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Assessment of tree data configurations on cooling effects in urban settings

Master's Thesis

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Picture cover page: The Hague by Arjan de Jager (https://www.independent.co.uk/climate-change/sustainable-living/the-hague-netherlands-sustainable-city-b1859944.html)

Title	Assessment of tree data configurations on cooling effects in urban settings
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Abstract

This study assesses the impact of tree placement strategies on thermal cooling in Dutch urban areas, focusing on their influence on thermal comfort. First, a literature study is conducted to answer the first and second research questions of what may be expected of trees regarding thermal comfort and the most optimal planting pattern for thermal comfort. In the methodology, three urban configurations are designed, two tree-planting scenarios are selected, and the Tygron software is detailly explained to answer the research question of how trees' thermal comfort can three urban configurations are designed, two tree-planting scenarios are selected, and the Tygron software is detailly explained to answer the research question of how can trees' thermal comfort be modelled using Tygron software. Three neighbourhoods in The Hague are selected to model conceptual neighbourhoods versus the real world. This answers the research question of how the model's results can be compared and configurated with current tree configurations. The sensitivity of the Tygron software is tested by adjusting meteorological data and answering the research question of the models' sensitivity by adjusting meteorological data. The study finds that trees positively impact thermal comfort by reducing PET through shading, evapotranspiration, and blocking solar radiation. The placement of trees also affects their cooling ability, with single trees in a line resulting in a lower PET than a pair of two trees planted with an interval of two trees, between 0,1-1,4 °C for road and 0,8-1,1°C for sidewalk measurements. The study highlights the impact of the shadow effect on PET results, with trees and buildings both affecting the PET. The Tygron software has been used to model urban configurations, plant trees, and calculate PET, and the study found that the location of measurement points and the height of trees in the model affect PET results. Overall, this study contributes to the existing knowledge gaps in research, such as 3D modelling and the Tygron software regarding thermal comfort and tree placement, providing valuable insights for future urban planning and tree planting strategies to improve thermal comfort in Dutch urban areas.

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Chapter 1

Introduction

More than half of the world's population lives in urban areas, which will grow to 68 per cent in 2050 (United Nations Human Settlements Programme, 2022). The increase in urbanisation leads to environmental problems in urban areas, such as climate change, extreme weather conditions and urban heat islands (UHIs) (Wang et al., 2022). Urban heat islands are cities' most studied climate effects (Filho et al., 2017). The UHI refers to the temperature difference between the built-up areas and their natural surroundings and is caused by human activity (Icaza et al., 2016; Filho et al., 2017). These environmental problems put pressure on the liveability of cities (Sharma et al., 2021). The leading cause of UHIs is the modification of land surfaces, meaning the removal of vegetation and the creation of paved surfaces and built-up areas (Filho et al., 2017; Abdi et al., 2020; Sharama et al., 2021). Removing vegetation and covering cities in built-up areas results in more heat storage (Marando et al., 2022). Consequences of UHIs are heatwaves, uncomfortable living conditions and extremer weather events.

One of the most effective ways to mitigate UHIs is by using urban green space (UGS) (Wang et al., 2022). Trees and vegetation provide natural cooling effects such as shading and evaporation of water from soil and evapotranspiration from leaves (Filho et al., 2017). This is known as thermal cooling. Trees provide a cooling effect because of shading, and trees release water via their leaves into the atmosphere, known as transpiration. This process cools the surrounding air. The presence of vegetation benefits the environment in a way that it sequesters carbon, releases oxygen and reduces temperature. UGS have an average lower temperature of 1-2 °C than the surrounding temperature (Abdi et al., 2020; Wang et al., 2022).

In the Netherlands, extreme heat occurs more frequently and intensely nowadays. The impact of heat stress in the Netherlands is a decrease in the liveability of cities, an increase in disease and mortality among the elderly, and a decrease in sleep quality and labour productivity (Klok & Kluck, 2018). It is expected that temperatures will increase even more (Rijksoverheid, 2022; Rousi et al., 2022). Previous research has already studied UHIs in the Netherlands (Steeneveld et al., 2011; Van Hove et al., 2011 & Icaza et al., 2016). In the research of Steeneveld et al. (2011), the UHI in 27 cities in the Netherlands has been studied. The UHI is defined as the urban air temperature minus the rural air temperature. Their study shows that the UHI decreases with an urban green cover, suggesting that the urban green vegetation significantly impacts extremely hot days (Steeneveld et al., 2011). Van Hove et al. (2011) focused on finding a relationship between UHI and city features, such as city size, configuration, and structure. This study concludes that high-density urban areas, with more than 85 per cent of the environment built, show a high UHI intensity. Urban green has a mitigating effect on the UHI. The average air temperature in an urban park is 1°C lower than in non-green areas. Trees provide shadow and lower air temperature (Van Hove et al., 2011). Icaza et al. (2016) studied the thermal behaviour of provincial parks during heat waves in the Netherlands to provide adaptation guidelines. Land use patches, such as forests, grassland, built areas, and more, were analysed based on their thermal behaviour using land surface temperature. Their study concludes that most hotspots with high temperatures are located next to grassland. To increase the cooling capacity of those patches, land use should change, or the NDVI of the existing grassland patches should increase (Icaza et al., 2016).

Cities that experience UHIs need to aim for adaptation strategies and restore ecosystem services, which means adjusting to the effects of high temperatures. Mitigation strategies must prevent cities from experiencing UHIs through previous adjustments. Urban planning is essential in avoiding UHIs because heat stress can be mitigated with appropriate urban design (Steeneveld et al., 2011; Taleghani et al., 2015). Urban greening is an essential topic in Dutch urban planning. Climate change is the Dutch National Environmental Vision (NOVI) priority. NOVI, the future perspective for 2050, presents climate-resilient cities where water and green prevent heat stress and flooding (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019).

In the Netherlands, taking heat adaptation actions at the local and municipal levels has yet to be realised (Klok & Kluck, 2018). Abdi et al. (2020) studied the importance of landscape patterns and the different arrangements of green spaces on temperature. They defined that the location of green spaces affects temperature and the exchange rate of heat in the environment. By appropriately planting trees, the temperature in urban areas can be reduced (Abdi et al., 2020). Urban planning plays an important role here, and little research explored how to design tree locations regarding UHIs and how trees influence cooling in urban areas (Zhao et al., 2018).

1.1 Research problem and objectives

1.1.1 Research problem

The relationship between trees and the cooling effect on urban areas and the UHI has been studied previously. In the scientific literature, some research has been conducted on the placement of trees in urban areas related to spatial planning concepts (Klemm et al., 2017; Lenzholzer & Van den Brink, 2017; Zhao et al., 2018 & Abdi et al., 2020). However, in the Netherlands, scientific research has yet to be found where the relationship between Dutch spatial planning concepts of neighbourhoods, the UHI and the placement of trees has been studied. Since warmer weather conditions and heat waves have occurred more recently, climate change is a topic with increasing attention. A recently published study by Ottburg et al. (2022) investigated the cooling effect of tiny forests with the result that the ground temperatures in tiny forests can be 20 °C lower than the surrounding. It will be interesting to apply these results in Dutch neighbourhoods and study the effect of the placement of trees on thermal cooling.

1.1.2 Research objectives

The overall research objective of this thesis is to assess tree placement concepts in urban planning and their influence on the thermal cooling effect in Dutch urban areas. The trees' cooling effect is analysed using the following planting strategies: spread, concentration, dilution, and densification. The idea of the concepts spread and concentration is to examine if the placement of trees, contiguous with a minimum spacing between trees or separated with wide spacing, has a different cooling effect in neighbourhoods. Dilution and densification focus on planting trees solidarity in a single or double row. Here, the focus is on the row density. Furthermore, paved surfaces' role in thermal comfort and the role of trees are studied. Tree species are studied, specifically whether planting different trees will increase the cooling effect in neighbourhoods. The following questions are answered to meet the research objective:

1. What may be expected of trees regarding thermal comfort?
2. How can trees be placed for optimal thermal comfort?
3. What form of urban configuration should be used to verify the impact of tree placement on thermal comfort?
4. How can trees' thermal comfort be modelled using Tygron software?
5. What is the models' sensitivity by adjusting meteorological data?
6. How can the model's results be compared and configurated with current tree configurations?

1.2 Research Scope

The following subjects are out of scope in this thesis. Firstly, a detailed design of urban planning is used. This design is based on the built-up area, paved surfaces and tree arrangements. Features such as water surface are not taken into account, although it influences thermal comfort. Secondly, this study does not cover in-depth research on Dutch urban planning. Explained is how neighbourhoods are set up and different neighbourhood structures are analysed; however, the question of why this has been done in a specific way is out of scope. Thirdly, the thermal impact of trees over time is not studied. Trees grow, and over time this will have a more extensive effect on thermal cooling. Finally, this thesis only focuses on thermal cooling as a climate issue, meaning that flooding or carbon emissions are not studied.

1.3 Reading Guide

The second chapter summarises previous research on urban heat islands regarding thermal comfort. Furthermore, different tree species and their effect on thermal comfort are studied in detail. Also, previous studies on tree placement and their effect on thermal comfort are studied. As a result, the first and second research questions of what may be expected of trees regarding thermal comfort and planting pattern are answered. In the third chapter, the methodology of this thesis is explained in detail. First, the design of the urban configuration is clarified, and the planting patterns are presented. Second, techniques are shown to research with the Tygron software. Furthermore, the selected geodata is shown and explained why and how this data will be used to perform the study. This chapter answers research questions three and four. The results of the study are presented in chapter four. The results are discussed according to the first four research questions, and the model's sensitivity is evaluated by answering question five. Furthermore, research question six is answered where the outcomes of this research are implemented and tested on three Dutch neighbourhoods. In the discussion and conclusion, the main conclusions of this study are presented, and recommendations for further research are given.

Chapter 2

Theoretical Background

This chapter starts with the cooling characteristics of trees. Second, the Physiological Equivalent Temperature (PET) is explained and compared with air temperature. Finally, the effect of trees on thermal comfort at a local/neighbourhood scale is explained. This chapter answers research questions "*What may be expected of trees regarding thermal comfort?*" and "*How can trees be placed for optimal thermal comfort?*".

2.1 Trees cooling characteristics

Extensive scientific research shows that UHIs influence cities' thermal comfort and liveability. Thermal comfort for humans describes a person's condition of mind in terms of feeling too warm or too cold. UHIs threaten the thermal comfort of humans in urban areas and the quality of life (Wang et al., 2022). Besides climate conditions, also personal human characteristics such as gender and culture impact human behaviour, and subjective evaluation of the environment influence thermal comfort (Lai et al., 2020). According to Hami et al. (2019) and Marando et al. (2022), spatial factors that influence thermal comfort are urban space morphology, the placement and design of spaces, and vegetation. The transition of natural surfaces into built-up paved areas using materials like cement, asphalt and concrete reduces the rate of evapotranspiration, rainwater absorption and the reflectivity of the surface changes (Hsieh et al., 2016; Filho et al., 2017; Hami et al., 2019; Sharma et al., 2021). Replacing vegetation and trees with built-up areas minimises the natural cooling effects of shading and evaporation of water from soil and leaves-evapotranspiration (Filho et al., 2017).

There are possibilities to reduce UHIs and ensure thermal comfort. These are the insulation of buildings (Hami et al., 2019), a change in urban morphology (Marando et al., 2022), water use for a cooling effect in cities (Hami et al., 2019) and green infrastructures (Hsieh et al., 2016). Using green infrastructures is the most effective strategy for mitigating UHIs and thermal comfort (Hsieh et al., 2016; Hami et al., 2019; Marando et al., 2022; Wang et al., 2022). The effects of green infrastructures are sequestering carbon, oxygen release, and reducing temperatures due to shading and evapotranspiration (Hami et al., 2019). Vegetation can lower the temperature by 1 to 2°C compared to the surrounding temperature (Wang et al., 2022). Trees significantly reduce the negative impacts of UHIs (Zhao et al., 2018; Abdi et al., 2020; Marando et al., 2022;).

Trees are the most effective vegetation for mitigating UHIs for several reasons. The shading effect of trees intercepts short-wave solar radiation by leaves and reduces the amount of radiation penetration to the surface. Trees are thus able to reduce air and surface temperature through their shading effect (Zhang et al., 2018; Zhao et al., 2018; Abdi et al., 2020). Furthermore, trees have a cooling effect because they can absorb heat and transform this into vapour, and trees release water vapour through their leaves; this process is known as evapotranspiration (Fan et al., 2015; Zhang et al., 2018; Zhao et al., 2018; Lee et al., 2020; Marando et al., 2022). Another reason trees are effective is the possibility to direct wind flows, which have a ventilation effect in cities. Placing trees at specific locations influences the wind's direction; for example, wind corridors promote ventilation and shading in parks and improve thermal comfort (Hsieh et al., 2016; Hami et al., 2019). Figure 2.1 shows the cooling effect of trees.

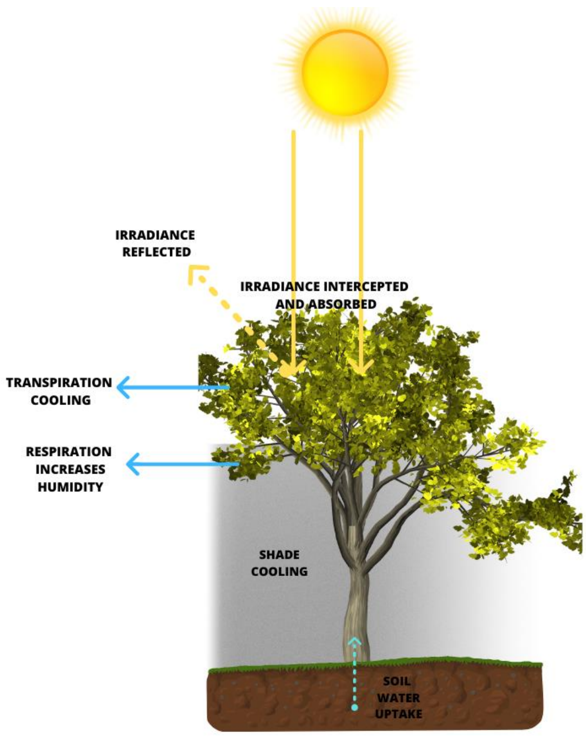


Figure 2.1 The cooling effect of trees (Zhang et al., 2019).

It should be mentioned that the UHIs mitigating effect of trees are overall general effects and may vary. The Leaf Area Index (LAI), the size of the leaf, shows that the size and shape of leaves have an impact on the cooling potential of trees (Abdi et al., 2020); trees with a higher LAI have a higher cooling effect below the tree canopy (Abdi et al., 2020; Rahman et al., 2020). Furthermore, the number of trees and tree species, based on the environmental climate and geographical location, influences the effect of cooling (Zhao et al., 2018; Rahman et al., 2020; Wang et al., 2022). Trees can be arranged in different setups, such as single trees in line or clustered, and the density of trees influences thermal comfort (Rahman et al., 2020; Marando et al., 2022). Urban topography and street canyon type influence thermal comfort. Important to note is that green infrastructure is not the only factor that can adapt UHIs and affects thermal comfort. Vehicle emissions, factories, and shops produce heat due to energy consumption.

2.2 Tree species and thermal cooling

The thermal cooling effect of trees differs between tree species. Therefore, exploring and evaluating the cooling potential of various tree species is relevant to identify those that offer the most effective means of mitigating urban heat islands and providing thermal comfort. Hiemstra (2018) developed an extensive tree overview with hundred species influencing climate, water management, air quality and biodiversity in the Netherlands. Limiting global warming is one of the seventeen categories that have been tested. Global warming limitation is divided into high, moderate and low contributions to limiting global warming. High contributions are large trees with broad and dense crowns, moderation contributions are smaller or large trees with an open or narrow crown, and low contributions are small trees or trees with a very thin pillar crown.

Trees with a high contribution to limiting global warming are selected for the most optimal cooling effect. This resulted in fourteen tree species. Characteristics of these fourteen families are that these trees are entirely wintered hard, which refers to the ability of trees to withstand periods of low temperatures (-17,8 °C to -23,3 °C). Furthermore, these fourteen species can capture a large amount of CO2. One explanation is that these tree species are large trees with extensive crowns and root systems (Hiemstra, 2018). Also, these fourteen tree species all are larger than 15 meters. However, these tree species have differences in drought tolerance and rainfall interception. Drought and rainfall are related to climate change and are interesting criteria when selecting trees for optimal cooling. An overview of tree families with high contributions to limiting global warming and their relation to drought and rainfall are shown in Table 2.1.

However, challenges arise when choosing trees with the best cooling effect since these trees are generally the largest with the broadest crown and are, therefore, not always an option to plant in neighbourhoods. Thus, another selection has been made of smaller trees with a height between 10-15 meters, which are more suitable to plant in neighbourhoods. Fifteen tree families have been selected, including twenty-one tree species. Most of these tree families are hardy and can compute large amounts of CO2. Generally, limiting global warming is less high than the large trees (>15 meters) selected in Table 2.1. However, there is still a moderate contribution to limiting global warming. There are five overarching tree species when comparing the trees higher than 15 meters and the trees between 10-15 meters.

Comparing Tables 2.1 and 2.2, based on the length of the tree and cooling effect, there are five tree species most suitable: Aceraceae (Maple), Aesculus (Horse chestnut), Fraxinus (Ash), Prunus (Cherry tree), and Ulmus (Elm). An overview of the decision process is visible in Figure 2.2. Characteristics of these trees are their large and wide crowns. They provide shade and, because of their leaf mass, can evapotranspiration water which has a cooling effect. The trees are visible in Figure 2.3.

Table 2.1 Trees with a high contribution to limiting global warming (>15 meters) (Hiemstra, 2018).

Tree Family	Number of tree species for optimal cooling (out of hundred)	Characteristics
Aceraceae	6	High drought tolerance Medium interception
Aesculus	2	Low drought tolerance Low interception
Castanea	1	No drought tolerance Medium interception
Fagus	1	No drought tolerance Medium interception
Fraxinus	1	No drought tolerance Medium interception
Juglans	2	Low to moderate drought tolerance Medium interception
Liriodendron	1	No drought tolerance Medium interception
Platanus	3	Moderate drought tolerance Medium interception
Populus	5	Low to high drought tolerance Medium interception
Prunus	1	No drought tolerance Low interception
Quercus	7	Moderate drought tolerance Medium interception
Salix	1	Moderate drought tolerance Medium interception
Tilia	5	Moderate drought tolerance Medium interception
Ulmus	3	Moderate drought tolerance No interception

Table 2.2 Trees with a moderate contribution in limiting global warming (10-15 meters) (Hiemstra, 2018).

