 16:00, as they were basically the only areas with extreme heat stress. At night the trees can trap some heat, resulting in lower thermal comfort levels.

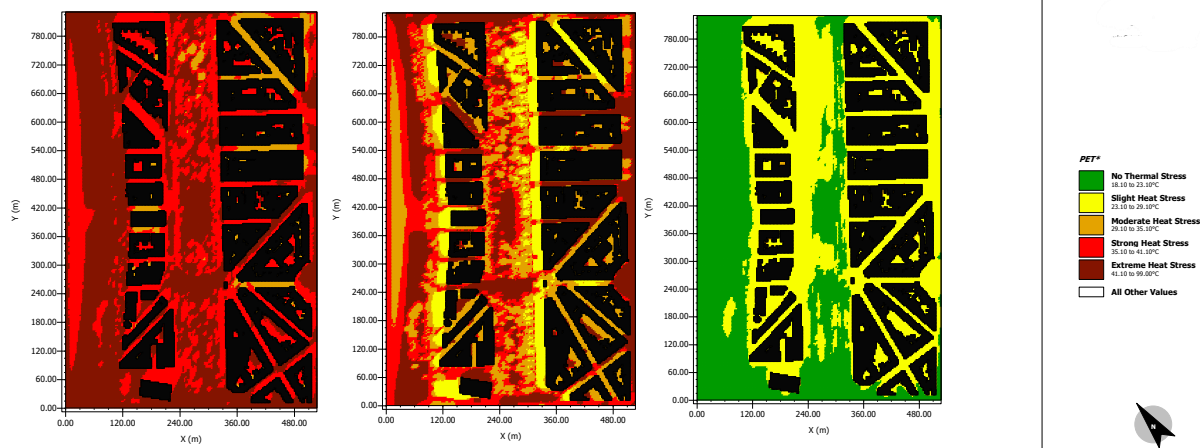


Figure 28: PET classification at 16:00 (left), 10:00 (middle) and 04:00 (right) for the future scenario.

Table 7: The PET classification at 16:00, 10:00 and 04:00 in the future scenario.

	At 16:00	At 10:00	At 04:00
Extreme heat stress	51.5%	22.4%	0.0%
Strong heat stress	46.3%	28.1%	0.0%
Moderate heat stress	2.2%	31.8%	0.3%
Slight heat stress	0.0%	17.7%	68.2%
Comfortable	0.0%	0.0%	31.5%

Figure 29 presents histograms of air temperature and PET for 04:00, 10:00, and 16:00. At 04:00, the present and future scenarios displayed similar temperature distributions, both shifted toward lower values compared to the parking scenario, while PET distributions were also closely aligned across all scenarios. The similar PET values, despite higher air temperatures in the parking scenario, can be explained by the lower wind speeds and higher MRT observed in multiple areas of the present and future scenarios (see maps Appendix 5). Tree canopies reduce airflow and intercept longwave radiation emitted by surfaces, re-emitting part of it back toward pedestrian level. This radiative trapping effect is particularly pronounced for shorter trees, whose canopies are closer to pedestrian height.

By 10:00, the distributions began to diverge. The future scenario was clearly skewed toward lower temperatures and PET values compared to the parking and present scenarios, indicating that the cooling effect of mature trees becomes apparent early in the day, delaying the onset of extreme heat

stress. The present scenario, while cooler than the parking case, showed a gradual rightward shift toward higher values, suggesting less persistent cooling. Additionally, the PET distribution in the present scenario displayed two distinct peaks, corresponding to shaded and non-shaded areas. In the future scenario, these peaks were less pronounced because only a small proportion of the park remained without substantial canopy cover. As a result, direct sun exposure was greatly reduced, and a larger share of grid cells experienced partial shade or diffuse radiation, producing a lower and more homogeneous distribution.

At 16:00, differences between scenarios were most pronounced for PET. The parking scenario exhibited a sharp peak of over 3,000 grid cells with PET values around 50 °C, indicating widespread extreme heat stress. The present scenario also had a concentration of high PET values but with a smaller peak and broader spread, consistent with localized shading effects. The future scenario's PET distribution was flatter, with far fewer cells in the extreme range and a greater proportion in lower categories, aligning with earlier maps (Figure 28) that showed a reduced spatial extent of high heat stress. At this time the two PET peaks were even more pronounced, indicating the same: shaded vs non-shaded areas.

These results highlight that, beyond lowering mean PET, mature tree canopies reduce the frequency and intensity of extreme values, a change that is particularly relevant for improving public comfort and reducing heat-related health risks.

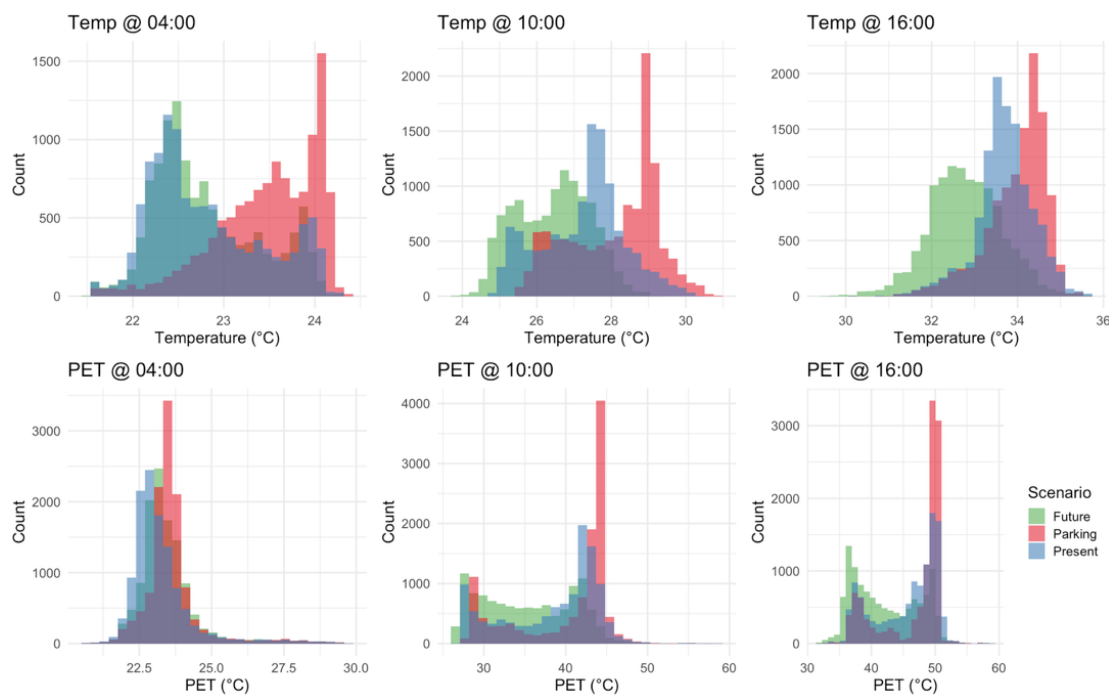


Figure 29: Temperature and PET histograms.

4.2.4 Cross Section Analysis

Three cross sections were extracted from the model domain to assess temperature and PET patterns at different park locations: along the walkway, along the grass field and along a general park area. The

whole park is located between grid points 65 and 113; outside this range, values were similar across scenarios since the surrounding built-up areas were unchanged.

At 04:00 (Figure 30, Figure 31 and Figure 32), all cross sections showed that the park was cooler than adjacent streets enclosed by buildings. The elevated temperatures in these built-up street sections were due to heat retention caused by longwave radiation being blocked from escaping by the surrounding building façades. Along the walkway (Figure 30), the present and future scenarios lower air temperatures than the parking scenario, while PET was comparable across all scenarios. In the grass field section (Figure 31), temperature patterns were similar, but the present scenario reached slightly lower values than the future scenario, as younger trees block less airflow and trap less heat. The coolest temperatures occurred in the centre of the grass field, an open vegetated area where longwave radiation can escape without obstruction. PET values in this cross section were highest in the parking scenario, further indicating the effect of heat storage in the pavement. In the general park cross section, temperature differences between parking and the vegetated scenarios (present and parking scenario) were larger, and the PET profile exhibited two peaks corresponding to tree clusters trapping radiant heat.

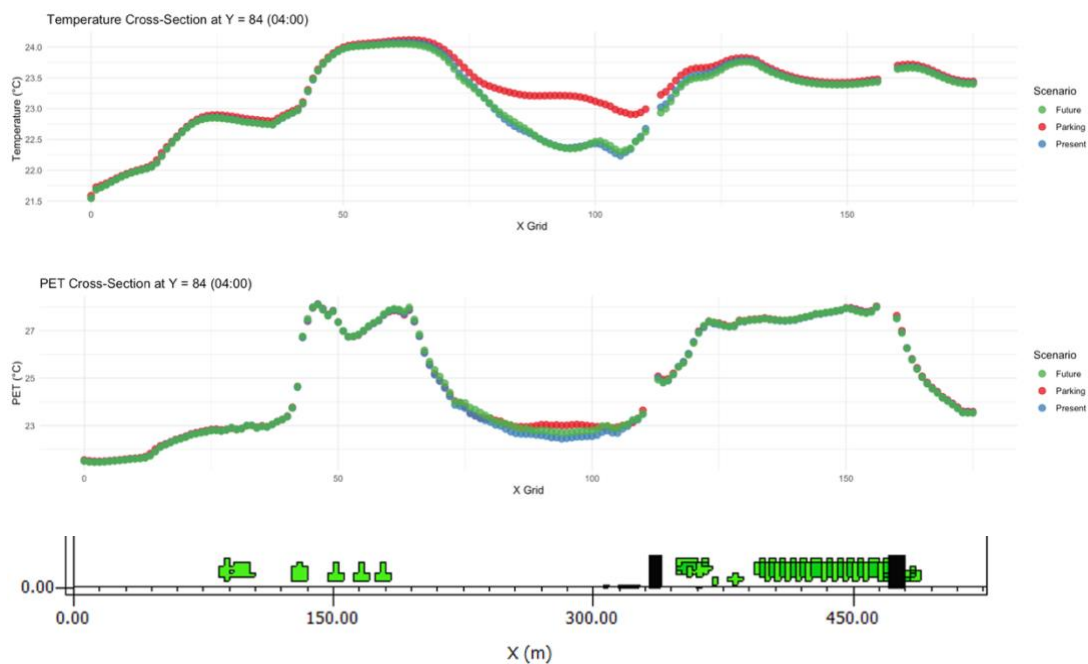


Figure 30: Cross-section at Y = 84 (along walkway) for temperature and PET at 04:00.