Tree Family	Number of tree species for optimal cooling (out of hundred)	Characteristics
Aceraceae	1	High drought tolerance Low interception
Aesculus	1	Low drought tolerance No interception
Alnus	3	Zero to low drought tolerance Low to medium interception
Betula	2	Zero to low drought tolerance Medium interception
Carpinus	1	Low drought tolerance Medium interception
Catalpa	1	Low drought tolerance No interception
Celtis	1	Moderate drought tolerance Medium interception
Cercidiphyllum	1	No drought tolerance Low interception
Fraxinus	2	Low drought tolerance Medium interception
Morus	2	Zero to low drought tolerance Medium interception
Parrotia persica	1	Moderate drought tolerance Medium interception
Paulownia tomentosa	1	No drought tolerance Medium interception
Prunus	2	Low drought tolerance Low interception
Taxus	1	Moderate drought tolerance Medium interception
Ulmus	1	Moderate drought tolerance Low to medium interception

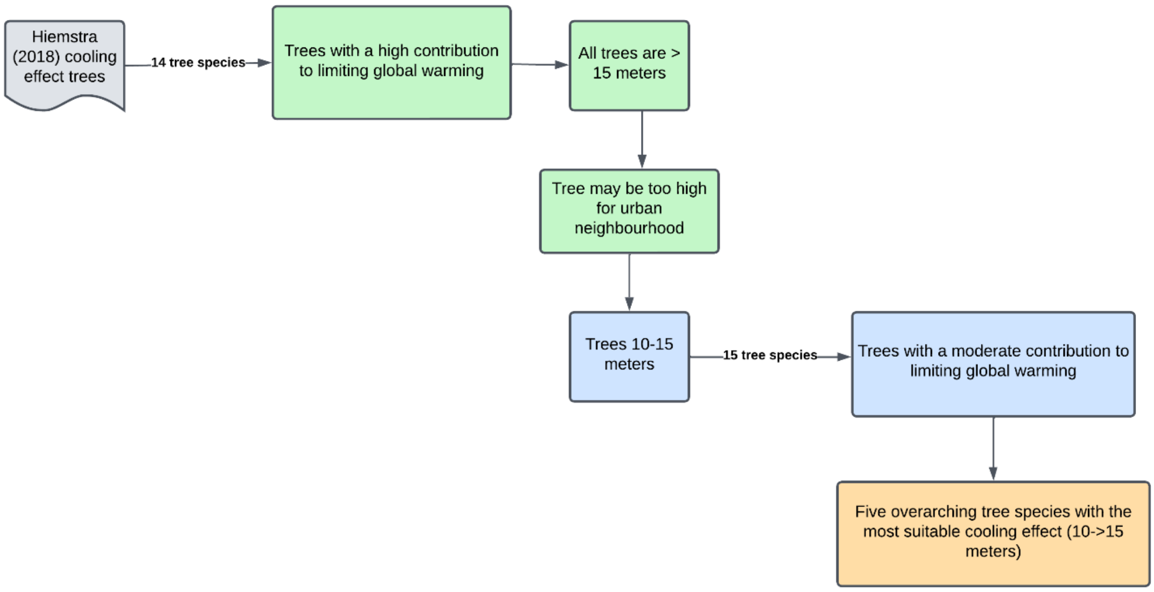


Figure 2.2 Decision tree choosing the most optimal tree species.

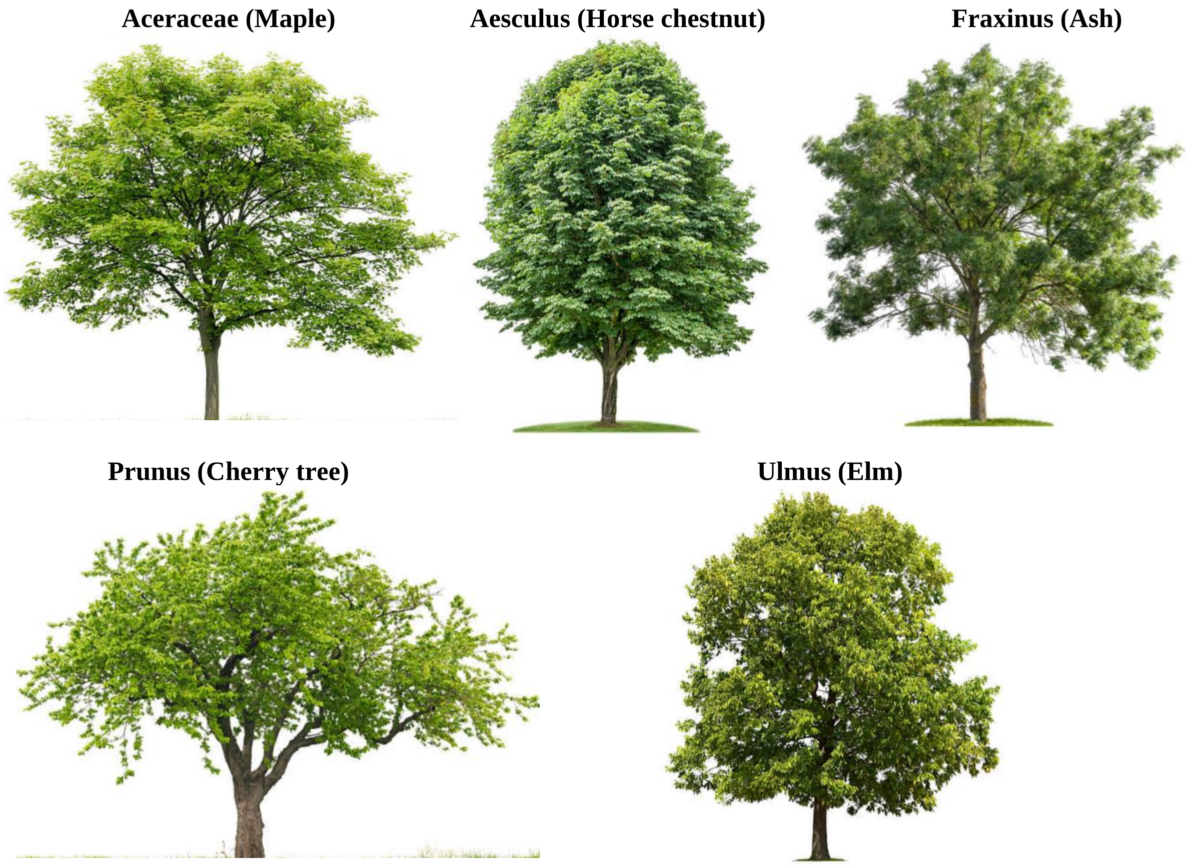


Figure 2.3 Five trees with a high cooling effect. Images retrieved from www.istockphoto.com.

2.3 Physiological Equivalent Temperature

Thermal comfort is a subjective concept and varies by person. Air temperature is commonly used in all studies to address UHIs but does not point out humans' perception of heat (Lee et al., 2020). Therefore, thermal comfort is a valuable addition to measuring UHIs, since it provides insight into cities' living conditions. Several variables are used to measure thermal comfort by computing the PET, see Figure 2.4. Overall, studies that calculate the PET all use the following variables: air temperature, mean radiant temperature, wind speed, and relative humidity (Hsieh et al., 2016; Zhao et al., 2018; Zhang et al., 2018; Lee et al., 2020; Rahman et al., 2020; Abdi et al., 2020). Other human variables such as gender, age, height, and clothing influence PET (Ridha et al., 2018). Table 2.3 overviews the PET ranges (Matzarakis & Amelung, 2008).

Table 2.3 Ranges of the PET (Matzarakis & Amelung, 2008).

PET	Thermal Perception	Grade physical stress
4°C	Very cold	Extreme cold stress
8°C	Cold	Strong cold stress
13°C	Cool	Moderate cold stress
18°C	Slightly cool	Slight cold stress
23°C	Comfortable	No thermal stress
29°C	Slightly warm	Slight heat stress
35°C	Warm	Moderate heat stress
41°C	Hot	Strong heat stress
	Very hot	Extreme heat stress

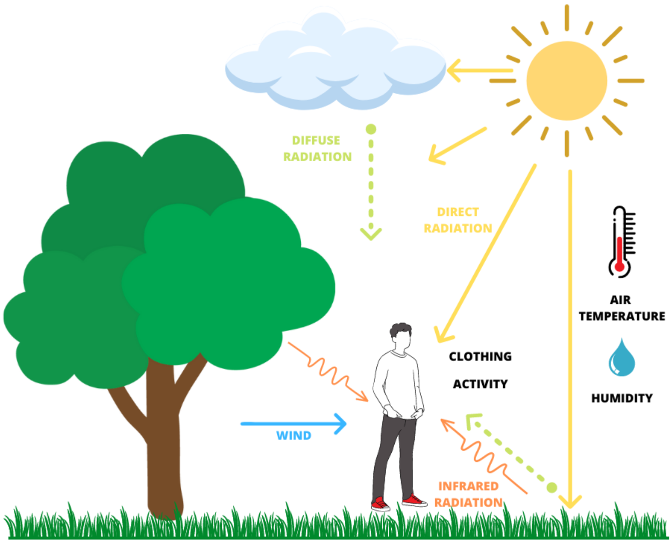


Figure 2.4 Variables that influence the PET (Ridha et al., 2018).

2.4 Thermal comfort of trees

Several studies have researched the cooling effects of trees in urban areas, and more specified different case studies studied specific tree types and tree arrangement about the built-up environment, climate characteristics and the positioning of trees (density, line, clustered). For this study, conditions have been applied to scientific research to find relevant literature. The urban scale of the study is a local/neighbourhood scale, meaning no individual objects but a street or small neighbourhood. Trees are the main vegetation object; preferably, tree characteristics and positioning are studied. Furthermore, for temperature measurements also, thermal comfort should be used.

Planning the placement of trees can improve shading and wind corridors (Hsieh et al., 2016; Zhao et al., 2018). Hsieh et al. (2016) found that thermal comfort was the highest in a shaded area with high wind speed. Placing trees with an equal interval of two trees reduces PET by 1–1,5 °C and provides optimal thermal comfort (Zhao et al., 2018). Matching results are found by Zhang et al. (2018), where the placement of 5 trees instead of 7 in one row, thus more distance between the trees, exhibited a better cooling effect (Zhang et al., 2018). This was because of the combination of exact tree placement and buildings that created more shade than when seven trees were planted in a row. Zhao et al. (2018) argue that higher tree density contributes to higher thermal comfort. However, the results of Hsieh et al. (2016), Zhao et al. (2018), and Zhang et al. (2018) show that tree density should not be too high as it can block the movement of cold air. Abdi et al. (2020) found that placing trees in rows perpendicular to the prevailing wind improves thermal comfort. A cluster of trees provides good thermal comfort (Zhao et al., 2018), and reducing the space between tree crowns reduces air temperature and PET (Zhao et al., 2018; Lee et al., 2020). Nevertheless, tree crowns should not touch or overlap because, otherwise, wind flows can reduce (Zhao et al., 2018; Lee et al., 2020). Tree characteristics also affect thermal cooling. The cooling effects of trees differ between species, even when trees are planted in the same pattern (Zhang et al., 2018; Rahman et al., 2020). Zhang et al. (2018) and Rahman et al. (2020) argued that trees with a larger LAI and a large crown had more impact on cooling effects and are, therefore, the best option for thermal cooling (Zhang et al., 2018). Figure 2.5 shows different tree types and their influence on PET in summer. The higher the tree density, the higher the reduction of the PET (Zhang et al., 2018). An individual tree can cool the air through transpiration up to 3 °C, cool the surface through shading up to 23 °C and reduce the PET by up to 11 °C (Rahman et al., 2020).

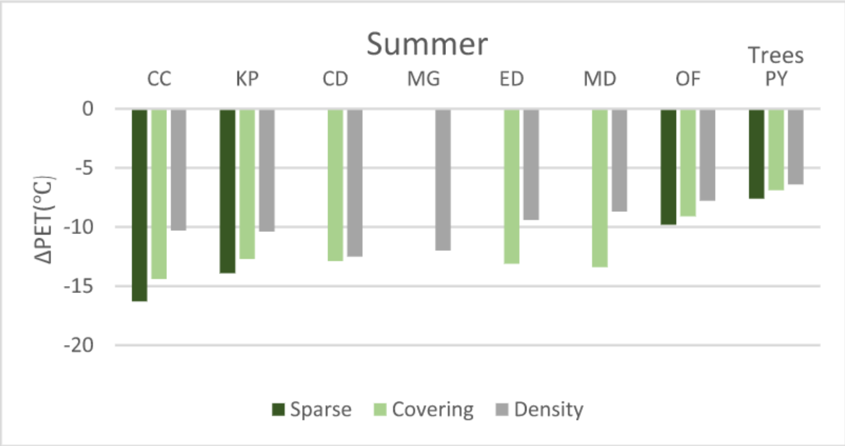


Figure 2.5 ΔPET due to vegetation in summer with tree types CC (Cinnamomum Camphora (L.) Presl., KP (Koelreuteria paniculata), CD (Cedrus deodara), MG (Metasequoia glyptostroboides), ED (Elaeocarpus decipiens Hemsl.), MD (Magnolia denudate), OF (Osmanthus fragrans (Thunb.) Lour., PY (Prunus x yedoensis) (Zhang et al., 2018).

The study area of this assessment is the Netherlands. Therefore, finding what kind of research has already been conducted on UHIs, tree characteristics, the cooling effect of trees, and thermal comfort in the Netherlands is interesting. Studies about UHIs and thermal comfort in the Netherlands, specifically on trees, are scarce. Steeneveld et al. (2011) are among the first studies on UHIs and human comfort in Dutch cities. UHIs in their research are quantified by the canopy layer, defined as the air temperature minus the rural air temperature. Google Maps has been used to quantify the green cover in cities. The results show that it is evident that Dutch cities experience UHIs compared to their rural areas. However, the study does not show the absolute numbers of the UHIs. Furthermore, meteorological measurements have been conducted at different heights, and other variables influencing UHIs have not been studied. Also, human comfort has not been studied correctly since radiation and wind conditions are unstable (Steeneveld et al., 2011). The focus on trees and their influence on thermal comfort is missing (Steeneveld et al., 2011). Around the same time, Van Hove et al. (2011) focus of the UHI study was to investigate if thermal comfort will be a critical issue considering urbanisation and climate change. Their study showed that heat stress and thermal comfort are likely to become critical in many Dutch urban areas. Their study mentions urban green and specific trees as a mitigator for UHI intensity. In addition, tall mature trees are appointed to provide shade and reduce the air temperature in an urban area. However, no definition of tall and mature is given. Suggestions on specific recommendations, for example, the influence of size, structure, and greening type, are missing and therefore lack information on how to incorporate greening into urban areas (Van Hove et al., 2011). Icaza et al. (2016) analysed different land use patches optimal for cooling effects on parks in South Holland, the Netherlands. Their study showed that when increasing the NDVI, the cooling effect also increases. During the day, the land surface temperature of the built area is the highest (37,9 °C) compared to forest patches (31,4 °C). Greenhouses and cropland have a lower land surface temperature (1,8 °C) than grassland. Reasons for this are the reflecting glass roofs of greenhouses and the difference between cropland and grassland because of cropland irrigation. However, also in this study, no specific details on trees are given (Icaza et al., 2016). In the study of Klemm et al. (2017), guidelines have been developed for implementing urban green infrastructure. This research advises landscape architects to correctly implement scientific research about green vegetation's cooling effect to create parks, streets, and cities. Noteworthy is the design of urban vegetation in streets. Trees with a large canopy cover should be placed in streets with high solar radiation, and streets should have a combination of sun or shadow locations. Furthermore, various heights of street canyons can improve thermal comfort (Klemm et al., 2017). More recently, Ottburg et al. (2022) found interesting results on the cooling effect of trees in Tiny Forests. The soil temperature of Tiny Forests compared with street soil temperature can be 20 °C lower during summer periods. Possible declarations are not presented but could be due to the concentration of trees causing dense foliage and, therefore, sunlight cannot warm up the soil directly. However, only minor differences in air temperatures are measured. Nevertheless, Tiny forests evolve, and the air temperature difference between streets and Tiny Forests is expected to increase (Ottburg et al., 2022). Table 2.4 provides an overview of the mentioned studies, including the research area, the methodology used and a summary of the studies.

Nevertheless, noteworthy discussion points are based on the previous studies' results. Explored is how tree locations, distance, and arrangements influence thermal comfort. Zhao et al. (2018) argue that research on how tree locations and arrangements benefit individual parcels and the surrounding area is missing. Most studies focus on public areas and less on combining public and private vegetation (Zhao et al., 2018). Furthermore, Zhang et al. (2018) mentioned performing a similar study using various building layouts because vegetation's cooling and ventilation effects may vary. Different tree species are used within neighbourhoods, which should also be tested (Zhang et al., 2018). Multiple studies address the existence of the built-up environment and the little research conducted on the effect of green vegetation mitigating urban heat (Rahman et al., 2020). In addition, the thermal comfort studies performed in the Netherlands are not as in-depth and detailed as the worldwide completed studies. Steenveld et al. (2011) and Van Hove et al. (2011) studies are performed nationally and are superficial and specific conclusions are missing. Furthermore, no distinction in vegetation type has been made (Steenveld et al., 2011; Van Hove et al., 2011); thus, tree specification is missing. Therefore, it is not feasible to provide recommendations on designing and planning urban green spaces (Van Hove et al., 2011). Functional is the study of Klemm et al. (2017), where guidelines for implementing trees on the street level are provided. The study by Otturg et al. (2022) is performed recently, and the relationship between Tiny Forests and heat stress in the long term is not yet evident. This needs to be further investigated (Otturg et al., 2022). Furthermore, none of the Dutch studies has used tree species, and the effect of wind flows on thermal comfort. In addition, most of the discussed studies determined the presence of green by satellite imagery or created their own tree database for executing models. Furthermore, none of the studies uses 3D models to visualise, for instance, shadows of trees or buildings. Overall, there are still many opportunities to gain in studying the placement of trees in Dutch neighbourhoods and assessing their effect on thermal comfort.

To conclude, trees are the most effective strategy to mitigate UHIs due to their shading effect, heat absorption, and direct wind flows to improve ventilation. To measure the severity of UHIs, PET is a commonly used tool. Variables used to measure PET are air temperature, mean radiant temperature, wind speed, and relative humidity. Many studies have been performed to study UHIs, trees' cooling effect, and PET. Functional studies completed in the Netherlands only use meteorological measurements and NDVI to measure UHIs. Specific cooling measurements of trees are missing and compared with worldwide studies where the cooling effect of trees and their impact on PET are studied in more detail. Mainly tree planting patterns are analysed and compared based on PET. Interesting insights are given on what benefits PET and tree planting patterns. However, there are some opportunities to study. Especially for the Netherlands' insights on the tree cooling effect combined with the built environment's influence on PET is interesting to study.

Table 2.4 Overview relevant literature.

Autor	Title	Research area	Tree data	Methodology	Findings
(Steeneveld et al., 2011)	Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands	27 Dutch cities, The Netherlands	No tree data was used. Green areas are determined with NDVI	Meteorological observations and statistical analysis	The UHI effect is present in Dutch cities. There is a correlation between population density and UHIs. Furthermore, there is a significant decrease in UHI and the percentage of surface area covered by green vegetation.
(Van Hove et al., 2011)	Exploring the Urban Heat Island Intensity of Dutch cities	The Netherlands	No tree data was used. Green areas are determined with NDVI	Meteorological observations and satellite images	Any vegetation reduces the air temperature. Trees may be more efficient during hot, dry days than grass in the long term because trees prevent excess water loss. Furthermore, parks over 10 hectares are more incredible than parks less than 3 hectares.
(Hsieh et al., 2016)	A simplified assessment of how tree allocation, wind environment, and shading affect human comfort	Tainan Park, Tainan, Taiwan	Fish eye lens to determine the sky view factory	Meteorological data and field measurements for the model's accuracy in WindPerfect software.	The cold wind that enters the park can be blocked by the overcrowding of plants, which results in temperature rises. Wind movement can decrease when there is no proper planning for planting vegetation. This has a negative effect on thermal comfort. Planning on vegetation placement improves the wind corridor and can improve shading, ventilation and thermal comfort.
(Icaza et al., 2016)	Using satellite imagery analysis to redesign provincial parks for a better cooling effect on cities – The case of South Holland	South Holland, The Netherlands	Satellite imagery to determine NDVI	Multiple regression analysis to understand the influence of parameters	UHIs are located next to grassland patches. To decrease these hotspots, a change in land use or an increase in NDVI of the existing grassland patches is needed.
(Klemm et al., 2017).	Developing green infrastructure design guidelines for urban climate	Utrecht, the Netherlands	-	Observations, plan analysis and questionnaires	Conclude the following guidelines: street canyons should be implemented at various heights in streets with high solar radiation trees with large canopies. Planting too many trees too close together in streets creates compact tree canopies that could hinder wind circulation.
(Zhang et al., 2018)	Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters	Wuhan, China	Tree location determined with satellite images	ENVI-met modelling and configuration with field measurements	The results demonstrated that tree distribution, crown width, and LAI influenced heat stress and ventilation. A density pattern of trees had a less cooling effect than a more sparse pattern. Tree species have different effects on thermal cooling. The higher the LAI index and the large crown, the higher the cooling effect.
(Zhao et al., 2018)	Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment	City of Tempe, AZ USA	Created trees to study the most optimal cooling effect	Fieldwork for model validation compared with ENVI-met modelling to evaluate the model accuracy.	An equal interval of two trees provided the most human thermal comfort benefits due to the importance of shading in a hot desert environment. Following a cluster of trees without canopy overlap.
(Abdi et al., 2020)	Impact of small-scale tree planting patterns on outdoor cooling and thermal comfort	University of Tabriz, Iran	Created trees to study the most optimal cooling effect	ENVI-met modelling and validation by comparing results with field measurements.	Planting in a rectangular pattern with evergreen trees in the outer rows and deciduous trees in the inner rows, in the perpendicular direction to the wind, improves thermal comfort.

Autor	Title	Research area	Tree data	Methodology	Findings
(Lee et al., 2020)	Impact of the spacing between tree crowns on the mitigation of daytime heat stress for pedestrians inside E-W urban street canyons under Central European conditions	Freiburg, Germany	Created trees to study the most optimal cooling effect	ENVI-met modelling to predict mean radiant temperature and PET.	The mean radiant temperature and the PET are lowered by the tree shading compared to the placement of no tree. Furthermore, the mean radiant temperature and the PET reduce more when the spacing between crowns decreases. However, tree crowns should not touch or overlap because otherwise, wind could be reduced. Buildings also prevent shadow, and by researching the effect of trees on thermal cooling, it is essential to include buildings, as their impact can make trees unimportant/irrelevant.
(Rahman et al., 2020)	Tree cooling effects and human thermal comfort under contrasting species and sites	Würzburg, Germany	Tree locations determined with aerial photos	Fieldwork, metrological measurements and statistical analysis with software package R	There are cooling differences between tree species from 4 °C to 11 ° C. Urban topography is important in controlling wind flows and human thermal comfort.
(Ottburg et al., 2022)	Tiny Forests: groene mini-oases in de stad	11 Tiny Dutch Forests	No specific tree locations included	Citizen science	The soil temperature of Tiny Forests compared with the soil temperature of streets can be 20 degrees during summer periods. Only minor differences in air temperatures are measured. However, Tiny forests evolve, and the air temperature difference between streets and Tiny Forests is expected to increase.

Chapter 3

Methodology

The methodology begins with the design of three urban configuration neighbourhoods. Next, three planting pattern scenarios are designed and based on tree cooling characteristics from theory chapter 2, the most optimal trees for cooling are selected. Furthermore, the Tygron PET algorithm, the Heat Stress overlay, and the modelling settings are explained in detail. Figure 3.1 shows the conceptual model to assess the cooling effect of trees. Based on the studied literature in the theoretical background, three scenarios are designed for planting trees. To perform the Heat Stress overlay, tree species, urban configuration, and tree planting patterns are modelled in the Tygron software with meteorological data. The result of the Heat Stress overlay is the PET in urban neighbourhoods.

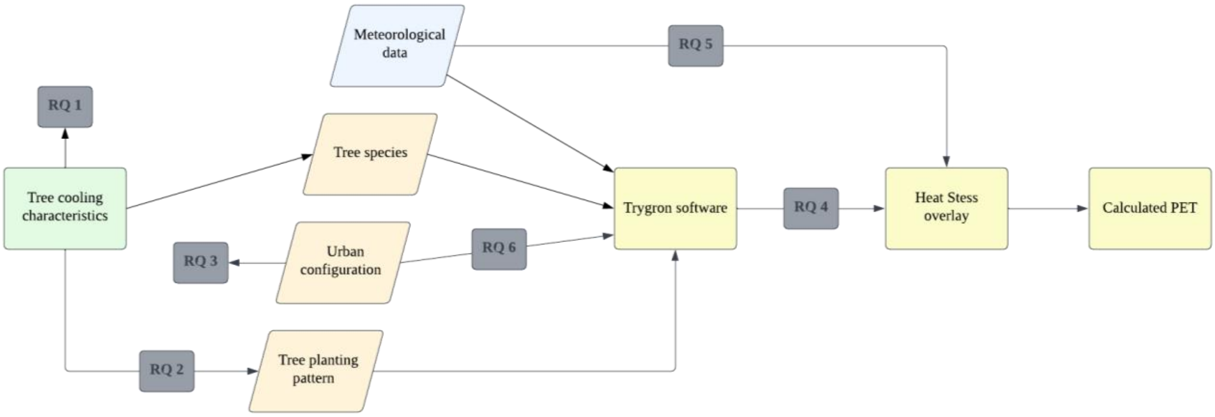


Figure 3.1 Methodology conceptual model.

3.1 Urban configuration

The placement of trees and tree species studies the cooling effects of trees. Three Dutch neighbourhood concepts are designed to assess the impact of trees' cooling effect. Average Dutch neighbourhoods from different periods in time inspire the concepts. The three neighbourhoods are designed based on specific characteristics. The neighbourhoods are a working-class neighbourhood, a suburban neighbourhood and a high-rise neighbourhood. Three steps are applied for the urban configuration. First, neighbourhood sketches are made to provide an impression. Second, the neighbourhoods are designed in ArcGIS Pro. Third, the ArcGIS Pro designs are used in the Tygron platform to model tree-cooling effects in Dutch neighbourhoods. Furthermore, based on studied literature in the theoretical background, tree placement patterns are designed in ArcGIS Pro, which is used for modelling the PET in the different urban configurations. Finally, three existing neighbourhoods in The Hague, Netherlands, are selected to represent the urban planning concepts for the final modelling process.

3.1.1 Neighbourhoods characteristics

The first part of the modelling process is applied to three self-designed neighbourhoods. Average Dutch neighbourhood concepts inspire the designs. The original working-class neighbourhoods in the Netherlands were built between 1900-1950. The residents of these neighbourhoods were originally labourers with low incomes. Most of these neighbourhoods developed into next-generation working-class neighbourhoods. The buildings are characterised by simple and tiny houses and only a few trees because of limited space. Due to population growth in Dutch cities, a housing shortage arose in the 1990s. This resulted in the construction of housing in the suburbs of cities, also known as Vinex neighbourhoods. Characteristics of suburban neighbourhoods are affordable housing, spacious gardens, the monotony of building structures, and more space for trees compared to working-class neighbourhoods. High-rise buildings with 7 to 12 levels are standard in the Netherlands. Most of the time, a few high-rise buildings are built together in one neighbourhood. Common is the presence of grass around a high-rise and lots of possibilities for vegetation. Figure 3.2 shows sketches of the three neighbourhoods to give an impression.

3.1.2 Neighbourhoods design

The second step in the urban configuration is designing three neighbourhoods in ArcGIS Pro. ArcGIS Pro is a powerful tool to visualise data and perform analysis (ArcGIS PRO, n.d.). The neighbourhoods are designed in proportion, meaning that measurements are considered. The length and width of the building blocks are equal for the three neighbourhoods. The building blocks each have a length of 60 meters (about 7 houses) and a width of 10 meters. The height of the working-class buildings is 6 meters (1 level roof excluded), the suburban buildings 9 meters (2 levels and roof), and the high-rise building blocks 24 meters (7 levels). The bicycle has a height of 1,8 meters and is used as a height reference for vertical length in the three scenes. The trees are placed on the sidewalks in working-class and suburban neighbourhoods, and grass is in high-rise neighbourhoods. The sketches of the neighbourhoods are visible in Figure 3.2.

Working-class neighbourhood

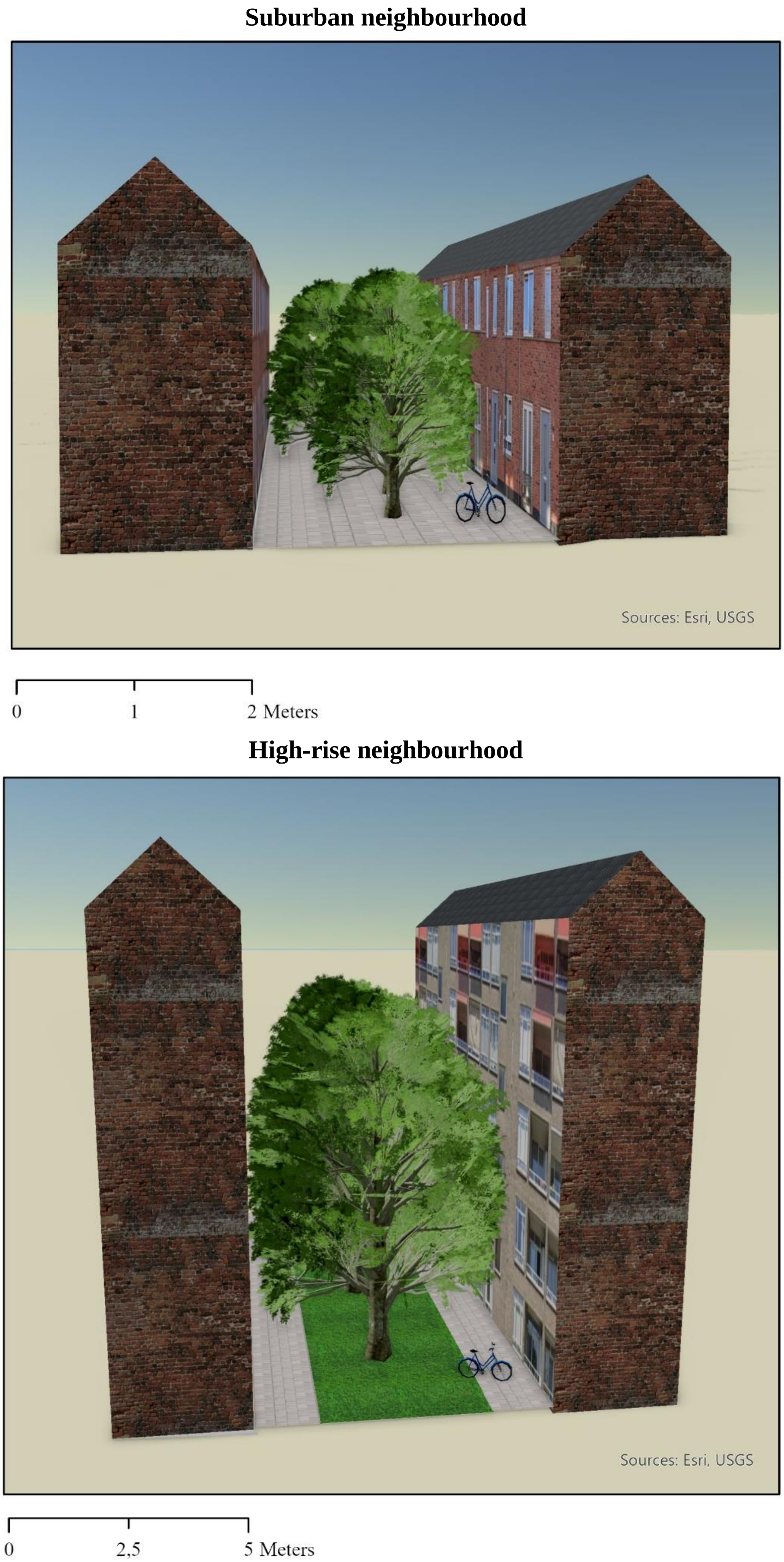


Figure 3.2 Neighbourhood sketches.

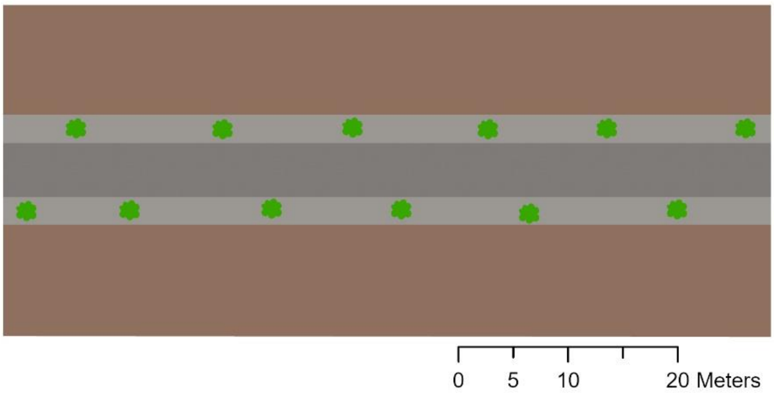
3.1.3 Tree Placement

Study outcomes of planting strategies are introduced in chapter 2, the theoretical background. These planting strategies have proven to have a positive influence on thermal cooling. The concepts are spread, concentration, dilution, and densification. The main findings in the theoretical background are:

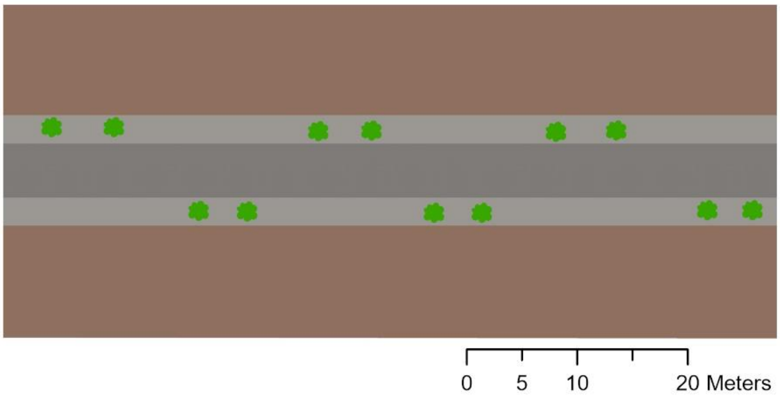
- Interval, placing trees with an equal interval of two trees reduces PET by 1–1,5 °C (Zhao et al., 2018);
- Number of trees, more trees do not necessarily mean a better cooling effect (Zhang et al., 2018);
- Tree density, trees can block wind flows but also could provide thermal comfort (Hsieh et al., 2016; Zhang et al., 2018 & Zhao et al., 2018);
- Wind flows, tree rows perpendicular to the prevailing wind improve thermal comfort (Abdi et al., 2020);
- Tree overlap, tree crowns should not overlap (Zhao et al., 2018; Lee et al., 2020);
- Tree species, the cooling effects of trees differ between species (Zhang et al., 2018; Rahman et al., 2020).

Based on these six main findings, the following three tree patterns are used to test the cooling effect of trees, see Figure 3.3. The first scenario is planting 6 trees in line on each side of the road. The tree crowns do not overlap, and the trees are placed at equal intervals. The second scenario is the cluster of 2 trees. Scenarios 1 and 2 can be compared by placing single trees or clustering. The exact amount of trees are used in the first scenario. In the third scenario, 12 shrubs are placed. Scenario 3 shows the cooling effect of the trees in scenarios 1 and 2. Furthermore, different tree species are added to the scenarios to show the difference in cooling effect between tree species.

Scenario 1 Single tree



Scenario 2 A cluster of two trees



Scenario 3 Shrubs

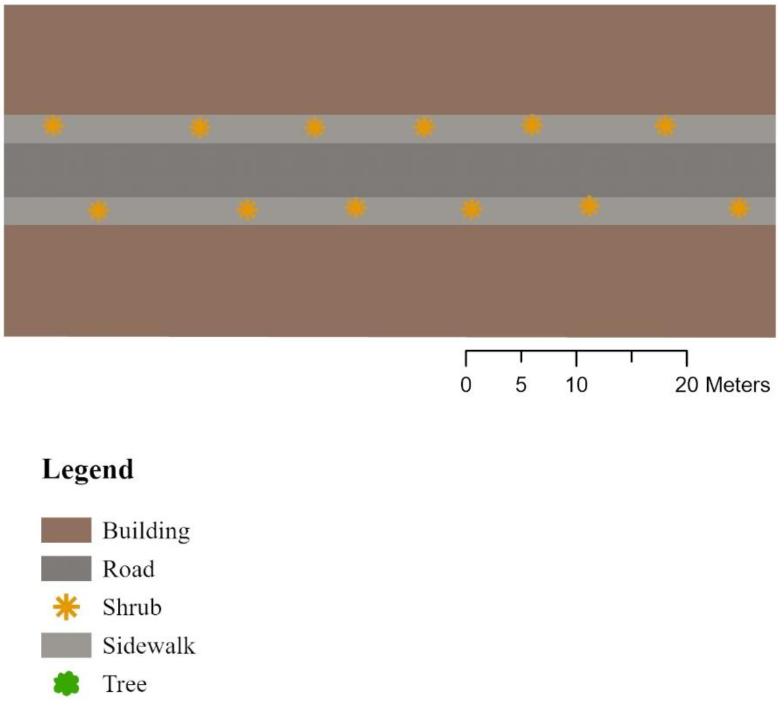


Figure 3.3 Tree planting patterns.

3.1.4 The Hague neighbourhood selection

The first part of modelling is performed on the designed urban configuration neighbourhoods to test the cooling effect of trees and calculate PET results. The second part of the modelling is performed in three existing neighbourhoods selected in The Hague, The Netherlands. In 2012, a study by Klok et al. (2012) concluded that The Hague has the strongest UHI effect of all Dutch cities. During the day, The Hague stands out with an average UHI of 8,6 °C and a maximum of 15,4 °C. This is partly due to the high degree of urbanisation and the relatively small amount of greenery in the city (Klok et al., 2012).

Three neighbourhoods in The Hague are selected to model the PET and the cooling effect of trees. For the working-class neighbourhood, Laakkwartier-Oost is selected. Laakkwartier-Oost is a lively, diverse neighbourhood where many families, students, and immigrants live. It has a mix of old (pre-war) and new buildings and several shops, cafes, and restaurants. There are also many parks and green spaces in the area. Lage Veld is selected as suburban neighbourhood. Lage Veld is a neighbourhood in the eastern part of The Hague in the Netherlands. It is a relatively new residential area developed in recent years to meet the growing demand for housing in The Hague. Lage Veld is known for its modern and spacious homes, many of which are designed to be energy-efficient and environmentally friendly. There are also several parks and green spaces in the area. Finally, Kampen is selected as high-rise neighbourhood. Kampen is a neighbourhood in the eastern part of The Hague in the Netherlands. It is a predominantly residential area, with a mix of older and newer houses and several parks and green spaces. Figure 3.4 shows the geographical location of the three neighbourhoods.