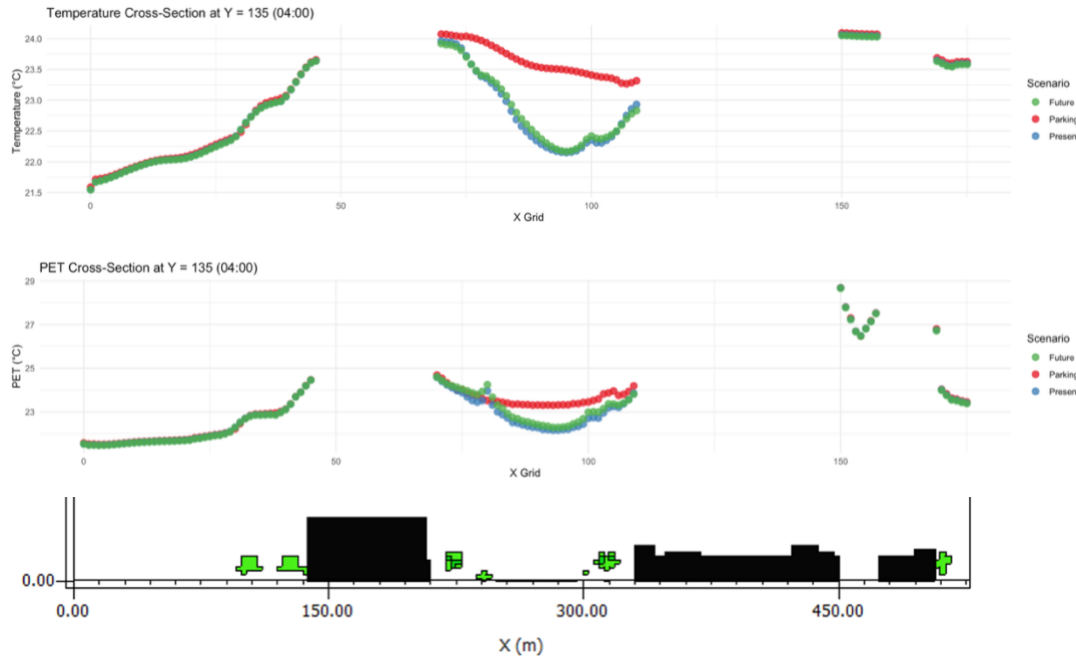


Figure 31: Cross-section at Y = 135 (along grass field) for temperature and PET at 04:00.

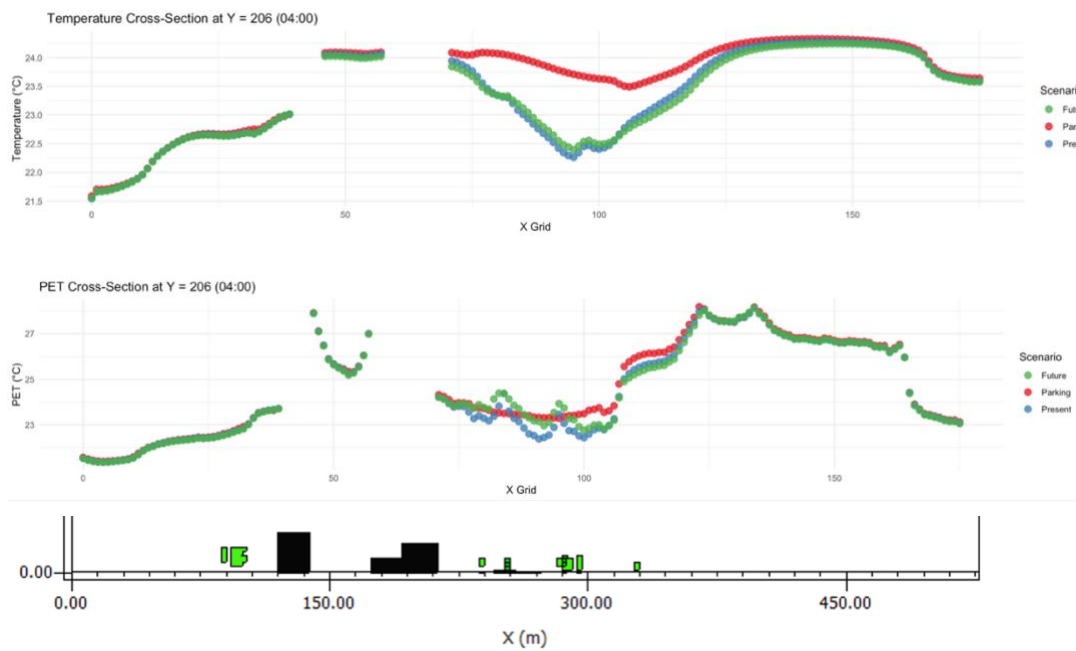


Figure 32: Cross-section at Y = 206 (along general park area) for temperature and PET at 04:00.

At 10:00 (Figure 33, Figure 34 and Figure 35), patterns began to invert: the streets enclosed by buildings started to have similar temperatures compared to the park, indicating that the park area heats up more quickly during the day due to the direct solar radiation. The temperature gap between the parking and vegetated scenarios widened in most locations, indicating a growing cooling effect from vegetation during the morning hours. Especially in the general park cross section (Figure 35), PET values were lower in the present scenario and lowest in the future scenario, further underscoring the positive cooling effect of vegetation. A notable drop in PET is visible at just over 300 m for the first two cross sections. This is the change to a shaded area (because of the build structure at 330 m) where MRT is drastically

reduced. Air temperature shows a more gradual decrease as it does not change as abruptly as MRT due to shade.

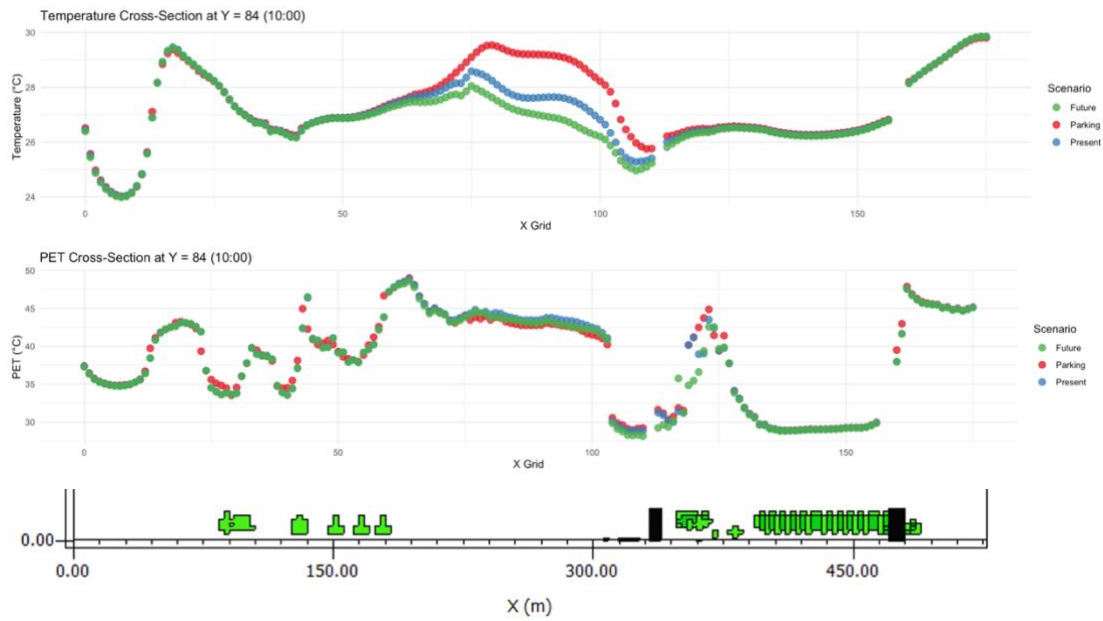


Figure 33: Cross-section at Y = 84 (along walkway) for temperature and PET at 10:00.