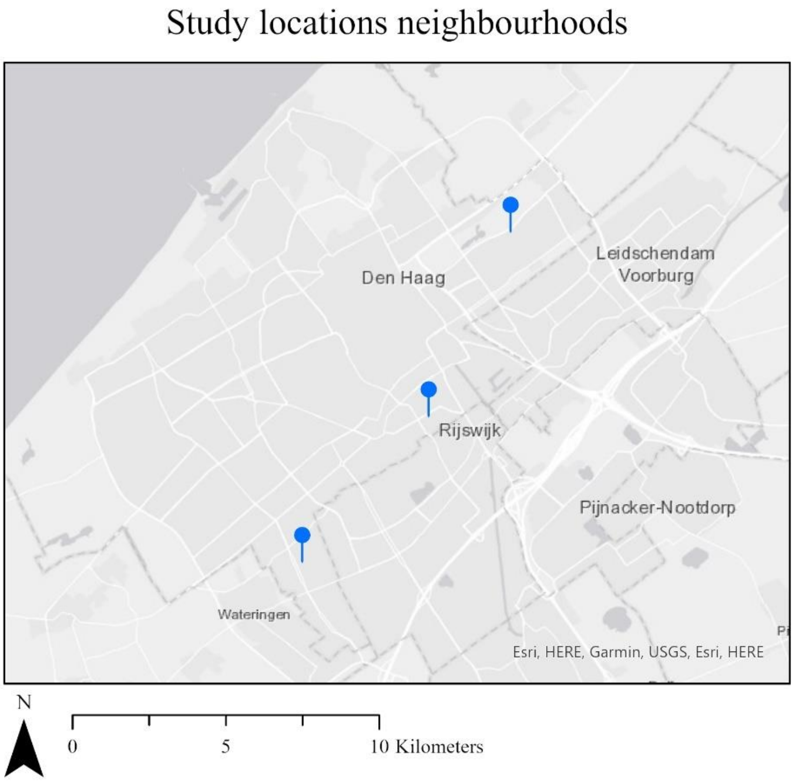


Figure 3.4 Study locations three neighbourhoods.

3.2 Tygron PET modelling

This thesis uses the Tygron Geodesign-Platform to model PET in the urban environment. Tygron is a GIS-based modelling software that provides an open digital infrastructure to support spatial planning solutions. Tygron connects automatically to Dutch open datasets where it processes, analyses and visualises geospatial data in 2D and 3D. Today's challenges, such as floods, droughts, heatwaves, energy, urban planning, infrastructure, liveability and economy, can all be measured and considered using Tygron (Tygron, n.d.). The Tygron model is used to assess the impact of trees on thermal cooling in Dutch neighbourhoods.

The Tygron software model uses several variables for the indication of Heat Stress. The data used in the Tygron Platform is open access and already integrated into the software; therefore, no extra datasets must be searched when not necessary. Tygron offers multiple services to import and connect with datasets. Catalogue services are an online catalogue standard for searching and datasets. The catalogues provided are ArcGIS Online, where private data developed in ArcGIS Pro can be uploaded into the Tygron software, and PDOK, The Dutch National Georegister, where open data is published. Furthermore, Web Services (WFS) connections, such as the BRO and BAG, can be made. In the Tygron software, using Excel, weather data from the KNMI (Royal Netherlands Metrological Institute) on any specific day and time can be imported. With the KNMI data, the following weather characteristics can be measured atmospheric temperature, radiation from the sun, sun altitude, wind speed, Wet bulb temperature, Bowen ratio and sky view factor. The Wet bulb temperature is the lowest temperature to which the evaporation of water can cool air temperature. The Bowen ratio calculates heat gain and loss in a substance. The Sky View Factor defines the percentage of sky visible from the ground. These variables influence the Physiological Equivalent Temperature (PET) for locations directly in the sun, and the PET will be used to express temperature. The Tygron Platform describes the algorithm used to calculate the Heat Module Theory; see Figure 3.5 (Heat Module theory - Tygron Support wiki, n.d.). The Heat Module theory is inspired by the Delta Plan on Spatial Adaptation (DPRA), a plan by Dutch governments to prevent flooding, heat stress and drought (Rijksoverheid, 2022).

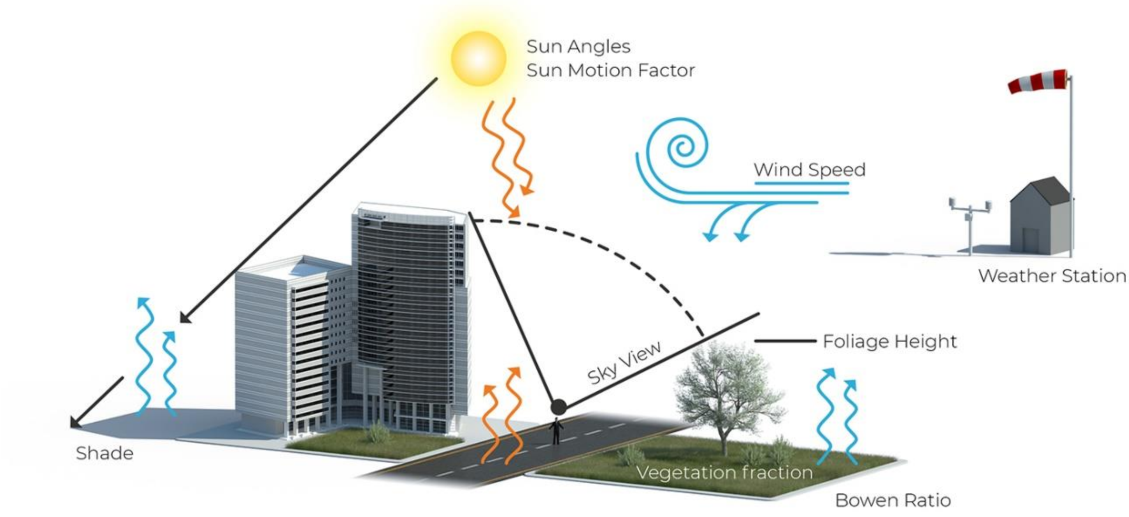


Figure 3.5 Tygron Heat stress PET measure ((Heat Overlay) - Tygron Support wiki, n.d.).

The algorithm of the PET model is divided into two parts. The first part is the setup of the model environment. Here calculations are performed regarding the built environment, vegetation, and weather data such as wind speed and sunlight. In the second part of the algorithm, the weather data of the KNMI is implemented and calculated based on timeframes. The model's outcome is the Urban Heat Stress over a selected period. For example, the Urban Heat Stress during a hot summer day between 08:00 in the morning and 20:00 or the difference between day and night of Urban Heat in urban areas. Subchapters 3.2.1 and 3.2.2 explain the methodology steps in minor detail. It provides a sketch of the methods used and will be described in more detail in this research.

3.2.1 First part of the Heat Stress algorithm

The algorithm starts with the calculation of the foliage height. Each grid cell will determine if the foliage is present and at what height. This data is used to calculate the Shade and the Sky View models (Foliage height calculation model ((Heat Overlay) - Tygron Support wiki, n.d.).

The second step is calculating the sky view factor, which measures how much sky is visible from any given location. The sky view factor is calculated as 1.2 meters above the surface. First, the model determines buildings, foliage, and terrain height. Second, the amount of rays is selected, and the sky view section is formed by determining the average length of two consecutive rays, see Figure 3.6.

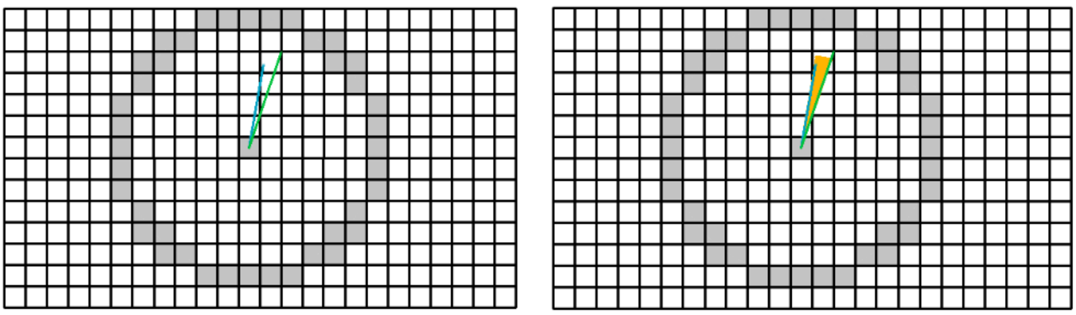


Figure 3.6 Determining the average length of two consecutive rays (Sky view factor calculation model (Heat Overlay) - Tygron Support wiki, n.d.).

The area of sky view section *i* is determined using the average projected ray length from these two rays, r1 and r2, as follows:

$$\propto = \arccos(x_{r1}x_{r2} + y_{r1} + y_{r2})$$

$$r_{avg} = \frac{r_1 + r_2}{2}$$

$$area_i = \frac{\alpha}{2_\pi}\pi(r_{avg})^2$$

The sky view area is the sum of the areas of the sky view sections. This can be calculated by dividing the sky view area by the area of the circle of the horizontal plane, see Figure 3.7 (Sky view factor calculation model (Heat Overlay) - Tygron Support wiki, n.d.):

$$svf = \sum_{1}^{n} \frac{area_i}{\pi r^2}$$

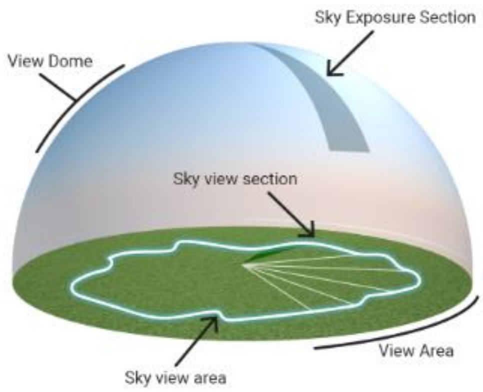


Figure 3.7 Visible sky section from any location projected onto a 2D plane (Sky view factor calculation model (Heat Overlay) - Tygron Support wiki, n.d.).

Thirdly, the average calculation model uses the wind speed and direction of the wind to determine the window for averaging values around a cell. An average cell-centred window with a wind speed lower than 1.5 meters per second is used. An oblong rectangle is used when the wind speed equals or exceeds 1.5 meters per second. A large window is used when the window is based on vegetation fraction and the sky view factor, and a small window is used when wind speed is the base. Figure 3.8 shows the four windows (Average calculation model (Heat Overlay) - Tygron Support wiki, n.d.).

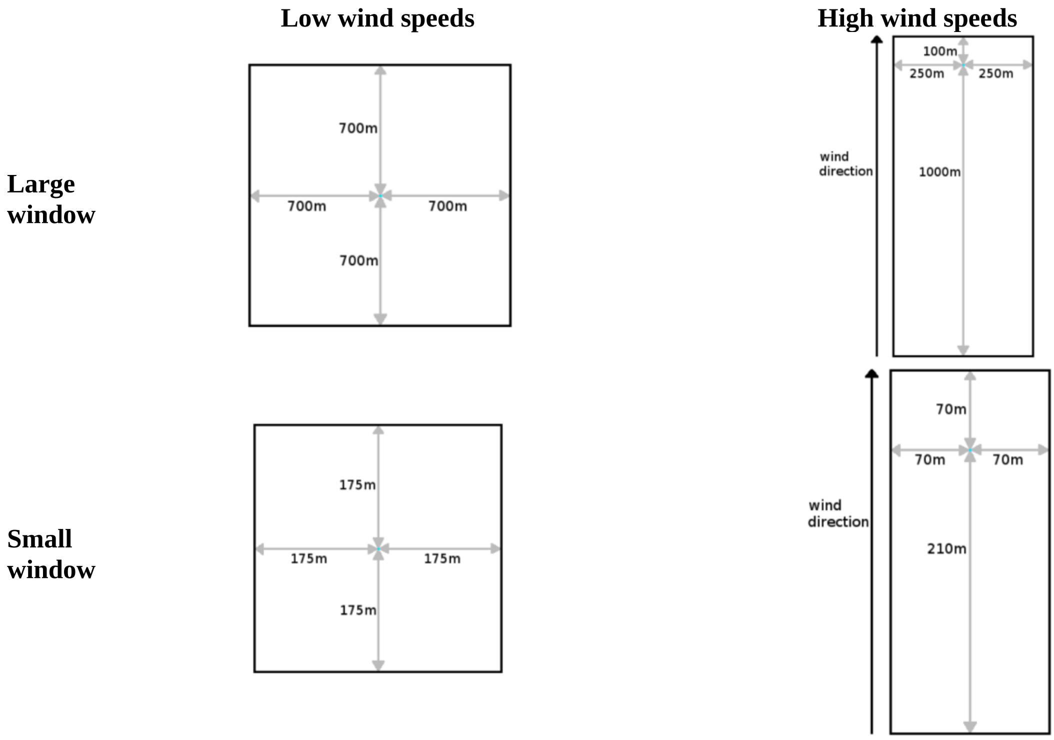


Figure 3.8 Average cell values for wind speed (Average calculation model (Heat Overlay) - Tygron Support wiki, n.d.).

The final formula of the first part is the UHI formula:

$$UHI_{max} = (2 - S_{vf} - F_{veg}) \cdot \sqrt[4]{\frac{S \cdot (T_{max} - T_{min})^3}{U}}$$

Where:
S_{vf} is the calculated average sky view factor;
F_{veg} is the calculated average vegetation fraction;
S is the calculated daily average global radiation in K(Kelvin) m/s;
T_{max} is the maximum temperature measured at a weather station over 12 hours;
T_{min} is the minimum temperature measured at a weather station over 12 hours;
U is the daily average wind speed measured at 10 meters above ground at a weather station;

This formula can be divided into two parts. The first part is the factor divided by the temperature effect. The sky view factor and the vegetation fraction range from 0 to 1, where 0 is the little sky and no vegetation. Thus, when there are many sky views and vegetation, the factor is near 0; therefore, the heat island is also low. For calculating the temperature, the daily average global radiation, the maximum temperature, the minimum temperature and the daily average wind speed are used (UHI formula (Heat Overlay) - Tygron Support wiki, n.d.).

3.2.2 Second part of the Heat Stress algorithm

For the calculation of the PET, the atmospheric and the Wet-bulb temperature formulas are used (Temperature formulas (Heat Overlay) - Tygron Support wiki, n.d.). The atmospheric temperature:

$$T_{a,t} = T_{station,t} + UHI_{max,t} \cdot f_{sun,t}$$

Where:
$T_{a,t}$ is the calculated atmospheric temperature at time t;
$T_{station,t}$ is the temperature measured at a weather station at time t;
$UHI_{max,t}$ is the calculated UHI effect at time t;
$f_{sun,t}$ is the sun daily motion factor at time t

The temperature is measured for a specific time, where the maximal UHI is divided by the sun's daily motion factor plus the measured temperature. The wet-bulb temperature is the lowest temperature to which the evaporation of water can cool air into the air:

$$T_{w,t} = T_{a,t} \cdot \arctan\left(0.151977 \cdot \sqrt{\emptyset + 8.313659}\right) + \arctan(T_a + \emptyset) - \arctan(\emptyset - 1.676331) + 0.00391838 \cdot \emptyset^{\frac{3}{2}} \arctan(0.023101 \cdot \emptyset) - 4.686935$$

Where:
$T_{w,t}$ is the calculated wet-bulb temperature;
$T_{a,t}$ is the calculated atmospheric temperature;
$\emptyset$ is the sun altitude angle;

The calculated atmospheric temperature is multiplied by, for instance, the sun's altitude angle. The constant values in this formula are used from the Dutch Heat stress report (De Nijs et al., 2019) published by the Dutch National Institute for Public Health and the Environment (RIVM). The shade calculation model is based on buildings, terrain and foliage and determines whether the function PET sun or PET shade/night is used (Shade calculation model (Heat Overlay) - Tygron Support wiki, n.d.). The location of the sun determines the shade. Each timeframe in the model is related to sun altitude and sun azimuth angle and, therefore, can be calculated if a specific cell in the raster is shaded. The street level wind speed is calculated using the measurements from the KNMI of 10 meters. The model uses the vertical surfaces of buildings perpendicular to the wind directions to determine how the wind speed is slowed down (Wind calculation model (Heat Overlay) - Tygron Support wiki, n.d.). Finally, the input of the variables described previously, the PET, can be calculated. Either the PET can be calculated for the night or in the shade, or the PET will be calculated in the sun (PET formulas (Heat Overlay) - Tygron Support wiki, n.d.):

$$PET_{sun} = -13.26 + 1.25 \cdot T_{a,t} + 0.011 \cdot Q_{gl,t} - 3.37 \cdot \ln(u_t) + 0.078 \cdot T_{w,t} + 0.0055 \cdot Q_{gl,t} \cdot \ln(u) + 5.56 \cdot \sin(\emptyset_t) - 0.0103 \cdot Q_{gl,t} \cdot \ln(u_t) - \sin(\emptyset_t) + 0.546 \cdot B_{b,t} + 1.94 \cdot S_{vf}$$

Where:
$T_{a,t}$ is the calculated atmospheric temperature;
$Q_{gl,t}$ is the hourly radiation at time t;
u_t is the calculated wind speed at 1.2 meters above ground time t;
$T_{w,t}$ is the calculated wet-bulb temperature;
$\emptyset_t$ is the sun altitude at time t;
$B_{b,t}$ is the Bowen ratio at time t;
S_{vf} is the calculated sky view factor;

Figure 3.9 shows a flow diagram of the heat stress algorithm. The datasets D1 to D6 are input variables to calculate 6 parameters. With these 6 parameters, 6 overlays are created. Depending on the presence of the sun, the PET in the sun and shadow are created, leading to the final PET overlay.

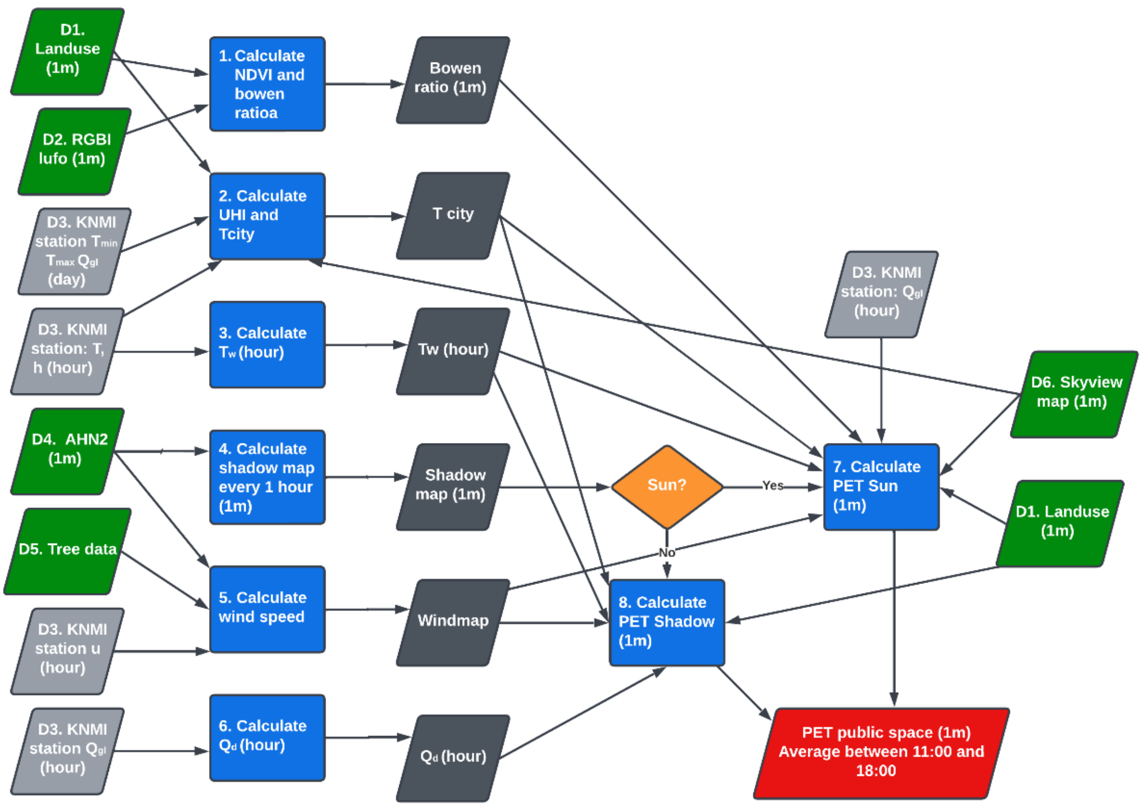


Figure 3.9 Flowchart to measure the PET. Data sources (D), Meteorological data sources (light grey), Calculation (blue), Overlay map (dark grey) and final overlay map (red) (Rijksoverheid, 2022).

3.2.3 Tree data in 3D

This thesis mainly focuses on assessing the cooling effect of trees. This effect has been studied previously according to the theoretical background in chapter 2. Most of the studies used meteorological observations and linked these observations to the presence of urban heat islands, greenness, and other variables in the built environment (Steeneveld et al., 2011; Van Hove et al., 2011; Hsieh et al., 2016; Icaza et al., 2016; Rahman et al., 2020; Ottburg et al., 2022). Other studies simulated the built environment and used meteorological observations to predict prospective meteorological conditions (Zhang et al., 2018; Zhao et al., 2018; Abdi et al., 2020). Moreover, some studies used the built environment to predict future meteorological conditions by using software packages (Lee et al., 2020). This thesis builds on predicting meteorological conditions, specifically the PET, using the built environment in three-dimensional (3D). Finding literature that models the built environment, specifically trees, in 3D to predict the PET is scarce. There are some advantages to using 3D modelling. Decision-making processes, such as city planning, are made more illustrative, understandable, and accessible because of the digital transformation of 3D spatial data and their standardised data models. The use of 3D city models is also essential for planning in a virtual setting for city management, performing different planning simulations, and risk and catastrophe scenarios (Neuenschwander et al., 2011; Buyukdemircioglu & Kocaman, 2020). Furthermore, users could engage with the geospatial data more naturally because of the 3D geometry (Jobst & Germanchis, 2007). In the Tygron software, the world is automatically visualised in 3D. This is possible because of the connections to open datasets to visualise the urban environment in 3D. The advantage of performing this study in 3D is the more realistic visualisation of trees and the more accurate showing of shade from trees or the built environment. Effects such as building height and tree height can be taken into account.

3.2.4 Tree species in Tygron

In the Tygron software, twelve tree species are offered as model input, visible in Table 3.1. They differ in model visualisation, height, and crown diameter. As mentioned in the theoretical background 2.4, height and crown diameter influence the cooling effect and impact heat stress in neighbourhoods. The research of Hiemstra (2018) has been used in the theoretical background 2.2 to select the most suitable trees to influence the cooling effect in the Netherlands. Based on height and cooling ability, five tree species have emerged as the most suitable trees for cooling in Dutch neighbourhoods.

Seven matching tree species compare Hiemstra (2018) and the Tygron platform. Table 3.2 divides the matching tree species into high or moderate contributions to limiting global warming and their height. Furthermore, Orchard and Palm trees are tree types unavailable in the overview of Hiemstra (2018) and do not have the desired cooling effect. In Tygron, there is also the option to add Bush and Heath, which is used for tree planting scenario 3. However, in the Tygron Platform, the tree type Default deciduous trees are available. This is an overarching tree type for deciduous trees. Comparing Default deciduous trees with Hiemstra (2018), most tree types in Tables 2.1 and 2.2 can be matched with those of Default deciduous trees.

In the Tygron software, tree settings can be adjusted. Based on the type of the tree, the Bowen Ratio, Foliage Crown Factor, and Heat Effect (°C) standard numbers are used, visible in table 3.3. These numbers can be adjusted based on preference. The Bowen Ratio is, in default, either 0,4 for trees and vegetation or 3,0 for other functions such as buildings. The Foliage Crown Factor depends on the height of the tree trunks and the diameter of the tree's foliage. For example, the Foliage Crown Factor differs between the Italian popular and the Oak because the Italian popular has a narrow columnar shape compared with the overall shape of the Oak. The default Heat Effect (°C) for trees is -10, which means that the cooling effect of a specific tree is -10°C.

Three tree species are chosen to model the PET in the neighbourhoods. The first specie selected is the default deciduous tree and is named in this thesis as a maple tree because it shares similar characteristics with deciduous trees. The other two species chosen are birch and pine trees. Birch trees have a narrower crown and lower leaf area index (LAI) than maple trees. While maple trees are highly tolerant to drought, birch trees have a low to zero drought tolerance. Both species exhibit medium interception of rain. On the other hand, pine trees have a lower cooling effect than maple and birch trees but are equally adapted to withstand drought and can intercept rainfall effectively (Hiemstra, 2018). Pine trees also differ in leaf type from birch and maple trees, making them an interesting subject for comparing the PET of different tree types. To ensure comparability of the tree types, the height of all three species was set to 10 meters.

Table 3.1 Tygron tree species (Tygron, n.d.).

Tree species
Birch
Bush
Default deciduous trees
Default pine trees
Heath
Italian popular
Larch
Oak
Orchard
Palm trees
Reeds
Willow

Table 3.2 Tree species division in high and moderate contribution to limiting global warming.

	> 15 meters	10-15 meters
Tree species with a high contribution to limiting global warming	*Acer* (Maple) *Populus* (Italian Poplar) *Quercus* (Oak) *Salix* (Willow)	
Tree species with a moderate contribution to limiting global warming	*Pinus* (Pine) *Larix* (Larch)	*Betula* (Birch)

Table 3.3 Tree characteristics (Tygron, n.d.).

	Height (meters)	**Bowen Ratio**	**Foliage Crown Factor**	**Heat Effect (°C)**
Birch	10,9	0,4	0,50	-10
Default deciduous trees	12,0	0,4	0,75	-10
Default pine trees	10,1	0,4	0,75	-10
Italian popular	15,0	0,4	0,25	-10
Larch	15,0	0,4	0,50	-10
Oak	14,5	0,4	1,00	-10
Willow	10,1	0,4	0,90	-10

3.2.5 Modelling settings

The first step in modelling with the Tygron platform is to adjust to model settings for the neighbourhoods and interpret the PET results. The Heat stress overlay shows detailed insight into the built-up environment in combination with temperature. Different colours indicate the PET. Heat stress can be reduced when vegetation, water, and different building structures compensate for the paved surface. To measure the PET, several measurement points are added to the model. Four measurement points are located in a line in the middle of the modelling area. In the working-class and suburban neighbourhoods, these measurement locations are on the paved road, and in the high-rise neighbourhood, the measurement points are on grass. Besides road measurements, four sidewalk measurements are also applied to model PET on sidewalks. By doing so, PET differences between roads and sidewalks are researched. The PET measurement per hour is the sum of the 4 measurement points divided by 4.

The Tygron Heat Stress overlay is activated to assess trees' cooling effect. The first step is to import weather data or use the default weather circumstances of August 2nd 2013. It should be mentioned that this weather data is default data and belongs specifically to 2 August 2013, and it is possible to adjust these settings based on your preference. Next, the model hours are selected. For this assessment, it has been decided to measure Heat Stress between 12 and 5 pm, with measurements every hour.

The selected weather data is from 2 August 2013, with a minimum temperature of 19 °C and a maximum temperature of 34 °C. Table 3.4 provides details about the weather data. It has been decided to use the default settings for modelling the PET in the default neighbourhoods. The Heat Stress overlay uses variables to model the PET. The sun's daily motion increases in time because the sun moves across the sky during the day. Air humidity refers to the amount of water vapour present in the air. It is essential in determining a region's weather and climate that affects human comfort levels (Rahman et al., 2020; Wang et al., 2022). High relative humidity levels can cause discomfort. The ideal relative humidity level for human comfort is between 40% and 60% (KNMI, n.d.). The humidity does not change during the day. The sun's radiation is a steady number that weather stations define. A wind speed of 3 m/s is a light breeze. The wind direction is the direction the wind is from and can be adjusted to north, south, east and west. However, the variables are adjusted to test the model's sensitivity by increasing humidity and wind speed and changing the wind direction. Figure 3.10 shows two impressions of the working-class neighbourhood without trees in the Tygron software at 1 pm. The road between the houses is the warmest surface. The PET around the two building blocks is cooler than the road because those areas are in the shade of the buildings.

Table 3.4 Calculated meteorological characteristics (Tygron, n.d.).

	Sun Daily motion	Humidity (%)	Sun Radiation (W/m2)	Temperature (°C)	Wind Speed (m/s)	Wind Direction (°)
12 pm	0,063	60	700	33 °C	3	0 (North)
1 pm	0,090	60	700	33 °C	3	0 (North)
2 pm	0,150	60	700	33 °C	3	0 (North)
3 pm	0,222	60	700	33 °C	3	0 (North)
4 pm	0,318	60	700	33 °C	3	0 (North)
5 pm	0,450	60	700	33 °C	3	0 (North)

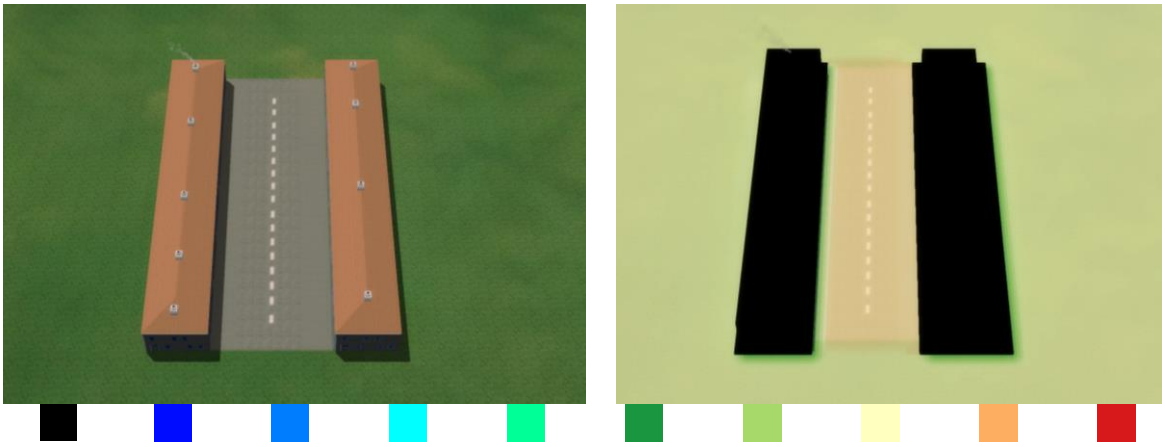


Figure 3.10 Working-class neighbourhood in Tygron (left) with Heat Stress PET (right).

Chapter 4

Results

The results of this thesis are divided into 3 subchapters. The first part analyses results based on three neighbourhood configurations to compare planting patterns, tree types, and two measurement locations: road and sidewalk. In the second part of the result chapter, the model's sensitivity is tested by adjusting sample density, wind speed, wind direction and humidity. In the final part of this chapter, the model is tested on three existing neighbourhoods in The Hague to model the PET. In this chapter, research questions *"What may be expected of trees regarding thermal comfort?"*, *"How can trees be placed for optimal thermal comfort?"*, *"What is the models' sensitivity by adjusting meteorological data?"* and *"How can the model's results be compared and configurated with current tree configurations?"* are answered.

4.1 Neighbourhood configurations

These chapters are divided into mean PET measurements, PET measurements over time and tree types. Mean PET measurements have been calculated by the sum of each PET measurement per hour and divided by the number of PET hours calculated (6 hours). PET per local hour shows the PET measurement for each specific hour and is presented in line graphs. Comparing tree types, only scenario 1 is used; scenarios 3 and 4 are excluded because scenario 3 is the plantation of shrubs, and scenario 4 excludes trees. Furthermore, PET measurements are rounded up to 1 decimal.

4.1.1 Working-class neighbourhood

4.1.1.1 Mean PET measurements

The working-class neighbourhood road measurements scenario 4 (planting no trees) gives a mean PET of 39,1 °C, and for the sidewalk, a mean PET of 37,5 °C (Table 4.1). Scenario 3 (planting shrubs) results in a mean PET of 39,0 °C for road measurements and 32,8 °C for sidewalk measurements, with a mean PET difference of 6,2 °C. Comparing road and sidewalk measurements for scenarios 3 and 4 shows that the mean PET of shrubs (scenario 3) affects sidewalk measurements with a mean PET decrease of 4,7 °C compared to road measurements with only a 0,1 °C mean PET decrease. For maple trees, sidewalk measurements scenarios 1, 2 and 3 result in a cooler mean PET than road measurements. For road and sidewalk measurements, birch trees in scenario 1 resulted in a mean PET decrease of 4,7 °C to 34,3 °C (road) and 32,8 °C (sidewalk), comparing scenario 4 with scenario 1. The mean PET decrease for scenario 2 is higher for road measurements (4,5 °C drop) than sidewalk measurements (3,6 °C drop). However, the sidewalk PET is still lower than the road PET in scenario 2. Pine trees show comparable mean PET results as maple and birch trees.

Table 4.1 Mean PET measurements for different scenarios and tree types in working-class neighbourhood.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Maple				
Road mean PET	34,2 °C	35,6 °C	39,0 °C	39,1 °C
Sidewalk mean PET	32,8 °C	33,9 °C	32,8 °C	37,5 °C
Birch				
Road mean PET	34,3 °C	34,6 °C	39,0 °C	39,1 °C
Sidewalk mean PET	32,8 °C	33,9 °C	32,8 °C	37,5 °C
Pine				
Road mean PET	34,2 °C	34,6 °C	39,0 °C	39,1 °C
Sidewalk mean PET	32,8 °C	33,9 °C	32,8 °C	37,5 °C

4.1.1.2 PET measurements over time

Over time, there are PET differences per hour between road and sidewalk measurements (Figure 4.1). Scenario 4 shows a PET of 42,6 °C for road measurements per hour between 1 and 3 pm, whereas sidewalk measurements have a PET of 37,8 °C. However, at 4 pm, the PET is 5,0 °C lower than the road measurement (32,0 °C). Between 12 and 3 pm, scenario 3 sidewalk measurements show a lower PET per hour than road measurements, where the PET decreases at 4 pm to 32,0 °C for road measurements and 32,8 °C for sidewalk measurements. For scenario 1 road measurements, maple trees show a PET of 41,3 °C at 12 pm, compared to sidewalk measurements where the PET is 8,3 °C lower (33,0 °C). Between 1 and 5 pm, the PET is reduced for road and sidewalk measurements to 32,8 °C. Comparing road and sidewalk measurements for scenario 2 between 12 and 1 pm, road measurements have a PET of 41,6 °C, whereas sidewalk measurements have a PET of 35,2 °C. However, between 2 and 5 pm, road measurements show a lower PET per hour than sidewalk measurements. Birch trees have a higher PET for road measurements (41,5 °C) than sidewalk measurements (32,8 °C) at 12 pm. However, between 1 and 5 pm, the PET shows comparable road and sidewalk measurement results. This also applies to birch trees in scenario 2, where road measurements show a higher PET (41,5 °C) than sidewalk measurements (35,2 °C) at 12 pm. Pine trees PET results show similar PET results for road and sidewalk measurements compared to birch and maple trees (Appendix 1).

4.1.1.3 Tree types

Comparisons can also be made based on tree type for the working-class neighbourhood (Figure 4.4). The road measurement boxplots are comparably in size, meaning there are no major differences between the tree types. Furthermore, each tree type has one outlier around 41 °C. All tree types show an equal cooling effect for scenario 1 road measurement in the working-class neighbourhood. The boxplots for scenario 1 sidewalk measurements are also comparable but smaller than the road measurements with no outliers. The PET for all three tree types is close together, between 32,7-33,0 °C. This means that between the three types, there are no differences measured for sidewalk measurements in the working-class neighbourhood.

4.1.2 Suburban neighbourhood

4.1.2.1 Mean PET measurements

The mean PET in the suburban neighbourhood without trees (scenario 4) for the road measurements results in a mean PET of 39,4 °C and for the sidewalk measurements of 37,1 °C (Table 4.2). Scenario 3 decreases the mean PET for road and sidewalk measurements with 0,7 °C for road measurements and 4,8 °C for sidewalk measurements. Road measurements show for maple, birch and pine trees in scenario 1 a mean PET of 36,0 °C, a decrease of 3,4 °C compared to scenario 4. Also, sidewalk measurements for scenario 1 have a mean PET of 32,7 °C for all tree types, which is 3,3 °C lower than scenario 1 road measurements. Scenario 2 road measurements show a mean PET of 36,1 °C for all tree types, a decrease of 3,3 °C compared to scenario 4. Maple trees show the lowest mean PET for scenario 2 sidewalk measurements, 33,1 °C. However, birch and pine have a slightly higher mean PET of 33,5 °C. Compared to the road measurements of scenario 2, is the mean PET for all the tree types lower for the sidewalk measurements.

Table 4.2 Mean PET measurements for different scenarios and tree types in suburban neighbourhood.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Maple				
Road mean PET	36,0 °C	36,1 °C	38,7 °C	39,4 °C
Sidewalk mean PET	32,7 °C	33,1 °C	32,3 °C	37,1 °C
Birch				
Road mean PET	36,0 °C	36,1 °C	38,7 °C	39,4 °C
Sidewalk mean PET	32,7 °C	33,5 °C	32,3 °C	37,1 °C
Pine				
Road mean PET	36,0 °C	36,1 °C	38,7 °C	39,4 °C
Sidewalk mean PET	32,7 °C	33,5 °C	32,3 °C	37,1 °C

4.1.2.2 PET measurements over time

Over time, PET differences exist between road and sidewalk measurements in the suburban neighbourhood (Figure 4.2). Comparing scenario 4 road (41,8 °C) and sidewalk (41,6 °C) measurements shows similar results. Between 1 and 3 pm, the mean PET of road measurements is 42,0 °C compared to sidewalk measurement with a PET of 37,3 °C. At 4 pm, road measurements show a lower PET (34,5 °C) than sidewalk measurements (37,7 °C). Sidewalk measurements for scenario 3 show a PET between 33,5-32,5 °C, where the PET for road measurement decreases from 42,2 °C at 12 pm to 32,5 °C at 5 pm. Maple trees have a higher PET for scenarios 1 (41,2 °C) and 2 (41,4 °C) when measuring at the road at 12 pm. Compared to sidewalk measurements for scenarios 1 (32,7 °C) and 2 (33,0 °C). Between 1 and 5 pm, the PET for road measurements decreases, whereas the PET for sidewalk measurements is steady between 32,7-32,9 °C. Birch trees show nearly the same PET for scenarios 1 and 2, around 35,0 °C for road measurements. An exception is the PET of 41,4 °C at 12 pm. Also, scenarios 1 and 2 for sidewalk measurements show the same PET of 32,7 °C, with a PET exception of 37,0 °C for scenario 2 at 12 pm. There are no differences in PET over time for pine trees scenarios 1 and 2 road measurements. In both scenarios, the PET is 41,4 °C at 12 pm, which decreases to a mean PET of 35,0 °C between 1 and 5 pm. Sidewalk measurement for pine trees scenario 1 shows a constant PET of 32,7 °C between 12 and 5 pm. However, scenario 2 sidewalk measurements show a higher pet of 37,0 °C at 12 pm, which decreases to 32,6 °C at 5 pm (Appendix 2).