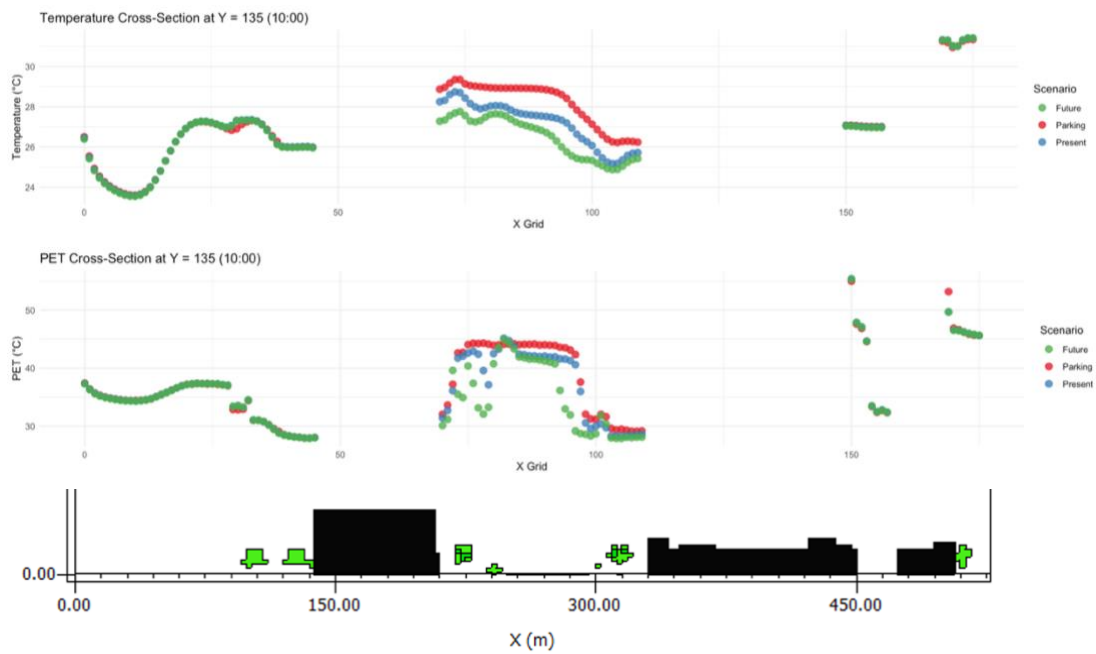


Figure 34: Cross-section at Y = 135 (along grass field) for temperature and PET at 10:00.

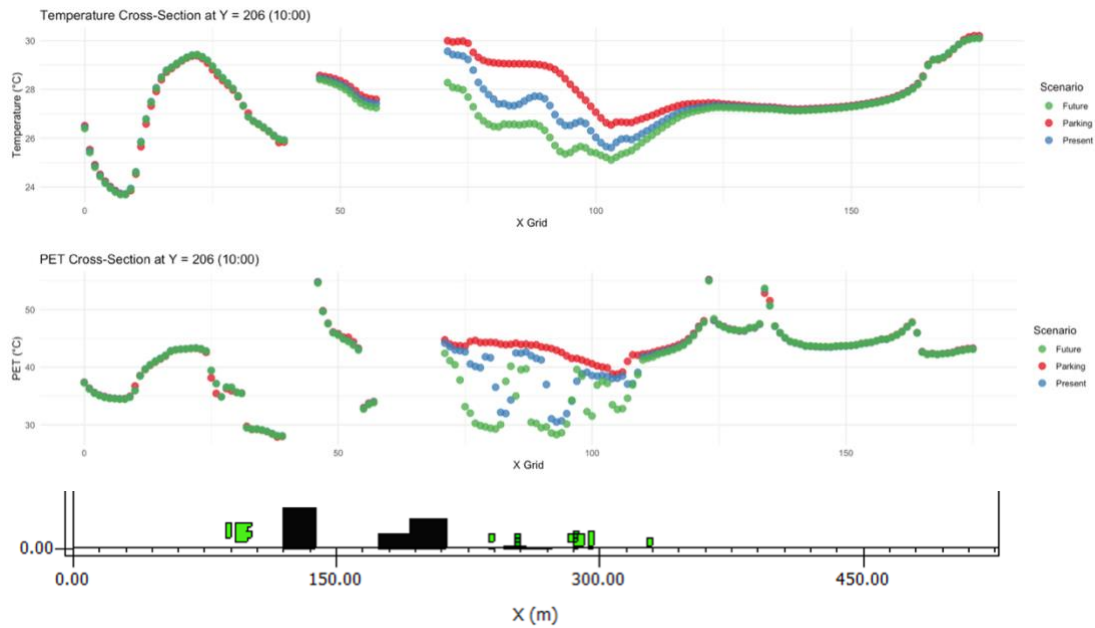


Figure 35: Cross-section at Y = 206 (along general park area) for temperature and PET at 10:00.

At 16:00 (Figure 36, Figure 37 and Figure 38), temperatures in the streets enclosed by buildings were lower than in the park across all cross sections. Air temperature differences between the present and future scenario became more pronounced, with the future scenario consistently showing the lowest values. PET along the walkway (Figure 36) remained similar across scenarios but showed distinct downward peaks in zones with tree cover. On the grass field (Figure 37), air temperatures for the parking and present scenarios were similar, while the future scenario remained cooler. The two major tree rows at both ends of the park are clearly visible, especially in Figure 37 and Figure 38 for the grass field and general park cross section.

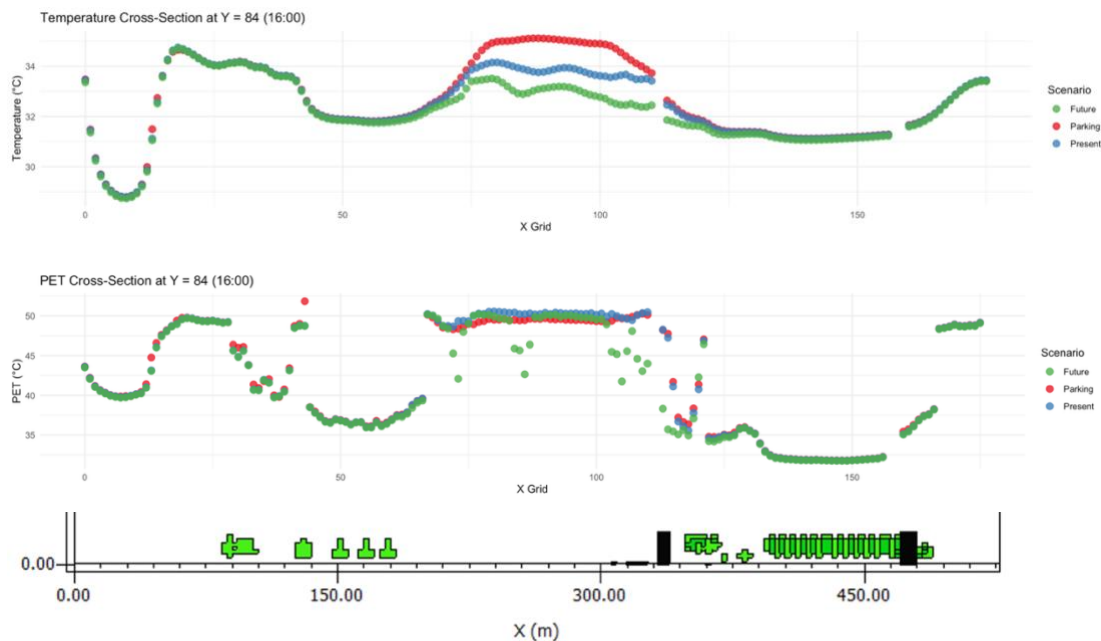


Figure 36: Cross-section at Y = 84 (along walkway) for temperature and PET at 16:00.

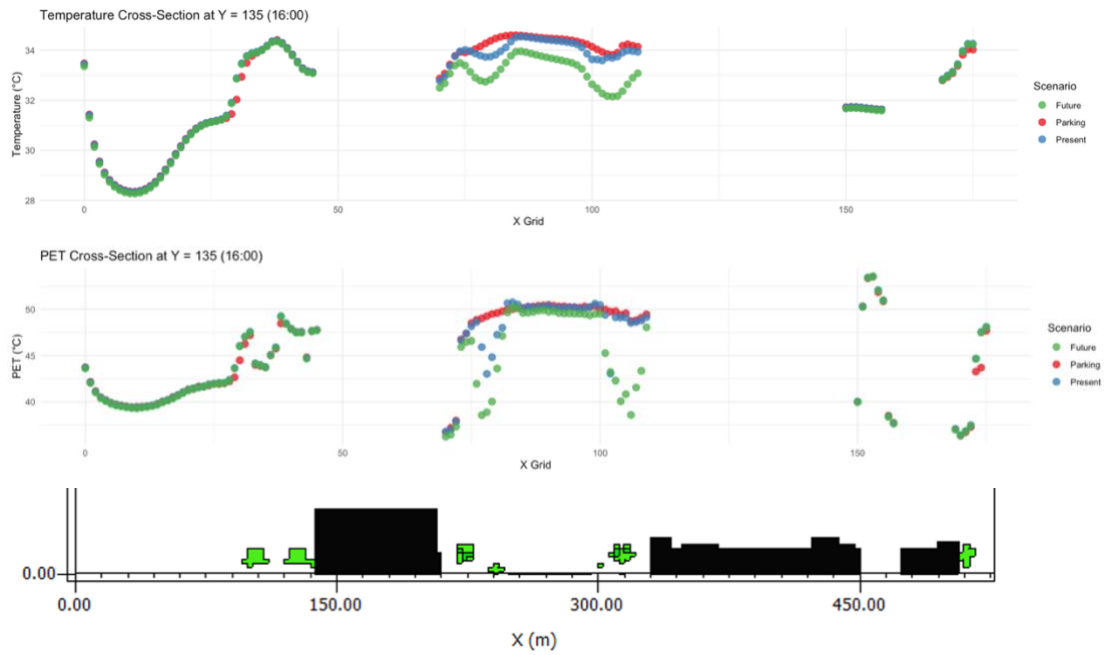


Figure 37: Cross-section at Y = 135 (along grass field) for temperature and PET at 16:00.

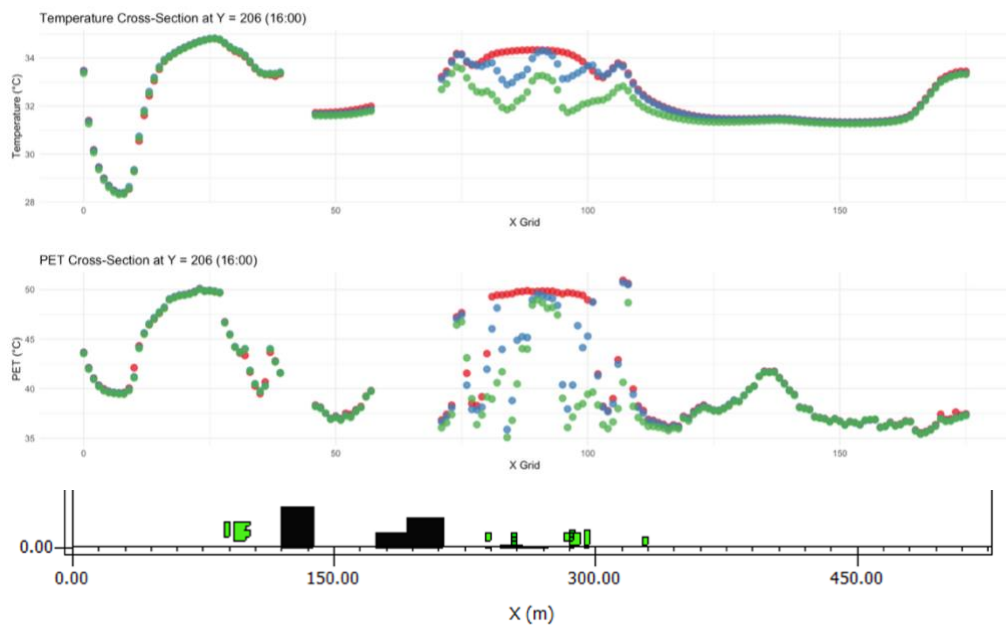


Figure 38: Cross section at Y = 206 (along general park area) for temperature and PET at 16:00.

Overall, the parking scenario exhibited more uniform temperature and PET profiles, whereas the present and future scenarios displayed greater variability, often with localized cooling peaks aligned with tree locations. This variability reflects the heterogeneous microclimatic effects of vegetation within the park.

In these cross sections the boundaries of the model are visible. At 10:00 and 16:00 an immediate decrease in both T and PET at the start (0 m) is visible because the Schelde is located at the boundary.

During the night this effect is slightly reversed because the water has a higher temperature than the given boundary condition.

4.2.5 Zone Analysis

Table 8 summarises the mean Physiological Equivalent Temperature (PET) for each zone under default, high metabolic rate and low metabolic rate conditions. Among the zones, the Stone Crossway recorded the highest average PET (50.3 °C), followed by the Sport Field (49.9 °C), the Grass Field (49.4 °C), and the Tree Row, which had the lowest PET (45.9 °C). The notably lower PET in the Tree Row suggests that shaded, vegetated areas may encourage pedestrian use while discouraging passage through more exposed, high-PET areas such as the Stone Crossway.

When metabolic rate increased to 6.28 met (based on 3 m/s running speed), such as during physical activity, PET rose substantially. Across most zones, exercising individuals (high metabolic rate) experienced a PET increase of 4–5 °C, with the tree row showing the largest increase (+7.97 °C) due to its lower baseline PET. Conversely, resting individuals with low metabolic rate (1.15 met, based on 0 m/s walking speed) experienced PET values approximately 3 °C lower than the default across all locations. From a public health and comfort perspective, these results indicate that intense physical activity during peak heat hours should be discouraged, even in shaded or vegetated areas, as elevated metabolic rates can push PET values into extreme heat stress categories.

Table 8: PET values for the different zones with default metabolic rate, high metabolic rate and low metabolic rate.

Zone	Default	High metabolic rate	Low metabolic rate
Grass field	49.4 °C	54.4 °C	46.5 °C
Sport field	49.9 °C	54.4 °C	47.0 °C
Stone crossway	50.3 °C	54.5 °C	47.4 °C
Tree row	45.9 °C	53.9 °C	42.9 °C

4.3 Additional Models

4.3.1 48 Hours

Extending the simulation to 48 hours produced only small differences in average air temperature and PET compared to the first day, visible in Figure 39 and Figure 40. On the second day, the parking scenario recorded an average air temperature of 28.6 °C, an increase of 0.5 °C relative to day 1. The present and future scenarios both showed an increase of 0.7 °C going to an average of 28.2 °C and 27.7 °C respectively for the second day. PET followed a comparable pattern: the parking scenario was 0.6 °C higher on day 2, while both present and future scenarios increased by 1.0 °C. At peak heats, differences between temperature for day 1 and day 2 reached 0.2 °C for the parking scenario and 0.3 °C for both vegetated scenarios. For PET the differences were 0.2 °C, 0.4 °C and 0.6 °C for parking, present and future respectively. These second day increases likely reflect cumulative heat storage effects, where residual heat from the previous day is retained in surface materials and released more slowly overnight. This stored heat reduces nighttime cooling potential and sets a warmer baseline for the following day, amplifying thermal stress during heatwaves.

The overall diurnal patterns remained consistent between the two days. However, during the second day, the present scenario warmed more rapidly in the morning compared to the parking scenario and reached higher temperatures during midday. At 15:00, the parking scenario once again recorded the highest values, reinforcing the persistent warming effect of low vegetation and hard surfaces. The greater second day warming during morning and early day in the present scenario is similar as Ambrosini et al. (2014) discovered for their 72-hour simulations. This unexpected pattern is explained by the latent heat flux being drastically reduced during the second day. Between the first and second day, the steeper increase in air temperature above the grass surface can be attributed to vegetation water stress. ENVI-met simulates this through stomatal resistance: as soil moisture becomes depleted, stomatal resistance increases, reducing transpiration and thus latent heat flux. With less evaporative cooling, a larger share of the available energy is converted into sensible heat, which accelerates the rise in air temperature. This explains why the grass location shows stronger warming on the second day, despite being cooler on the first day. Moreover, with limited latent heat flux, the grassy area warms the air faster due to its lower heat capacity compared to asphalt and granite. Appendix 6 shows the difference in stomatal resistance and latent heat flux between day 1 and 2.

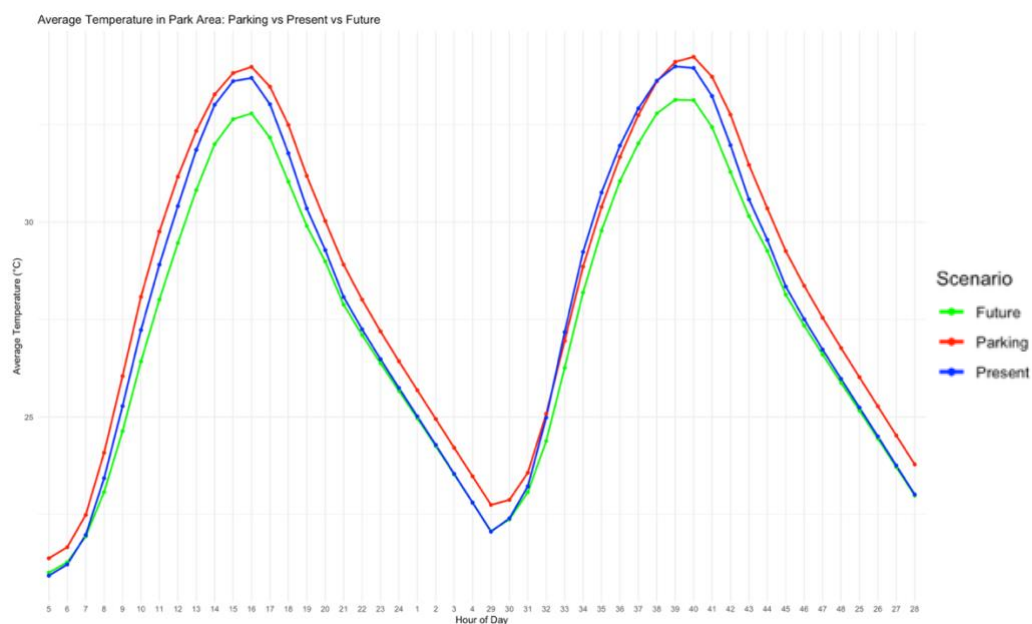


Figure 39: The average hourly temperature in the park area for all three scenarios during a period of 48 hours. The days start at 05:00. For the second day, each hour of day is 24 lower (e.g. 40 = 16:00).

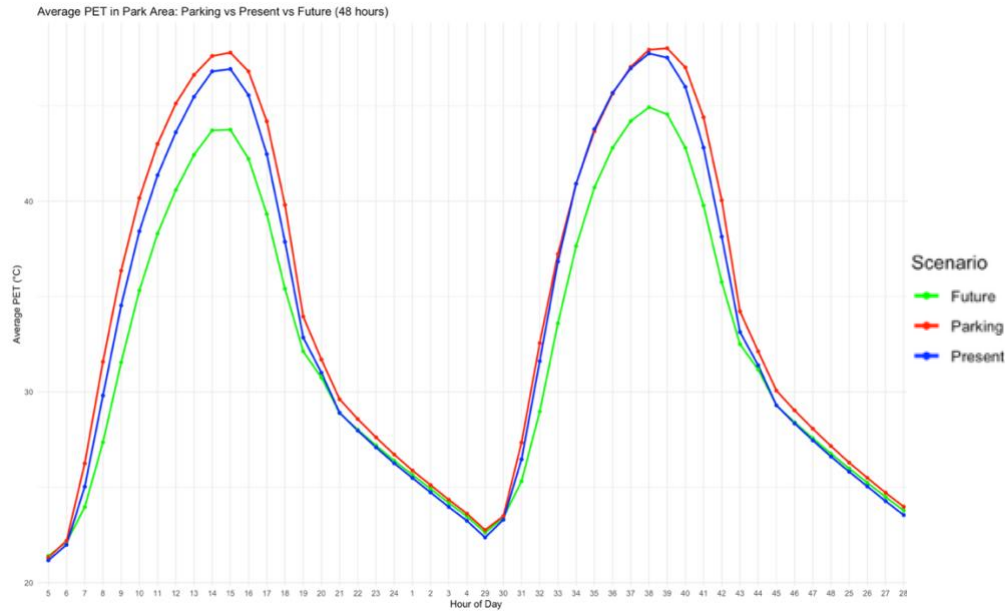


Figure 40: The average hourly PET in the park area for all three scenarios during a period of 48 hours. The days start at 05:00. For the second day, each hour of day is 24 lower (e.g. 40 = 16:00).