4.1.2.3 Tree types suburban neighbourhood

PET results of the three tree types and shrubs have been discussed for the suburban neighbourhood. Additionally, based on the two planting scenarios, a comparison can be made based on tree type (Figure 4.4). All three boxplots for the road measurements are comparatively short, meaning that overall, the PET corresponds for all tree types. However, each boxplot has one outlier around 41 °C. Since there is no great difference in height, it can be mentioned that there is hardly any difference between tree types for road measurements in scenario 1. Scenario 1 sidewalk measurements do not differ in size, but the boxplot of maple trees is lower, meaning they have a better cooling effect than the other tree types.

4.1.3 High-rise neighbourhood

4.1.3.1 Mean PET measurements

In the high-rise neighbourhood, the road measurements result in a lower mean PET than sidewalk measurements for scenarios 1, 2 and 3 (Table 4.3). Scenario 4 gives for both measurements a mean PET of 37,0 °C. Furthermore, scenario's 3 mean PET sidewalk measurements result in 37,0 °C, whereas road measurements mean PET is 0,7 °C lower (36,3 °C). For maple trees, scenarios 1 and 2 both have a mean PET of 32,7 °C for road measurements. The mean PET for sidewalk measurements is slightly higher for scenarios 1 (35,5 °C) and 2 (36,4 °C). The sidewalk measurements for birch trees in scenarios 1 and 2 have a mean PET of 36,2 °C. Compared to the road measurements, birch trees have a lower mean PET in scenarios 1 (33,9 °C) and 2 (35,1 °C). Pine trees almost have the same mean PET road and sidewalk measurements in scenarios 1 and 2.

Table 4.3 Mean PET measurements for different scenarios and tree types in high-rise neighbourhood.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Maple				
Road mean PET	32,7 °C	32,7 °C	36,3 °C	37,0 °C
Sidewalk mean PET	35,5 °C	36,4 °C	37,0 °C	37,0 °C
Birch				
Road mean PET	33,9 °C	35,1 °C	36,3 °C	37,0 °C
Sidewalk mean PET	36,2 °C	36,2 °C	37,0 °C	37,0 °C
Pine				
Road mean PET	33,9 °C	35,1 °C	36,3 °C	37,0 °C
Sidewalk mean PET	36,4 °C	36,2 °C	37,0 °C	37,0 °C

4.1.3.2 PET measurements over time

Over time, there are differences between scenarios and road and sidewalk measurements in the high-rise neighbourhood (Figure 4.3). The road measurement for maple trees at 12 pm is different from the other two neighbourhoods discussed earlier. Road measurements for maple trees between 12 and 5 pm show a steady PET of 32,7 °C for scenarios 1 and 2. Compared to sidewalk measurements, scenario 1 shows a PET of 41,3 °C and scenario 2 41,4 °C at 12 pm. Between 1 and 2 pm, the PET decreases to 37,4-37,1 °C in scenario 1, and in scenario 2, the PET stays constant at around 37,5 °C between 1 to 3 pm. Finally, at 5 pm, the PET decreases to 32,4 °C for sidewalk measurements in both scenarios. Birch trees for road measurements begin with a PET of 39,7 °C at 12 pm, but the PET decreases to 32,4 °C at 5 pm. Sidewalk measurements of birch trees show the same PET decline. However, the first measurement for scenarios 1 and 2 shows a PET of 41,3 °C, 1,6 °C higher than road measurements at 12 pm. Finally, the PET decreases to 32,4 °C at 5 pm for both measurements. Pine trees PET over time shows comparable results as birch trees for road measurements and maple trees for sidewalk measurements (Appendix 3).

4.1.3.3 Tree types high-rise neighbourhood

Based on tree type, comparisons can be made for scenario 1 in the high-rise neighbourhood (Figure 4.4). The very small boxplot for maple trees is notable for road measurements, meaning that the PET for all the measurement points are equal and there are no outliers. The distribution of birch and pine trees is similar; they have one outlier around 39,5 °C. Therefore, it can be mentioned that maple trees offer the best cooling effect for scenario 1 road measurements in the high-rise neighbourhood. Compared to the scenario 1 sidewalk measurement, maple trees are more equally distributed than birch and pine trees, see Figure 4.1.18. All tree types offer comparable PET results for scenario 1 sidewalk measurements in the high-rise neighbourhood.

4.1.4 Conclusion subchapter 4.1

The study measures the mean and hourly PET (Physiological Equivalent Temperature) values of roads and sidewalks in working-class, suburban and high-rise neighbourhoods with different tree planting scenarios and tree types. Overall, all three neighbourhoods modelled that planting trees reduces the PET, and thus, it can be mentioned that trees have a positive cooling effect in urban areas.

Results show that in all three neighbourhoods, scenario 1, planting twelve single trees in a line showed the most optimal cooling effect. Furthermore, despite minor differences, maple trees are the type that showed the most optimal cooling effect. Sidewalk measurement showed the lowest PET in the working-class and suburban neighbourhood, compared to the high-rise neighbourhood, where the PET was more optimal for road measurements. Furthermore, the first measurement at 12 pm greatly influences the mean PET. Due to major PET differences of sometimes 8,0 °C, the mean PET was affected. These differences became visible in the PET measures over time and were represented in the boxplots as outliers in all three neighbourhoods' road measurements.

The study also found PET differences between road and sidewalk measurements over time. Road measurements had a higher PET in the afternoon, mainly between 1 pm and 3 pm, while sidewalk measurements showed more consistent results. Maple trees had the lowest mean PET for road measurements in scenarios 1 and 2. In contrast, birch trees showed the most consistent results among the highest PET value of all tree types at 33°C for sidewalk measurements in scenario 1. Overall, the study suggests that trees can be essential in mitigating heat stress in urban environments, and the type of tree and planting scenario impact the cooling effect.

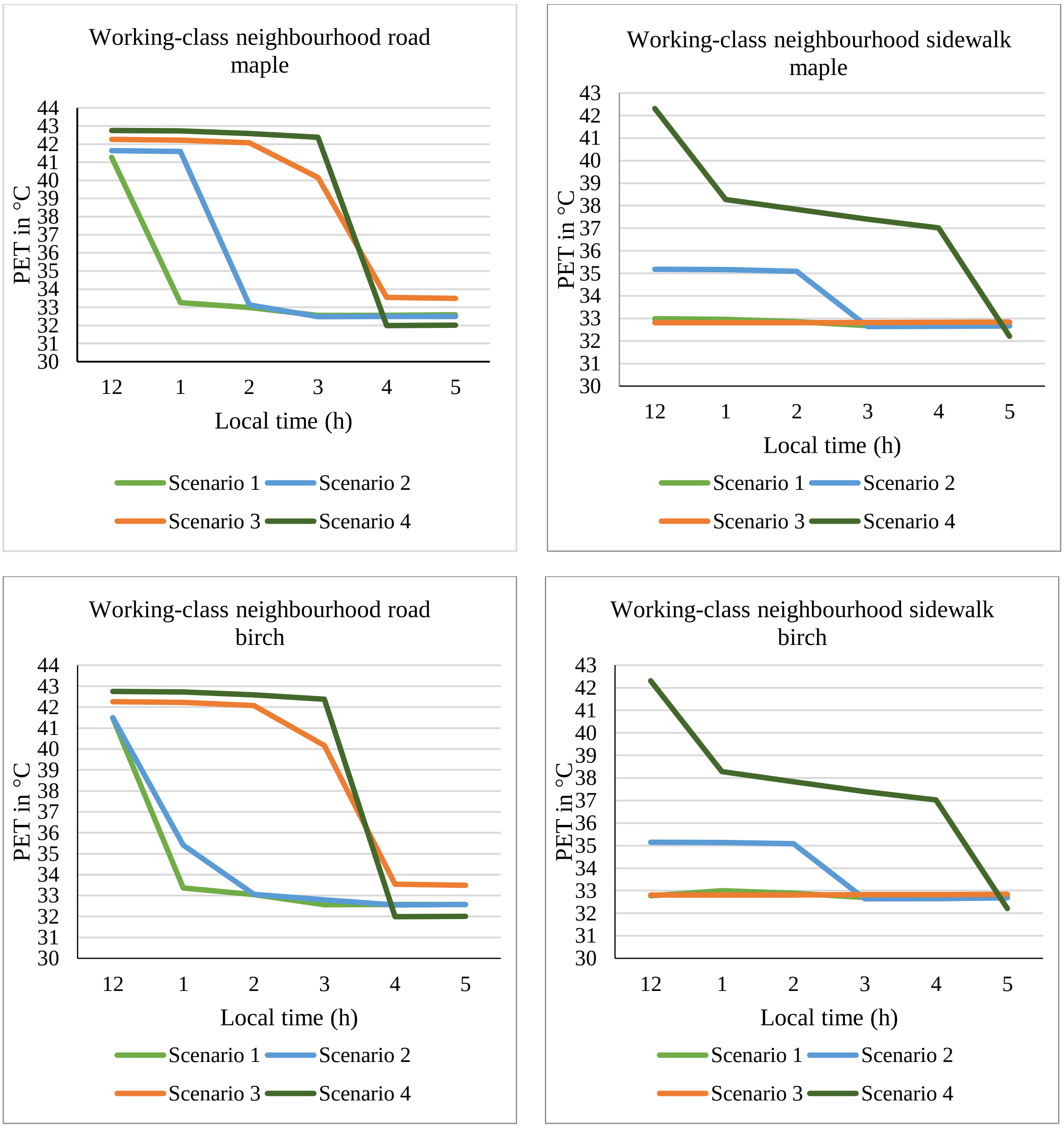


Figure 4.1 PET over time for maple and birch trees road vs sidewalk measurements working-class neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.

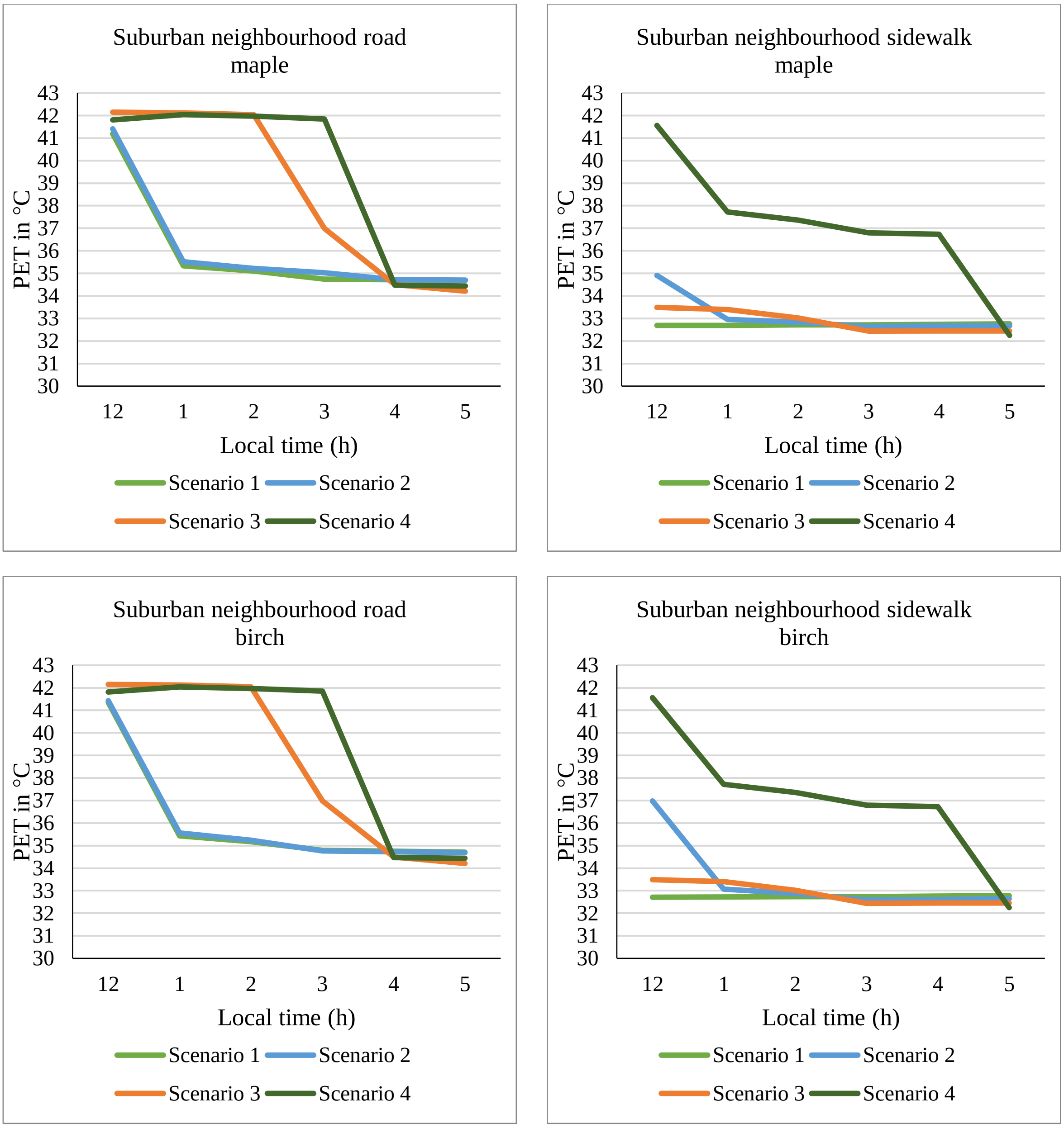


Figure 4.2 PET over time for maple and birch trees road vs sidewalk measurements suburban neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.

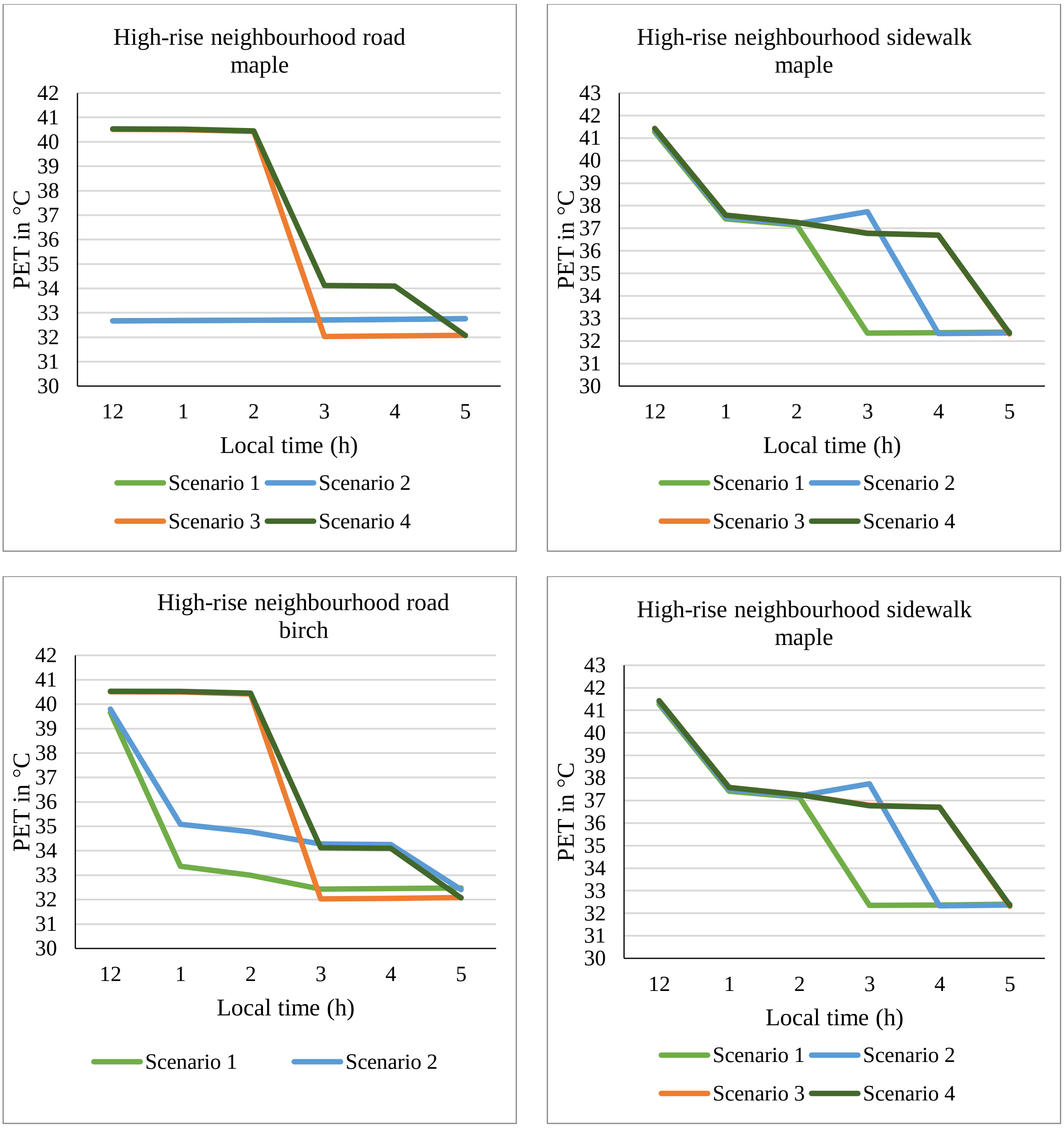


Figure 4.3 PET over time for maple and birch trees road vs sidewalk measurements high-rise neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.

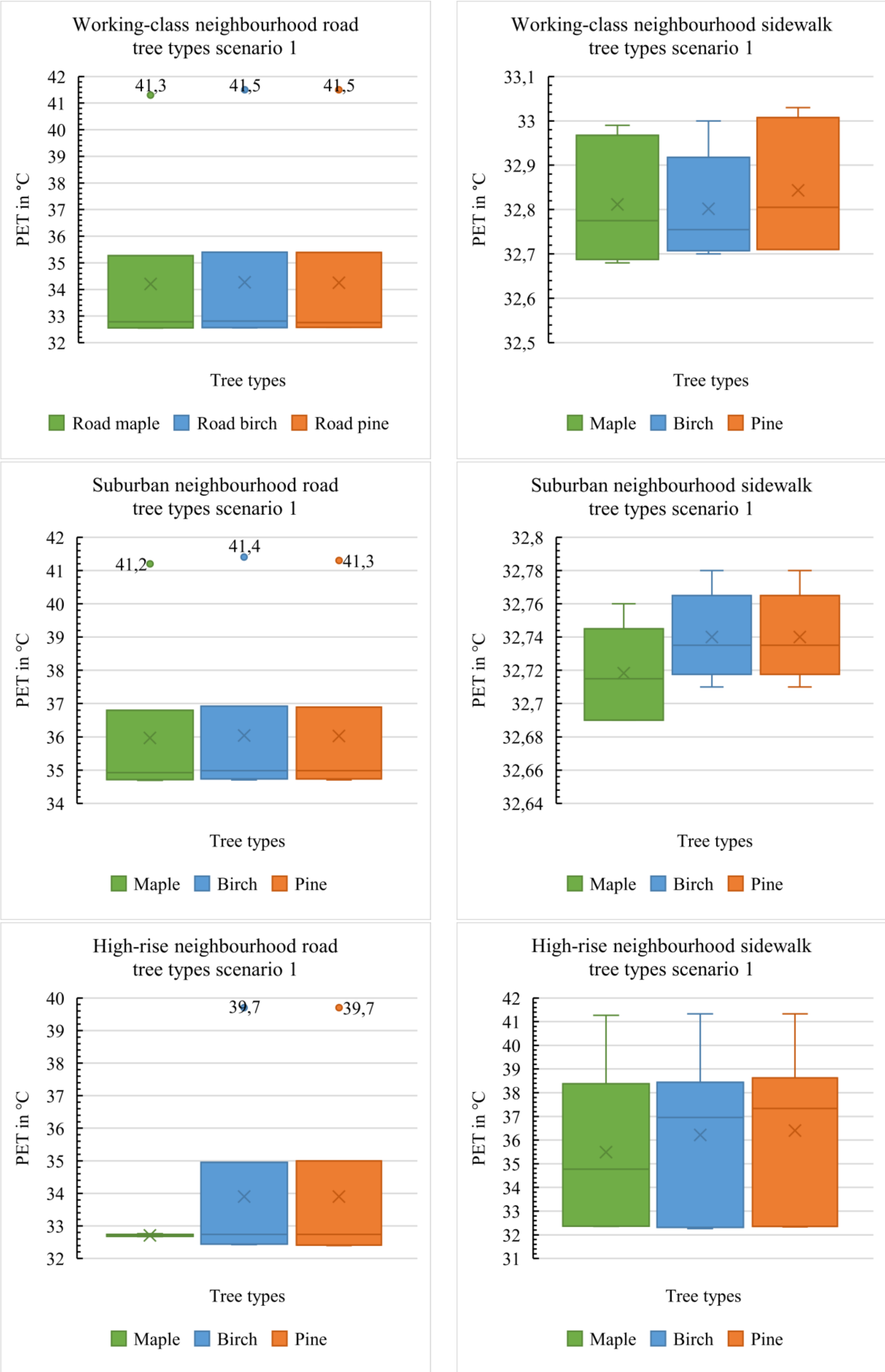


Figure 4.4 PET tree-type scenario 1 in three neighbourhoods.