4.3.2 Wind Direction

A change in wind direction to SE altered both air temperature and PET values. For instance, at 16:00 the average air temperature was 32.6 °C, which is 1.1 °C lower than under the prevailing SW wind conditions. However, the average PET increased to 46.2 °C, 0.6 °C higher than in the SW wind case. This apparent contradiction arises from a decrease in average wind speed in the park, from 1.48 m/s to 0.890 m/s, which reduced convective heat loss of the human body and increased perceived thermal stress despite the lower air temperature. This illustrates a key principle of thermal comfort: PET is influenced not only by air temperature and radiation but also by wind speed, with lower air movement significantly reducing the body's ability to dissipate heat. The lower windspeed is caused by the array of buildings blocking the airflow.

The spatial distribution of the PET classification can be found in Figure 41 with the exact percentages visible in Table 9. At 04:00, only 2.5% of the park experienced comfortable conditions, while 97.2% fell into the slight heat stress category and the remaining 0.3% into moderate heat stress. This reduction in comfortable conditions is mainly caused by the decreased nighttime cooling capacity when airflow is blocked and slowed down. By 10:00, extreme heat stress already covered 53.4% of the park, with the remainder comprising 20.7% strong heat stress, 25.6% moderate heat stress, and 0.3% slight heat stress. At 16:00, extreme heat stress increased to 76.1%, followed by 23.2% strong heat stress and 0.7% moderate heat stress. These results suggest the potential of natural ventilation systems in increasing thermal comfort. Additionally, the effect of a NW wind, with no blocking of the buildings might result in lower PET values as this can introduce a sea breeze effect. Additionally, at night the upwind section of the streets next to the park experienced comfortable conditions at the start of the street, downstream experienced slight heat stress just like most of the park.

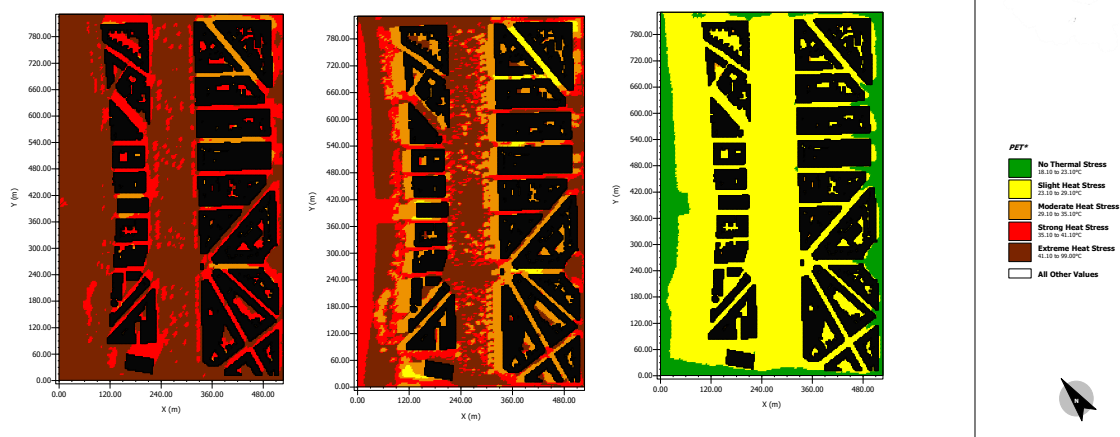


Figure 41: PET classification at 16:00, 10:00 and 04:00 in the present scenario with a SE wind.

Table 9: The changes in PET classification introduced by a change in wind direction from SW to SE.

	At 16:00	At 10:00	At 04:00
Extreme heat stress	75.6% → 76.1%	48% → 53.4%	0.0% → 0.0%
Strong heat stress	24.0% → 23.2%	23.7% → 20.7%	0.0% → 0.0%
Moderate heat stress	0.4% → 0.7%	16.1% → 25.6%	0.3% → 0.3%
Slight heat stress	0.0% → 0.0%	12.2% → 0.3%	48.3% → 97.2%
Comfortable	0.0% → 0.0%	0.0% → 0.0%	51.4% → 2.5%

4.3.3 Wind Speed

Figure 42 and Table 10 indicate that increased wind speed consistently improved thermal comfort across all investigated hours. The largest benefit occurred in the morning (10:00), when extreme heat stress coverage was reduced by 44%, leaving only 4% of the park in this category. At night (04:00), comfortable conditions prevailed over 84.4% of the park, indicating highly effective nighttime cooling. In the afternoon peak (16:00), the reduction in extreme heat stress was more modest at 7.3%, but still noteworthy. These results indicate that interventions enhancing wind flow or increasing local wind speeds could substantially improve thermal comfort, particularly during the morning warm-up and nighttime cooling periods. Ideally increased wind speeds are combined with smart placement of trees to enhance cooling breezeways and optimally cooling the area.

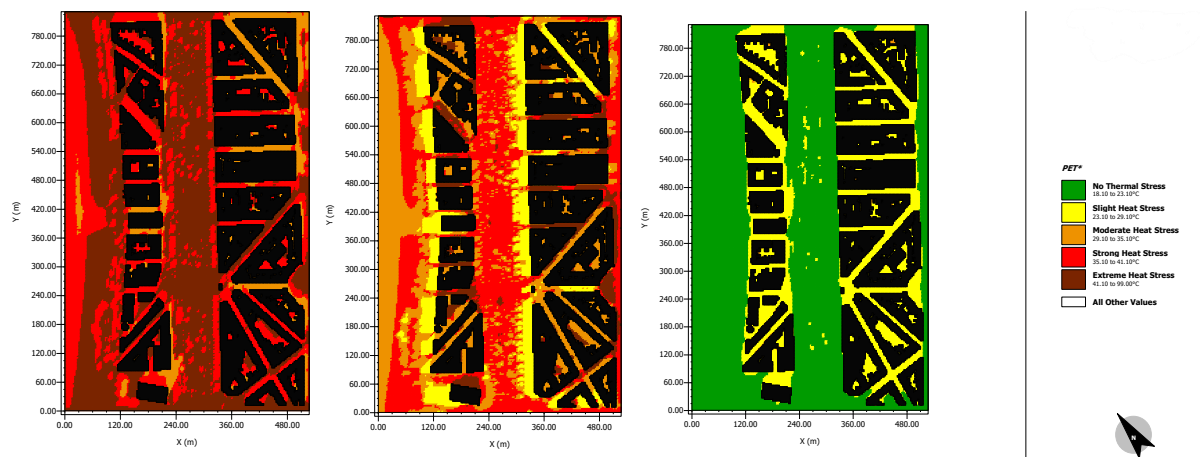


Figure 42: PET classification at 16:00, 10:00 and 04:00 in the present scenario with a windspeed of 5 m/s.

Table 10: The changes in PET classification introduced by a change in wind speed from 2 m/s to 5 m/s.

	At 16:00	At 10:00	At 04:00
Extreme heat stress	75.6% → 68.3%	48.0% → 4.0%	0.0% → 0.0%
Strong heat stress	24.0% → 26.6%	23.7% → 56.2%	0.0% → 0.0%
Moderate heat stress	0.4% → 5.4%	16.1% → 21.8%	0.3% → 0.2%
Slight heat stress	0.0% → 0.0%	12.2% → 18.0%	48.3% → 15.4%
Comfortable	0.0% → 0.0%	0.0% → 0.0%	51.4% → 84.4%

4.3.4 Radiation

Differences in air temperature, humidity, and wind speed between the base (30°) and advanced radiation (15°) settings were minimal, with mean deviations close to zero (Table 11). Some grid cells exhibited slightly higher PET differences, but the overall averages ranged only from 0.04 °C to 0.072 °C. These small PET variations were primarily driven by minor differences in MRT, which averaged 0.10 °C to 0.156 °C between the two settings. The spatial MRT pattern of the park remained essentially unchanged, with the largest differences occurring in non-shaded areas, where MRT values were higher. Since the radiation setting influences only the way radiation is modelled and does not alter the thermal properties of materials or evapotranspiration, MRT is the only thermal comfort variable slightly affected. While the advanced radiation setting increased simulation run time by approximately three hours, the results indicate that the default radiation setting captures sufficient spatial and temporal detail for this study. Although an even higher detail setting could be explored, the validated MRT performance against field measurements suggests that the additional computational demand is unlikely to yield meaningful improvements.

Table 11: Mean differences of air temperature, MRT, RH, WS and PET between the base (30°) and advanced (15°) radiation setting.

Time	Mean temperature difference (°C)	Mean MRT difference (°C)	Mean RH difference (%)	Mean WS difference (m/s)	Mean PET difference (°C)
4	0.0149	0.105	0.00137	0.000274	0.0400
10	0.0142	0.156	0.00123	0.000419	0.0716
16	0.0105	0.153	0.000435	0.000350	0.0672

4.3.5 Grid Size

Table 12 represents the average differences between the base grid and the broader (B) and finer (F) grid. Across the three selected hours, mean differences between the base grid and the coarser configuration were small for all variables, with temperature differences not exceeding 0.1 °C, MRT differences within ~0.6 °C, RH differences below 0.02 %, WS differences below 0.01 m/s, and PET differences within ~0.3 °C. Comparisons between the base grid and the finer configuration similarly showed minimal deviations, with temperature differences ≤ 0.13 °C, MRT differences ≤ 0.33 °C, RH differences ≤ 0.04 %, WS differences ≤ 0.04 m/s, and PET differences ≤ 0.19 °C. MRT showed the largest differences, likely because it is highly sensitive to shading and surface geometry. Changes in grid resolution can slightly alter shadow patterns and radiative exchanges, leading to greater variability

than for the other microclimatic variables. Just like Crank et al. (2018), who argued that grid effects can be considered negligible when they are an order of magnitude smaller than the impacts of the interventions being studied, the present differences fall well within such a margin, supporting the conclusion that the model results are effectively grid independent for the purposes of this study.

Table 12: Average differences in temperature, MRT, RH, WS and PET for the finer grid (2 x 2 m) (F) and the broader grid (4 x 4 m) (B). The base present scenario (3 x 3m) is the reference.

Time	Temp F (°C)	Temp B (°C)	MRT F (°C)	MRT B (°C)	RH F (%)	RH B (%)	WS F (m/s)	WS B (m/s)	PET F (°C)	PET B (°C)
04:00	0.05	0	0.03	0.04	-0.02	0.01	0.02	-0.01	0.02	0.02
10:00	0.04	-0.1	0.22	-0.52	0.05	-0.01	0.04	-0.01	0.03	-0.27
16:00	0.14	-0.12	0.50	-0.63	0.01	0.01	0.03	-0.01	0.26	-0.34

4.3.6 Telescoping (Grid Stretching)

Across the three selected hours, the introduction of telescoping at 15 m (T_15) or 45 m (T_45) produced negligible changes in all microclimatic variables relative to the base present scenario (Table 13). Air temperature differences were smaller than 0.04 °C for both configurations at all times. MRT differences were similarly small, not exceeding 0.14 °C for T_15 and 0.0 °C for T_45. Relative humidity changes remained within ± 0.03 %, wind speed differences within ± 0.02 m/s, and PET differences within ± 0.11 °C (T_15) and ± 0.04 °C (T_45). These values are even lower than for the grid testing, suggesting that for the present study domain, telescoping has minimal influence on near-surface microclimate outputs.

Table 13: Average differences in temperature, MRT, RH, WS and PET for the telescoping starting at 15 m (T_15) and for the telescoping starting at 45 m (T_45). The base present scenario is the reference.

Time	Temp T_15 (°C)	Temp T_45 (°C)	MRT T_15 (°C)	MRT T_45 (°C)	RH T_15 (%)	RH T_45 (%)	WS T_15 (m/s)	WS T_45 (m/s)	PET T_15 (°C)	PET T_45 (°C)
04:00	0.01	0.0	-0.01	0.0	0.0	-0.01	-0.01	-0.01	0.01	0.01
10:00	0.01	0.01	0.14	0.0	0.0	0.03	-0.02	0.02	0.11	-0.04
16:00	-0.04	0.02	0.06	0.0	-0.01	0.0	-0.01	0.0	0.01	-0.01

4.3.7 Enhanced Detail

The introduction of brick walls with window consideration resulted in only minor changes across all examined parameters (Table 14). Compared to the base configuration, air temperature differences ranged from -0.02 to -0.04 °C, MRT differences from -0.15 to -0.31 °C, and PET differences from -0.07 to -0.15 °C across the three representative hours. All changes were negative, indicating slightly lower values for the brick configuration, but the magnitude of these differences is negligible. This suggests that wall material changes of this nature have minimal influence on park-scale thermal conditions under the simulated scenarios. The investigation of other materials and surface temperatures could be an interesting topic for future research.

Table 14: Average differences in air temperature, MRT and PET between the base and enhanced detail / brick model.

Time	Mean temperature difference (°C)	Mean difference (°C)	MRT Mean difference (°C)	PET Mean difference (°C)
4	-0.040	-0.150	-0.070	
10	-0.020	-0.310	-0.150	
16	-0.030	-0.230	-0.120	

5. General Remarks and Recommendations for Future Research

The results of this study confirm that the transformation of a paved parking lot into a vegetated urban park can deliver measurable improvements in thermal comfort and moderate the urban heat island effect. The reductions in air temperature (0.6 °C and 1.1 °C for the whole day or 0.3 °C and 1.2 °C for the peak hour) are somewhat similar than the 1 °C typically reported for urban parks in systematic reviews (Bowler et al., 2010). Studies discussing higher reductions up to 7 °C (Ghale et al., 2025), are not reached in this thesis, which is likely explained by the before–after design of this study rather than a direct comparison between park and non-park sites. The decreases in PET of 1.2 °C in the present scenario and up to 4.6 °C in the future scenario align well with findings that parks and shaded green spaces can provide substantial relief from thermal stress at pedestrian level (Zölch et al., 2016).

The comparative analysis of the three scenarios illustrates the central role of vegetation, and in particular mature tree canopies, in lowering both air temperature and PET during the hottest hours of the day, delaying the onset of extreme heat stress, and reducing its duration. This confirms previous work showing that canopy cover is among the most effective measures for urban cooling (Shashua-Bar et al., 2010; Rahman et al., 2019, 2020) and can lower thermal stress categories (Coutts et al., 2015). To maximise these benefits, long-term planning should provide adequate space for full canopy development, select species with favourable traits such as high leaf area index or diffuse-porous wood anatomy, and ensure continuous maintenance so that trees reach maturity. At night trees tend to have a reverse effect on air temperature and PET, because they block airflow and trap heat / radiation. This increase in MRT at night has already been pointed out by (Coutts et al., 2015). The value of grass cover and ground vegetation, which can also lower surface and globe temperatures (Armson et al., 2012), supports the case for multi-layered vegetation structures. Vegetation under stress showed lower temperature decrease, because the latent heat flux went down.

The results further highlight the importance of wind. Reduced airflow in certain configurations, such as southeast winds obstructed by surrounding buildings, led to higher PET despite lower ambient air temperatures, whereas increased wind speeds significantly enhanced thermal comfort, particularly in the morning and evening. These findings align with studies emphasising the importance of airflow in urban design, where tree arrangement and park layout can either improve or reduce ventilation (Coutts et al., 2015; Morakinyo & Lam, 2016). Preserving ventilation corridors, aligning planting strategies with prevailing winds, and avoiding excessive sheltering of breezeways should therefore be central considerations in park design.

Beyond the specific case of Zuidpark, the study reinforces the value of integrating field measurements with microclimate modelling for evaluating urban heat mitigation strategies. Previous research has shown that ENVI-met models can provide robust estimates of radiation and surface energy exchange but often require local calibration and validation for air temperature accuracy (Ayyad & Sharples, 2019; Ouyang et al., 2021). However, a literature review by Topalar et al. (2017) stated that multiple CFD

studies, including ENVI-met studies, are published without validation, especially comparative studies can be published without the need for (extensive) validation. Future research should ideally include pre- and post-intervention measurement campaigns to validate simulated changes more directly. Another improvement on the measurements conducted could be continuous measurements covering the three locations at the same time. Looking into remote sensing options to validate the model through thermal infrared sensing for surface temperatures could be another addition to the validation.

The model itself presented some additional remarks. Firstly, it should be noted that the parking model did not include the thermal and aerodynamic influences of parked or moving vehicles, which can affect MRT, air velocity, and local heat storage (Matias et al., 2025). This omission may result in under- or overestimation of thermal sensation, particularly under sunny or low-wind conditions. Secondly, the transition from 04:00 to 05:00, which is the end of the simulation, and the beginning of the simulation was smooth. The model ends with a higher temperature than it starts with, most likely linked to heat storage of the materials. If diurnal patterns are discussed, it could be wise to run models for an additional 24 hours, just like the additional model for 48 hours pointed out. Ambrosini et al. (2014) ran simulations for 72 hours and only used the third day for the results as it was clear that temperatures increased up to the third day (higher baseline for each day due to heat storage). Thirdly, the WS is probably overestimated as there are no buildings blocking the inflow of the model, while in the actual area there are buildings present in front of the boundary. A future simulation with a larger model area can investigate the potential difference. A prediction of the effect can be made based on the additional SE wind direction model as wind speed was slowed down in the park, reducing average PET slightly. Lastly, the sizes of the plane trees in the parking and present scenario are probably underestimated as they already seem well-grown and higher than 20 m. In the parking and present model, they are not fully matured and only 17,86 m high.

Further investigation for the impact of telescoping on the pedestrian level thermal environment is required. In this thesis the impact is negligible for starting at 15, 30 or 45 m. Although ENVI-met recommends only starting at a height higher than the highest building (ENVI-met Model Architecture, n.d.). Liu et al. (2018) even started telescoping with a factor of 10% after 2 m. Incorporating additional real-world features into modelling, such as parked vehicles (Matias et al., 2025) or full detail of wadi systems and other forms of blue-green infrastructure, would further improve simulation reliability and ensure a more realistic representation of heterogeneous urban environments

Expanding the zoning analysis to evaluate thermal suitability for different activities and times of day would provide more nuanced design guidance, ensuring shaded, ventilated, and open areas are distributed in line with park use. Additionally, UTCI can be calculated for these zones and used for thermal classification to discover whether there are significant differences with PET classification. The modelling framework applied here could also be extended to test other mitigation strategies emphasised in the literature review, such as water bodies (Manteghi et al., 2015), green walls (Koch et al., 2020), or reflective surfaces and green roofs (Santamouris, 2012), either individually or in combination.