4.2 Variables change

In this subchapter, the influence of variables is tested and compared with the default settings of subchapter 4.1. The variables that are changed and tested are sample density, wind speed, wind direction and humidity. The variable change is applied to scenarios 1 and 4 only because, in subchapter 4.1, it has been found that the results of scenarios 1 and 2 are nearly equal. Furthermore, the effect of the variable change is visible in scenario 4, when no trees are planted. Additionally, results in subchapter 4.1 have shown that PET differences between tree types are nihil. Therefore, this subchapter tests variable change and the effect on PET with only deciduous trees.

4.2.1 Sample density

In the default modelling settings, four road and four sidewalk measurement points have been used to calculate the PET in subchapters 4.1.1, 4.1.2 and 4.1.3. The computed variables are mean PET and PET over time. Additional measurement points are added to test the model's sensitivity. Four extra measurement points are added to the road and four to the sidewalk. Adding extra measurement points in the working-class neighbourhood shows no mean PET change for scenario 4 road measurements. However, the mean PET increases with 0,2 °C for sidewalk measurements (Table 4.4). The additional measurement points show in scenario 3 a decrease of 0,6 °C for road measurements but do not influence the sidewalk measurements. There are mean PET differences between the tree types. For instance, the mean PET decreases for maple trees for road measurements in scenario 1 but decreases in scenario 2. In scenario 2, the mean PET decreases by 0,6 °C for sidewalk measurements of maple, birch, and pine trees. In the suburban neighbourhood, the additional measurement points do not influence the mean PET for scenarios 3 and 4 road measurements (Table 4.5). For scenarios 1 and 2, some mean PET increases are measured when adding additional measurement points. However, scenarios 3 and 4 are influenced by sidewalk measurements, showing a mean PET increase of 0,1 °C (scenario 4) and 0,2 °C (scenario 3). Maple, birch and pine trees show a 0,9 °C mean PET decrease for road measurements in scenario 1. Finally, many mean PET increases are measured in the high-rise neighbourhood when adding additional measurement points (Table 4.6). The mean PET increase for road and sidewalk measurements is between 0,1-1,4 °C. Overall, adding other measurement points shows differences in the mean PET. The mean PET increases for slightly more than half of the mean PET measurements. However, it should be mentioned that the increase is primarily small. Furthermore, the mean PET increases slightly more often for sidewalk measurements than road measurements. Additionally, the mean PET decreased more often for road measurements than sidewalk measurements.

Table 4.4 Working-class neighbourhood additional measurement points mean PET change.

	S1	PET change	S2	PET change	S3	PET change	S4	PET change
Maple								
Road mean PET	34,0 °C	- 0,2 °C	35,8 °C	+ 0,2 °C	38,4 °C	-0,6 °C	39,1 °C	+-0,0 °C
Sidewalk mean PET	32,8 °C	+-0,0 °C	33,3 °C	-0,6 °C	32,8 °C	+-0,0 °C	37,7 °C	+ 0,2 °C
Birch								
Road mean PET	34,4 °C	+ 0,1 °C	35,2 °C	+ 0,6 °C	38,4 °C	- 0,6 °C	39,1 °C	+-0,0 °C
Sidewalk mean PET	32,8 °C	+-0,0 °C	33,3 °C	-0,6 °C	32,8 °C	+-0,0 °C	37,7 °C	+ 0,2 °C
Pine								
Road mean PET	34,4 °C	+ 0,2 °C	34,8 °C	+ 0,2 °C	38,4 °C	- 0,6 °C	39,1 °C	+-0,0 °C
Sidewalk mean PET	32,8 °C	+-0,0 °C	33,3 °C	-0,6 °C	32,8 °C	+-0,0 °C	37,7 °C	+ 0,2 °C

Table 4.5 Suburban neighbourhood additional measurement points mean PET change.

	S1	PET change	S2	PET change	S3	PET change	S4	PET change
Maple								
Road mean PET	35,1 °C	- 0,9 °C	35,7 °C	- 0,4 °C	38,0 °C	+-0,0 °C	39,4 °C	+-0,0 °C
Sidewalk mean PET	32,7 °C	+-0,0 °C	33,1 °C	+-0,0 °C	32,9 °C	+ 0,2 °C	37,2 °C	+ 0,1 °C
Birch								
Road mean PET	35,1 °C	- 0,9 °C	35,7 °C	- 0,4 °C	38,0 °C	+-0,0 °C	39,4 °C	+-0,0 °C
Sidewalk mean PET	32,7 °C	+-0,0 °C	33,3 °C	- 0,2 °C	32,9 °C	+ 0,2 °C	37,2 °C	+ 0,1 °C
Pine								
Road mean PET	35,1 °C	- 0,9 °C	35,7 °C	- 0,4 °C	38,0 °C	+-0,0 °C	39,4 °C	+-0,0 °C
Sidewalk mean PET	32,8 °C	+ 0,1 °C	33,3 °C	- 0,2 °C	32,9 °C	+ 0,2 °C	37,2 °C	+ 0,1 °C

Table 4.6 High-rise neighbourhood additional measurement points mean PET change.

	S1	PET change	S2	PET change	S3	PET change	S4	PET change
Maple								
Road mean PET	34,1°C	+ 1,4 °C	33,5 °C	+ 0,8 °C	36,9 °C	+ 0,3 °C	37,0 °C	+ 0,1 °C
Sidewalk mean PET	35,5 °C	+-0,0 °C	36,4 °C	+ 0,1 °C	37,2 °C	+ 0,2 °C	37,2 °C	+ 0,2 °C
Birch								
Road mean PET	34,7 °C	+ 0,8 °C	35,3 °C	+ 0,2 °C	36,9 °C	+ 0,3 °C	37,0 °C	+ 0,1 °C
Sidewalk mean PET	36,3 °C	+ 0,1 °C	36,3 °C	+ 0,1 °C	37,2 °C	+ 0,2 °C	37,2 °C	+ 0,2 °C
Pine								
Road mean PET	34,7 °C	+ 0,8 °C	35,3 °C	+ 0,2 °C	36,9 °C	+ 0,3 °C	37,0 °C	+ 0,1 °C
Sidewalk mean PET	36,4 °C	- 0,1 °C	36,4 °C	+ 0,2 °C	37,2 °C	+ 0,2 °C	37,2 °C	+ 0,2 °C

4.2.2 Wind speed

In the default settings, the wind speed of 3 m/s, a slight breeze, has been used to model the PET. The wind speed has been increased to 8 m/s, a relatively strong wind, to test the impact of the wind speed variable on the PET. When planting no trees in the working-class neighbourhood, the mean PET for road measurements decreased by 4,1 °C (from 39,0 °C to 34,9 °C) when the wind speed increased to 8 m/s (Figure 4.5). For sidewalk measurements, the mean PET decreased by 5,2 °C (from 37,5 °C to 32,3 °C) when the wind speed increased to 8 m/s. Over time, the PET for road measurements decreases from 3 pm, whereas the PET for sidewalk measurement decreases after 12 pm in scenario 4 for both windspeeds. Applying scenario 1, the mean PET for road measurements decreased by 2,2 °C (from 34,2 °C to 32,0 °C) when increasing the wind speed to 8 m/s, and for sidewalk measurements, the PET decreased by 1,5 °C (32,8 °C to 31,3 °C). The results for scenarios 2 and 3 are similar to scenario 1: increasing wind speed causes a PET decrease.

Furthermore, the suburban neighbourhood shows comparable wind results with the working-class neighbourhood, meaning that a wind speed of 8 m/s decreased the PET for road and sidewalk measurements (Appendix 4). However, in the high-rise neighbourhood, there are some noteworthy points. The PET for road measurements in scenario 1 with the wind speed of 8 m/s is 0,8 °C higher than the wind speed of 3 m/s at 12 pm. This also applies to scenario 1 sidewalk measurements at 3 pm (Figure 4.5).

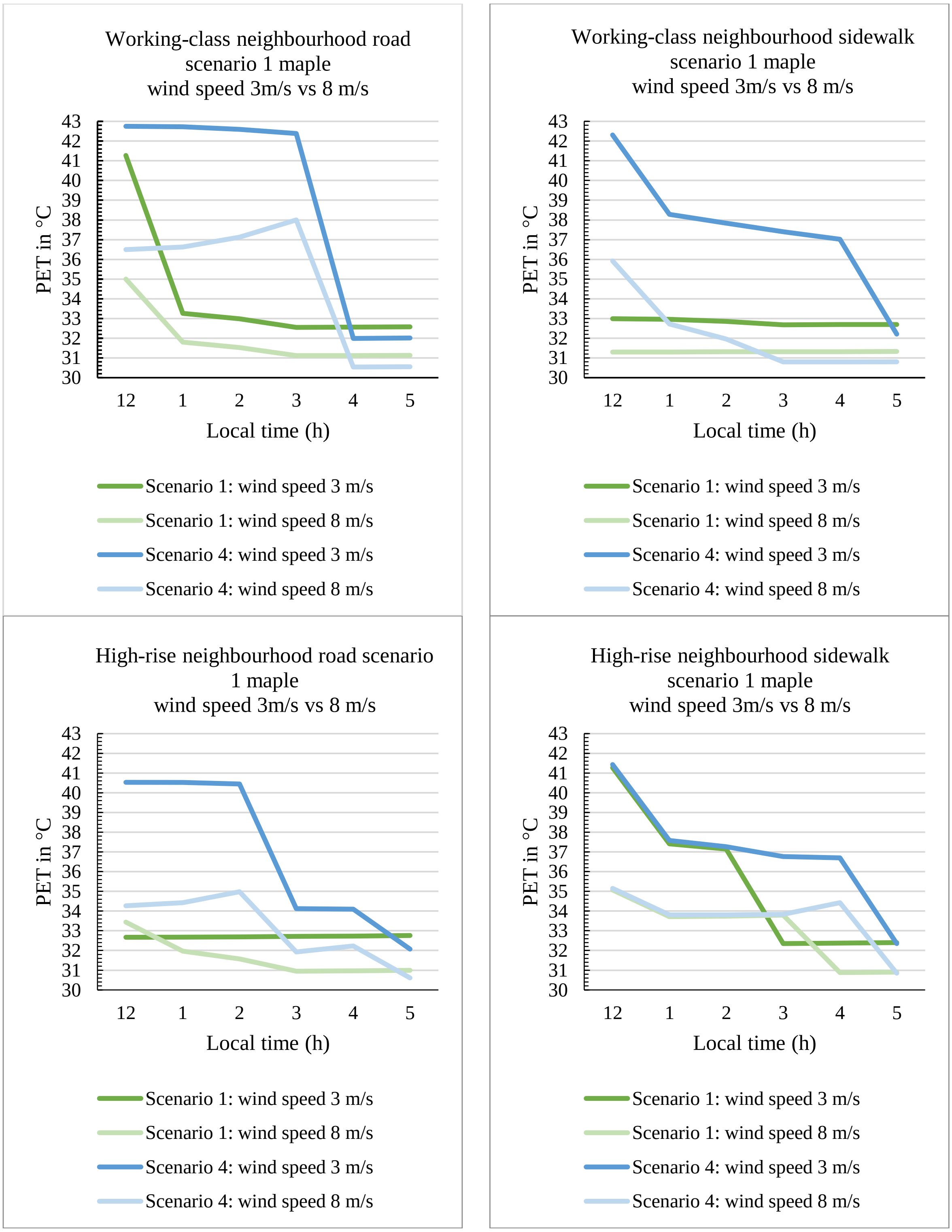


Figure 4.5 Wind speed 3 m/s vs 8 m/s in scenario 1 maple road and sidewalk measurements working-class and high-rise neighbourhood.

4.2.3 Wind direction

The wind direction is the direction the wind is from. In the default setting, the wind blows from the north. Besides changing the wind speed, the direction wind can be adjusted in the model. In this subchapter, the east, south and west wind directions are modelled based on scenarios 1 and 4, and maple trees are used as tree type. This model's input is equal to subchapters 4.1.1, 4.1.2 and 4.1.3.

Results show that for the working-class neighbourhood in scenario 4, wind directions east, south and west sidewalk measurements show the most optimal mean PET compared to road measurements with a difference of 1,7 °C for the east and south and 1,6 °C the for the west (Table 4.7). Comparing the mean PET measurements of the east, south and west with the default northern wind direction, road measurements show a higher mean PET and sidewalk measurements a lower mean PET. However, the differences are minor. Applying scenario 1 in the working-class neighbourhood, the wind directions score equal (south wind direction road measurement) or a higher mean than the northern default wind directions for road and sidewalk measurements (Table 4.8).

Comparing road and sidewalk measurements for the other two neighbourhoods, the east, south and west wind directions do not show a better cooling effect than the northern wind direction (Table 4.9). However, some equal mean PETs measured regarding the southern wind direction in the suburban and high-rise neighbourhood measured. The suburban and high-rise neighbourhood tables of the PET measurements over time are in Appendix 5, 6, 7 and 8. Overall, the northern wind direction is the wind flow with the most optimal cooling effect when comparing the results for the different neighbourhoods. However, the mean PET of the east, south and west wind directions are slightly higher. Therefore, it can be concluded that the wind direction influences the mean PET and thus impacts cooling in urban areas, despite the small differences between the wind directions for the mean PET.

Table 4.7 Wind directions north, east, south and west scenario 4 working-class neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	42,8	42,7	42,6	42,4	32,0	32,0	39,0 °C	
Sidewalk wind direction north	42,8	42,7	42,6	42,4	32,0	32,0	39,0 °C	
Road wind direction east	43,1	43,1	42,9	42,6	32,1	32,1	39,3 °C	+ 0,3 °C
Sidewalk wind direction east	42,7	38,5	38,0	37,3	32,3	32,3	37,6 °C	- 1,4 °C
Road wind direction south	42,8	42,7	42,6	42,4	32,0	32,0	39,1 °C	+ 0,1 °C
Sidewalk wind direction south	41,8	38,3	37,8	37,2	32,2	32,2	37,4 °C	- 1,6 °C
Road wind direction west	43,1	43,1	42,9	42,6	32,1	32,1	39,3 °C	+ 0,3 °C
Sidewalk wind direction west	42,7	38,5	38,0	37,3	32,3	32,3	37,7 °C	- 1,3 °C

Table 4.8 Wind directions north, east, south and west scenario 1 working-class neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	41,3	33,3	33,0	32,6	32,6	32,6	34,2 °C	
Sidewalk wind direction north	33,0	33,0	32,9	32,7	32,7	32,7	32,8 °C	
Road wind direction east	42,1	33,4	33,2	32,7	32,8	32,8	34,5 °C	+ 0,3 °C
Sidewalk wind direction east	33,2	33,1	33,0	32,9	32,9	32,9	33,0 °C	+ 0,2 °C
Road wind direction south	41,3	33,3	33,0	32,6	32,6	32,6	34,2 °C	+-0,0 °C
Sidewalk wind direction south	33,0	33,0	32,8	35,4	32,7	32,7	33,3 °C	+ 0,5 °C
Road wind direction west	42,1	33,4	33,2	32,7	32,8	32,8	34,5 °C	+ 0,3 °C
Sidewalk wind direction west	33,2	33,1	33,0	32,9	32,9	32,9	33,0 °C	+ 0,2 °C

Table 4.9 Wind directions north, east, south and west scenarios 4 and 1 suburban and high-rise neighbourhood.

	Suburban neighbourhood		Highrise neighbourhood	
	Scenario 4	Scenario 1	Scenario 4	Scenario 1
Road wind direction north mean PET	**39,4 °C**	**36,0 °C**	**37,0 °C**	**32,7 °C**
Sidewalk wind direction north mean PET	**37,1 °C**	**32,7 °C**	**37,0°C**	**35,5 °C**
Road wind direction east	+ 0,6 °C	+ 0,5 °C	+ 0,8 °C	+ 2,0 °C
Sidewalk wind direction east	+ 0,4 °C	+ 0,3 °C	+ 0,7 °C	+ 1,9 °C
Road wind direction south	+ 0,1 °C	+-0,0 °C	+-0,0 °C	+ 1,2 °C
Sidewalk wind direction south	+-0,0 °C	+-0,0 °C	+-0,0 °C	+ 0,7 °C
Road wind direction west	+ 0,6 °C	+ 0,5 °C	+ 0,8 °C	+ 2,0 °C
Sidewalk wind direction west	+ 0,3 °C	+ 0,3 °C	+ 0,7 °C	+ 1,9 °C

4.2.4 Humidity

Another variable to test the sensitivity of the model is humidity. The model's default humidity setting is 60%, used in the PET modelling in subchapters 4.1.1, 4.1.2, and 4.1.3. To assess the model's sensitivity, the humidity is increased to 80%, which can lead to discomfort due to the warm and heavy feeling in the air.

Results show in Table 4.10 that the mean PET increases when the humidity increases to 80% for all three neighbourhoods, both road and sidewalk measurements. The PET increase is overall very little, with a PET increase between 0,1-0,2 °C. However, there are some noteworthy PET differences to mention. In the suburban neighbourhood, the mean PET increases by 5,2 °C with a humidity increase of 80% for road measurements. Furthermore, in the high-rise neighbourhood, road (+ 1,3 °C) and sidewalk (+ 0,9 °C) measurements show a higher mean PET increase than other mean PET measurements. More detailed tables with over time PET measurements are in Appendix 9, 10 and 11. Overall, it can be concluded that humidity influences the PET in this model.

Table 4.10 Humidity 60% vs 80% for scenarios 1 and 4 in working-class, suburban and high-rise neighbourhoods.