This study supports the conclusion that well-designed urban parks can serve as critical climate adaptation solutions in temperate maritime cities.

6. Conclusion

This thesis investigated the effects of transforming a fully paved parking area into an urban park on local microclimate and thermal comfort, using Zuidpark in Antwerp as a case study. Through ENVI-met modelling of parking, present, and future scenarios, combined with field measurements, the research addressed four main questions.

- 1) Transformation effects: The conversion from parking lot to urban park reduced both air temperature and PET, thereby mitigating the local UHI effect and improving thermal comfort. Compared to the pre-park scenario, the present park configuration lowered mean PET by ≈ 1.2 °C during peak heat hours and expanded the share of the park within more acceptable PET thresholds, particularly during evening and night-time. At 16:00, the share of extreme heat stress declined by $\approx 4\%$ relative to the parking scenario, while comfortable or slight heat stress conditions became dominant at night. These results confirm hypotheses 1 and 2.
- 2) Effect of tree maturity: The future scenario, with fully developed canopies, further enhanced cooling. At peak hours, air temperature decreased by an additional 0.9 °C and PET by 3.4 °C compared to the present park. Moreover, the onset of extreme heat stress was delayed by 1 to 2 hours, and its duration was shortened. These findings support hypothesis 3, showing that mature tree cover substantially strengthens UHI mitigation and thermal comfort benefits. However, at night mature tree canopies can have a reverse effect by trapping heat and air flow.
- 3) Park vs. surrounding urban area: Cross-section analysis revealed that, at night, the park cooled more effectively than adjacent built-up streets, while during the day, the park exhibited higher temperatures and PET values. This partially validates hypothesis 4, confirming that the park has a cooling effect, but that surrounded build-up urban areas can have lower temperature and PET due to the provided shade of the buildings.
- 4) Optimal activity zones: Zone-level analysis identified continuous tree rows as the most suitable areas for resting, walking, and sports, owing to their reduced PET values. Conversely, paved crossways and exposed sports fields consistently produced the highest heat stress levels. The grass field provided slightly more comfortable conditions than the sports field. These results align with hypothesis 5, while also suggesting that the current park design partly matches optimal comfort zones, though exposed paved areas remain problematic during peak hours.

Overall, the redevelopment of Zuidpark demonstrates that urban parks can effectively mitigate local UHI intensity and improve outdoor thermal comfort, even in temperate maritime climates. By prioritising dense tree cover, diversifying surface materials, and ensuring ventilation pathways, planners can maximise the adaptive capacity of urban green spaces. This thesis thus provides empirical and model-based evidence to support climate-responsive urban design in Antwerp and comparable European cities.

7. Societal Finality

Heat stress represents a growing societal challenge in the context of accelerating climate change and urbanisation. As highlighted in the introduction and literature review, elevated temperatures are associated with significant increases in premature mortality and economic costs. Vulnerable groups, including children, the elderly, and individuals of lower socio-economic status, are disproportionately affected, as they often lack the means to mitigate or adapt to heat exposure. Consequently, heat stress is not only an environmental concern but also a pressing issue of public health and social equity.

The results of this thesis highlight the potential of targeted urban design interventions to alleviate heat stress in cities. By investigating the cooling effects of the redevelopment of Zuidpark, this study provides practical evidence that municipalities can successfully implement climate adaptation strategies. Local governments can therefore translate these findings into guidelines for park planning. Public health agencies may also employ such evidence to develop heat-exposure thresholds, similar to air-quality standards, thereby strengthening early warning systems and preparedness plans for vulnerable populations.

The private sector equally stands to benefit from these insights. Urban planners, architects, and landscape designers can incorporate vegetation structures, material choices, and spatial layouts that maximise thermal comfort into their projects. This aligns with a broader transition toward climate-sensitive design, where mitigation and adaptation measures are integrated into everyday development practices.

For Antwerp specifically, this research underscores the role of Zuidpark as a multifunctional climate adaptation project. The demonstrated thermal benefits add to the park's ecological, recreational, and social values, providing further justification for municipal investment in similar initiatives. By evidencing measurable improvements in thermal comfort, this thesis contributes to the policy goals outlined in the Antwerp Climate Plan 2030 and the Flemish Climate Adaptation Plan, which emphasise the deployment of nature-based solutions to mitigate climate risks. Finally, the fieldwork also revealed a high level of public interest, with passers-by expressing support and awareness of the importance of trees and vegetation. Such engagement indicates that this study not only generate policy-relevant knowledge but can also foster societal awareness and collective responsibility for adapting cities to a warming climate.

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Appendices

Appendix 1: Literature Table

Table 15: Literature table including similar papers.

NO.	Author (Year)	Study area	Objective / focus	Methods	Validation	Variables	TC indicator	Key findings
This study	Tim Goossens (2025)	Antwerp, Belgium	Assess the global effect of an urban park on air temperature and thermal comfort	ENVI-met + field measurements	Ta, RH and MRT	Canopy cover, tree species, shade, Surface materials	PET (+UTCI)	See conclusion
1	Karimi et al. (2020)	Tehran, Iran	impact of tree species and pavement albedo on thermal comfort in urban park	Modelling: ENVI-met + RayMan	Air temperature	Air temperature, surface temperature, wind speed, MRT, SVF, vegetation, albedo	PET	Pine trees with tall trunks improved comfort most; vegetation was more influential than albedo; SVF not reliable alone; low-albedo pavements better for PET
2	Sun et al. (2017)	Beijing, China	effect of green space and landscape on outdoor TC in a park	Modelling: ENVI-met + RayMan	Air temperature and relative humidity	Trees, grass, hardened ground, water, buildings, air temperature, RH, windspeed, MRT	PET	Tall trees most effective for TC; hardened surfaces worsen PET; uncovered zones inside parks may feel hotter than surrounding city at peak times.
3	Quad et al. (2016)	Putrajaya, Malaysia	Investigate intra-urban UHI and thermal comfort in low-rise, high-rise, and boulevard zones	Mobile & fixed measurements + modelling: ENVI-met	Air temperature	Ta, RH, WS, solar radiation (direct/diffuse/reflected), surface temp, building height	MRT, PET	Low-rise areas had highest PET; high-rise & boulevard cooler by up to 4°C; surface temp and reflected radiation raised PET; height and wind reduced it
4	Lai et al. (2023)	Shanghai, China	Assess impact of 17 different tree layouts on microclimate and thermal comfort in green space	Field measurements + Modelling: ENVI-met	Air temperature (WS and MRT were compared with simulated data as well)	Tree layout, Ta, RH, WS, MRT	PET	Tree shade reduced PET by 11 °C and MRT by 20°C; low-wind cavities raised PET by 7°C; wind and shade more influential than air temperature; recommendation to place trees downstream of wind

5	Abd Elraouf et al. (2022)	Port Said, Egypt	Validate ENVI-met for outdoor TC assessment	Field measurements + Modelling: ENVI-met + RayMan	Yes: Ta, MRT, RH, WS	Ta, MRT, RH, WS	PET, PMV, PPD, UTCI	PET and MRT predictions matched well with measured data; air velocity least accurate; ENVI-met is useable for the evaluation of outdoor thermal comfort in the domain of urban design
6	Battista et al. (2023)	Rome, Italy	Assess UHI mitigation strategies in urban square	ENVI-met field measurement	+ Ta and RH	Ta, RH, surface material, albedo, vegetation, shade	/	Grass pavers most effective (-2.1 °C); shade roofs and vegetation also helped
7	Alves et al. (2022)	Valladolid, Spain	Assess impact on microclimate in industrial area	NBS on field measurement	+ Ta	Ta, RH, WS, MRT, vegetation	/	NBS reduced air temperature by 4.96 °C and MRT by 19 °C; model less accurate for wind
8	Wang et al. (2023)	Hangzhou, China	Assess effects of tree canopy structure and tree coverage ratio	ENVI-met field measurement	+ Ta and RH	Tree layout, Ta, RH, vegetation type, canopy width	/	Dense trees lowered Ta by up to 2.6°C; wider canopies are more effective; cooling extended 6-15 m beyond trees
9	Yilmaz et al. (2024)	Istanbul, Turkey	Analyse TC during summer with multiple TC indices	Field measurements	/	Ta, RH, WS, land cover	PET, UTCI, PT, AT, HI, WBGT	Green districts showed lowest stress; Ta alone is insufficient to reflect comfort accurately; PET and PT captured variation the best
10	Boussaidi et al. (2023)	Annaba, Algeria	Assess impact of vegetation TC in two urban plazas	ENVI-met field measurements + surveys	+ Yes	Ta, RH, MRT, vegetation cover, plaza layout	PET, SET, UTCI	Vegetation reduced PET by up to 10 °C and MRT by 12 – 16 °C; ENVI-met reliable tool for studying urban microclimate

Appendix 2: Tree Map and Masterplan, Provided by the City of Antwerp



Figure 43: Tree map with all the species present on Zuidpark. The diameter of the circle represents the canopy size.



Figure 44: Masterplan conducted for Zuidpark with an indication of all surface materials used.

Upon request these maps can be provided in higher quality PD

Appendix 3: Materials Used

Table 16: All the materials used in the ENVI-met models.

Material	ENVI-met ID	Where	Model
Single stone granite	0200GS	Walkways	All
Dark asphalt	0200ST	Roads	All
Light-coloured concrete	0200PL	Pedestrian paths	Present, Future
Sandy loam	0200SL	Unsealed surfaces	All
Deep water	0200WW	The Schelde river	All
Default soil profile underneath a building	CELLAR	Ground under buildings	All
Sand	0200SD	Designated Park areas	Present, Future
Concrete pavement	0200PP	Paved areas	All
Grey-coloured concrete	0200PG	Paved areas inside the park	Present, Future

Appendix 4: List of Tree Species

Table 17: This list contains all the tree species present in the park area. Note that more trees are included in the total model but these are not mentioned in the list

Tree species	Most comparable tree species (if not present in ENVI-met database)	ENVI-met ID
<i>Acer campestre</i>	/	020020
<i>Acer monspessulanum</i>	<i>Acer campestre</i>	020020
<i>Aesculus indica</i>	<i>Aesculus hippocastanum</i>	020050
<i>Albizia julibrissin</i>	/	0000AJ
<i>Alnus glutinosa</i>	<i>Alnus x spaethii</i>	020039
<i>Alnus x spaethii</i>	/	020039
<i>Betula nigra</i>	<i>Betula pendula</i>	020111
<i>Carpinus betulus</i>	/	020070
<i>Catalpa bignonioides</i>	/	020641
<i>Cedrus libani</i>	<i>Picea abies</i>	0000C4
<i>Celtis australis</i>	<i>Alnus x spaethii</i>	020039
<i>Cercidiphyllum japonicum</i>	<i>Carpinus betulus</i>	020070
<i>Cladastris kentukea</i>	<i>Tilia cordata</i>	020010
<i>Clerodendron trichotomum</i>	<i>Malus domestica</i>	020100
<i>Cornus</i>	<i>Prunus padus</i>	010800

<i>Cornus kousa</i>	<i>Malus domestica</i>	020100
<i>Cornus mas</i>	<i>Prunus padus</i>	010800
<i>Corylus colurna</i>	/	020190
<i>Cydonia oblonga</i>	<i>Malus domestica</i>	020100
<i>Devidia incolucrata</i>	<i>Tilia cordata</i>	020010
<i>Fagus sylvatica</i>	/	020450
<i>Franklinia alatomahia</i>	<i>Malus domestica</i>	020100
<i>Gleditsia triacanthus</i>	/	020170
<i>Gymnocladus dioicus</i>	<i>Gleditsia triacanthos</i>	020170
<i>Halesia monticola</i>	<i>Tilia cordata</i>	020010
<i>Heptacodium miconioides</i>	<i>Sorbus aucuparia</i>	020025
<i>Juglans nigra</i>	<i>Juglans regia</i>	020430
<i>Liquidambar styraciflua</i>	/	020160
<i>Liriodendron tulipifera</i>	/	020652
<i>Maackia amurensis</i>	<i>Robinia pseudoacacia</i>	020090
<i>Magnolia grandiflora</i>	<i>Liriodendron tulipifera</i>	020652
<i>Magnolia loebneri</i>	<i>Malus domestica</i>	020100
<i>Malus domestica</i>	/	020100
<i>Metasequoia glyptostroboides</i>	/	030660
<i>Morus nigra</i>	<i>Tilia cordata</i>	020010
<i>Nyssa sylvatica</i>	<i>Tilia cordata</i>	020010
<i>Ostrya carpinifolia</i>	<i>Carpinus betulus</i>	020070
<i>Paulownia tomentosa</i>	/	020031
<i>Pinus parviflora</i>	<i>Pinus sylvestris</i>	020027
<i>Pinus sylvestris</i>	/	020027
<i>Platanus hispanicus</i>	/	020060
<i>Prunus domestica</i>	<i>Prunus avium Plena</i>	020140
<i>Prunus padus</i>	<i>Prunus padus</i>	010800
<i>Prunus x yedoensis</i>	<i>Prunus avium Plena</i>	020140
<i>Pseudolarix amabilis</i>	<i>Ginkgo biloba</i>	020150
<i>Pterocarya fraxinifolia</i>	<i>Fraxinus excelsior</i>	020080
<i>Pyrus calleryana</i>	<i>Malus domestica</i>	020100
<i>Pyrus communis</i>	<i>Malus domestica</i>	020100
<i>Pyrus salicifolia</i>	<i>Malus domestica</i>	020100
<i>Quercus cerris</i>	<i>Quercus robur</i>	020040
<i>Quercus Robur</i>	/	020040
<i>Robinia pseudoaccaria</i>	/	020090
<i>Robinia x margaretta</i>	<i>Robinia pseudoaccaria</i>	020090
<i>Salix alba</i>	/	020600
<i>Sorbus domestica</i>	<i>Sorbus aucuparia</i>	020025
<i>Styphnolobium japonicum</i>	<i>Gleditsia triacanthos</i>	020170
<i>Taxodium ascendens</i>	<i>Populus tremula</i>	020200
<i>Taxus baccata</i>	<i>Picea abies</i>	0000C4
<i>Tilia cordata</i>	/	020010
<i>Tilia tomentosa</i>	<i>Tilia cordata</i>	020010

<i>Toona sinensis</i>	<i>Gleditsia triacanthos</i>	020170
<i>Ulmus (New Horizon)</i>	<i>Ulmus x hollandica Lobel</i>	020120
<i>Zelkova serrata</i>	<i>Prunus avium Plena</i>	020140

Appendix 5: MRT and WS differences at night

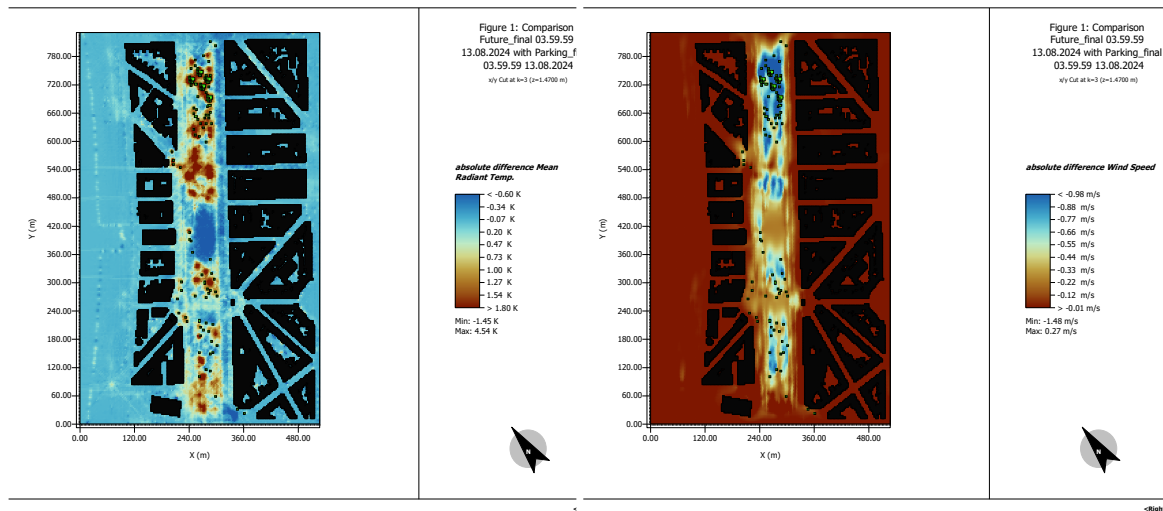


Figure 45: Difference in radiant temperature (a) and wind speed (b) between the parking and future model at night. The future model has higher MRT and lower WS in areas with small trees.

Appendix 6: Latent heat flux and stomatal resistance differences for the present scenario

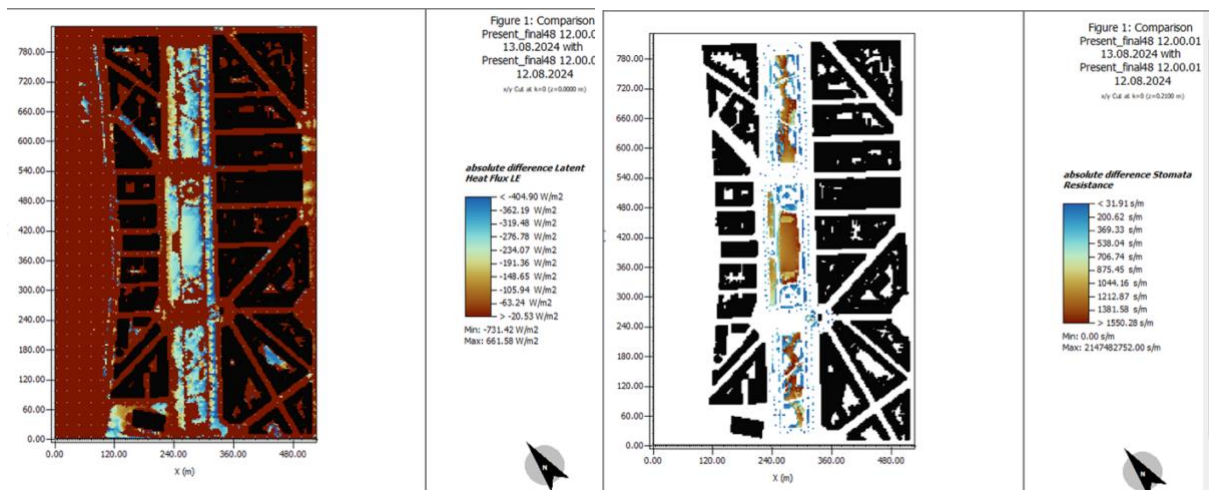


Figure 46: Difference between latent heat flux (a) and stomatal resistance (b) between day one and two for the present scenario. The second day has lower latent heat flux and higher stomatal resistance.