	Working-class		**Suburban**		**High-rise**	
	Mean PET	PET difference	Mean PET	PET difference	Mean PET	PET difference
Scenario 4: road 60%	39,0 °C		34,4 °C		37,0 °C	
Scenario 4: sidewalk 60%	37,5 °C		37,0 °C		37,0 °C	
Scenario 4: road 80%	39,2 °C	+ 0,2 °C	39,6 °C	+ 5,2 °C	37,1 °C	+ 0,1 °C
Scenario 4: sidewalk 80%	37,6 °C	+ 0,1 °C	37,2 °C	+ 0,2 °C	37,1 °C	+ 0,1 °C
Scenario 1: road 60%	34,2 °C		36,0 °C		32,7 °C	
Scenario 1: sidewalk 60%	32,8 °C		32,7 °C		35,5 °C	
Scenario 1: road 80%	34,3 °C	+ 0,1 °C	36,1 °C	+ 0,1 °C	34,0 °C	+ 1,3 °C
Scenario 1: sidewalk 80%	32,9 °C	+ 0,1 °C	32,9°C	+ 0,2 °C	36,4 °C	+ 0,9 °C

4.2.5 Conclusion subchapter 4.2

In conclusion, this study investigated the sensitivity of a model that calculates the mean physiological equivalent temperature (PET) in urban areas to various factors, including measurement point locations, wind speed, wind direction, and humidity. The study's default settings for measuring the PET involved four road and four sidewalk measurement points. Additional measurement points were added in each neighbourhood to test the model's sensitivity, which revealed differences in mean PET values. Adding more measurement points generally resulted in slight increases in mean PET values, particularly for sidewalk measurements. The maple, birch, and pine trees showed different mean PET values depending on the scenario. Generally, the mean PET increased more often for sidewalk measurements than road measurements.

Furthermore, increasing wind speed caused a decrease in mean PET for both road and sidewalk measurements in most scenarios, except for the high-rise neighbourhood, where the results were inconsistent. Over time, the PET for road measurements decreases from 3 pm, while sidewalk measurements decrease after 12 pm. The same decrease in mean PET is observed for scenarios 1, 2, and 3. When the wind speed increases, the suburban neighbourhood also reduces mean PET for road and sidewalk measurements. Wind direction also slightly impacted mean PET and cooling, but the differences were small.

The model's sensitivity to humidity was tested. It was found that increasing humidity to 80% leads to a slight increase in PET for all three neighbourhoods in both road and sidewalk measurements. The PET increase is minimal overall, with an increase between 0,1-0,2 °C. However, the suburban neighbourhood showed a mean PET increase of 5,2 °C for road measurements. In contrast, the high-rise neighbourhood showed a higher mean PET increase than other neighbourhoods for road and sidewalk measurements. The findings suggest that the PET model can be sensitive to different factors, which should be considered when modelling the PET in urban areas.

4.3 Urban configuration

This final subchapter applies the modelling process for the default neighbourhoods to three existing neighbourhoods in The Hague. The decision was made to model only the current state and scenarios 1 and 4, as the differences between scenarios 1 and 2 are minimal. Similarly, only maple trees were used for modelling in the real world. The urban configuration is modelled using the default settings from subchapters 4.1.1, 4.1.2 and 4.1.3. The model variables consist of August 2nd, 2013, 6 model hours (from 12 pm to 5 pm), a humidity level of 60%, 700 W/m2 of sun radiation, a temperature of 33,0°C, a wind speed of 3 m/s, and a northern wind direction.

4.3.1 Laakkwartier-Oost (working-class neighbourhood)

4.3.1.1 Mean PET measurements

Laakkwartier-Oost applying scenario 1, shows a lower mean PET than the current state (Table 4.11). The mean PET decreases by 6,5 °C (to 37,0 °C) for road and 6,6 °C (to 36,1 °C) for sidewalk measurements when applying scenario 1. Figure 4.6 shows PET results for the current state and scenario 4. Removing all trees from the street (scenario 4) shows no mean PET differences with the current state.

Table 4.11 Mean PET measurements current state Laakkwartier-Oost vs scenarios 1 and 4.

	Current state	Scenario 1	Scenario 4
Road mean PET	43,5 °C	37,1 °C	43,5 °C
Sidewalk mean PET	42,7 °C	35,7 °C	42,7 °C

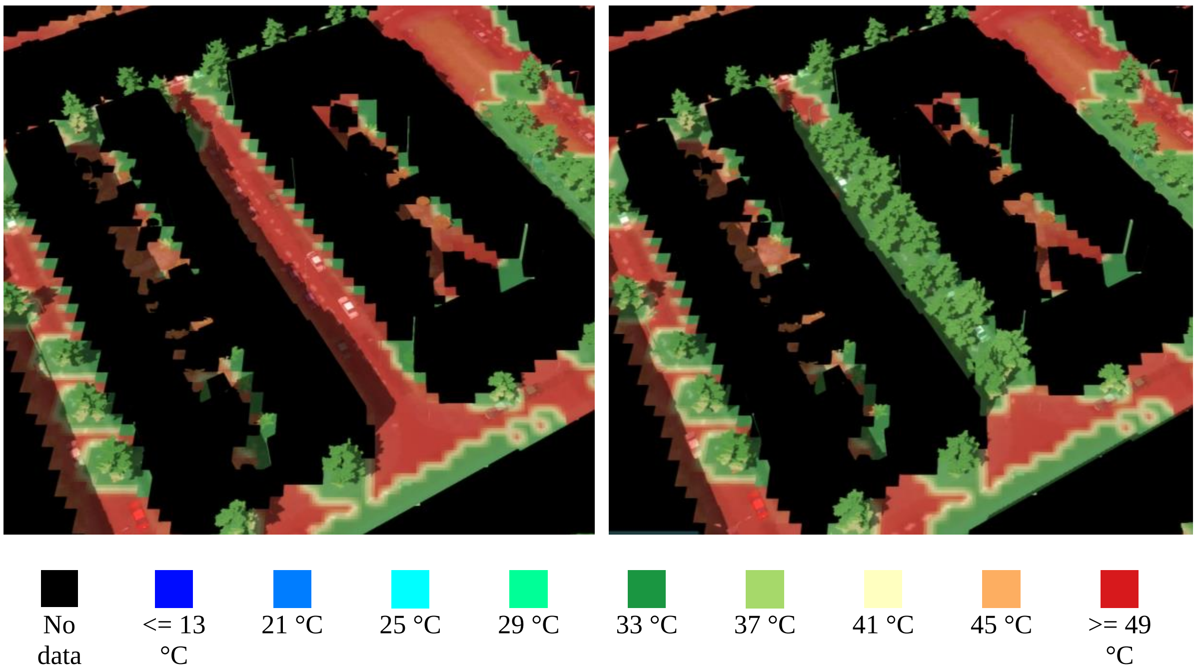


Figure 4.6 Laakkwartier-Oost current state (left) and scenario 4 (right) on August 2nd 2013, at 1 pm.

4.2.1.2 PET measurements over time

In Laakkwartier-Oost, results indicate that the PET road measurements are equivalent to scenario 4 (Figure 4.7) for the same area. The PET reached 48,4°C from 12 pm to 1 pm, gradually decreasing to 35,5°C in both the current state and scenario 4. These PET values are higher than those observed in the default working-class neighbourhood. When scenario 1 is implemented in Laakkwartier-Oost, there is a PET difference of 8,4°C at 12 pm compared to the current state. Although the PET values decrease over time in scenario 1, by 5 pm, the current state and scenario 1 record the same PET results. The analysis shows that sidewalk measurements in Laakkwartier-Oost have similar trends to road measurements (Figure 4.8). Specifically, the current state and scenario 4 exhibit comparable PET values over time. In contrast, scenarios 1 and 4 from the default working-class neighbourhood show lower PET values over time. Applying scenario 1 in Laakkwartier-Oost produces more favourable PET results than the current state.

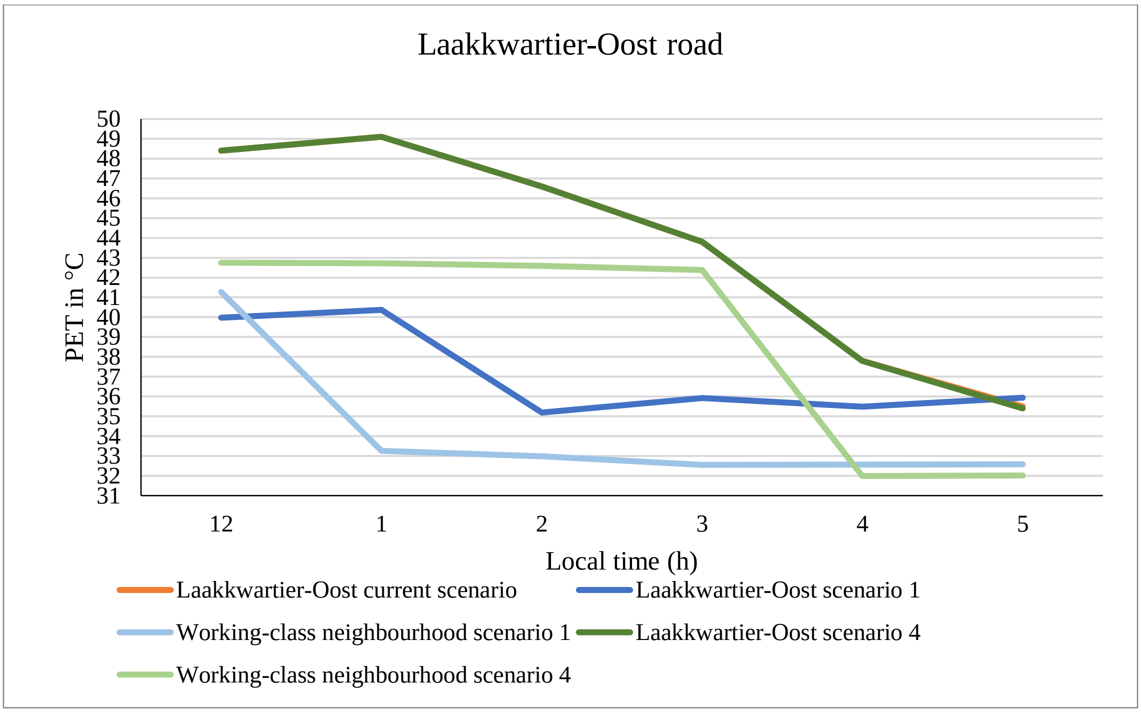


Figure 4.7 PET over time for maple trees road measurements Laakkwartier-Oost. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

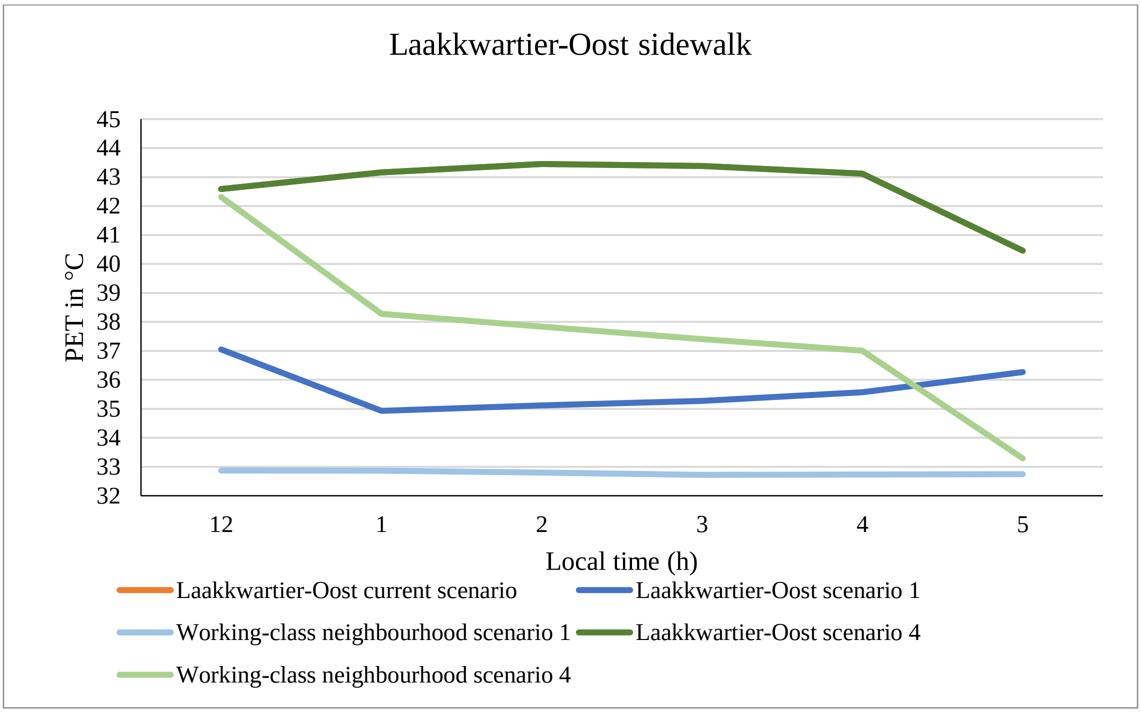


Figure 4.8 PET over time for maple trees sidewalk measurements Laakkwartier-Oost. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

4.3.2 Lage Veld (suburban neighbourhood)

4.3.2.1 Mean PET measurements

In Lage Veld, removing all trees (scenario 4) results in a mean PET increase of 2,5 °C to 47,0 °C for road measurements (Table 4.12). For sidewalk measurements, the mean PET decreases when removing all trees. However, this is only a mean PET decrease of 0,3 °C. For both measurements, scenario 1 shows a mean PET decrease of 0,3 °C for road and 6,0 °C for sidewalk measurements. Figure 4.9 shows PET results for scenarios 1 and 4 in Lage Veld.

Table 4.12 Mean PET measurements current state Lage Veld vs scenarios 1 and 4.

	Current state	**Scenario 1**	**Scenario 4**
Road mean PET	44,5 °C	44,2 °C	47,0 °C
Sidewalk mean PET	42,7 °C	36,7 °C	42,4 °C

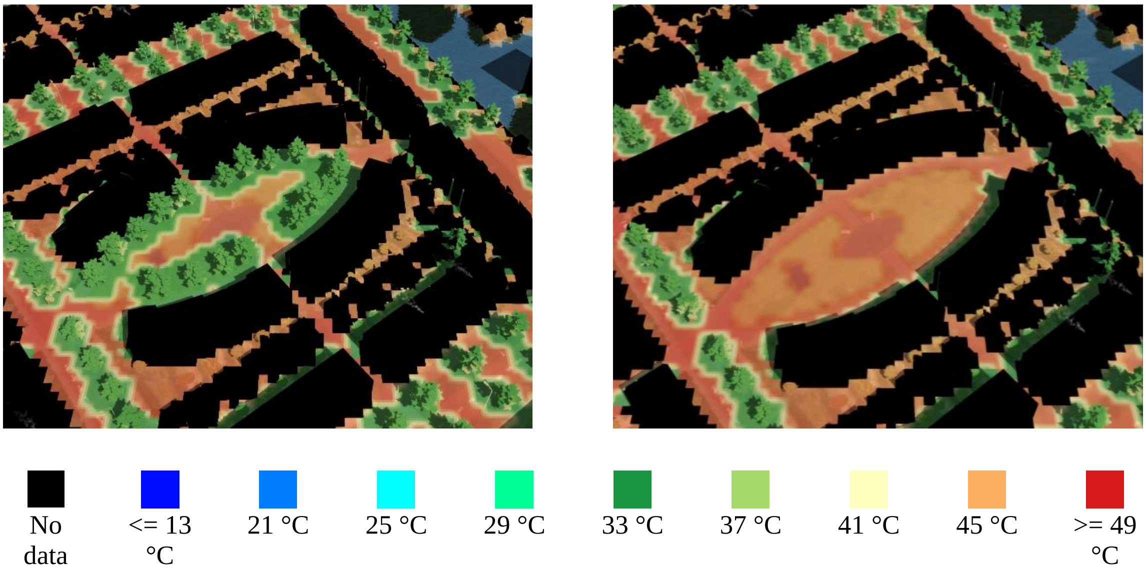


Figure 4.9 Lage Veld scenarios 1 (left) and 4 (right) on August 2nd 2013, at 1 pm.

4.3.2.2 PET measurements over time

Over time, Lage Veld scenario 4 road measurements show a steady PET, decreasing at 4 pm (Figure 4.10). Based on scenario 4, the PET of Lage Veld road measurements is higher than the suburban neighbourhood over time. However, study areas show a PET decrease at 3 pm for the suburban neighbourhood and 4 pm for Lage Veld. Sidewalk measurements show comparable results with road measurements (Figure 4.11). Lage Veld scores a higher PET than the suburban neighbourhood for scenario 4. Scenario 1 for Lage Veld shows non-linear results for road measurements. Between 12 and 1 pm, the PET decreases. However, between 1 and 2 pm, the PET increases, and finally, from 4 to 5 pm, the PET reduces again. Compared to the road measurements in the suburban neighbourhood, which show a PET decrease between 12 and 1 pm followed by a slight reduction until 5 pm. The sidewalk measurements show a comparable result with Lage Veld scenario 1, however, from 2 to 5 pm, the PET remains steady.

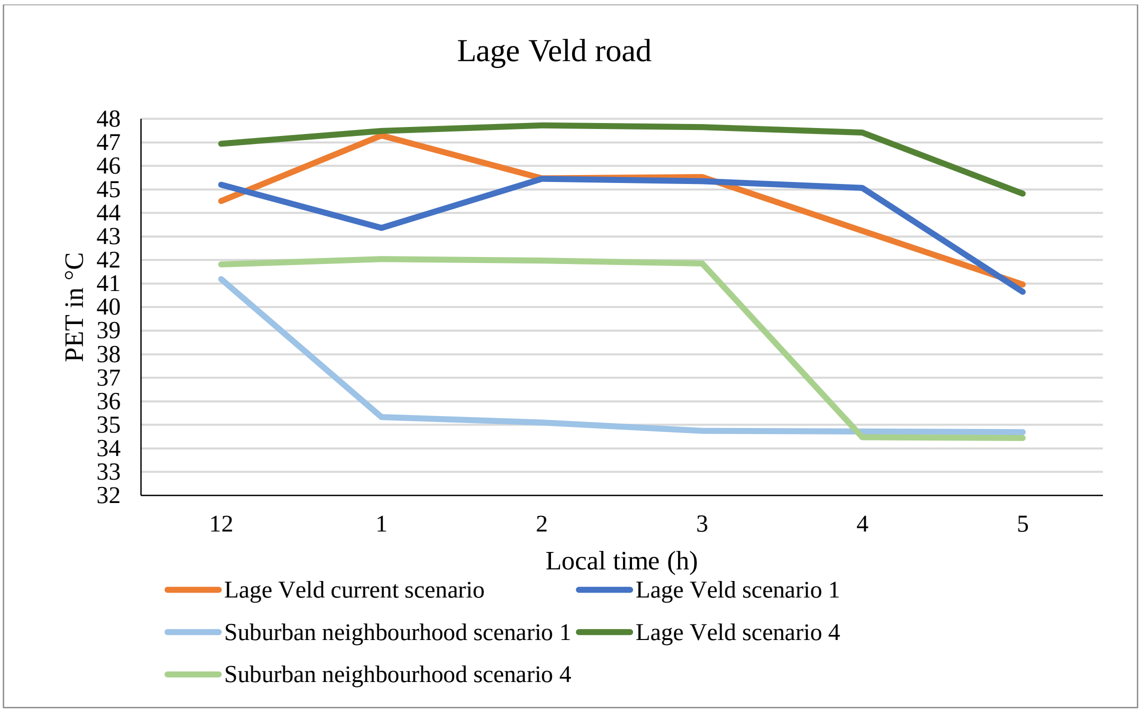


Figure 4.10 PET over time for maple trees road measurements Lage Veld. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

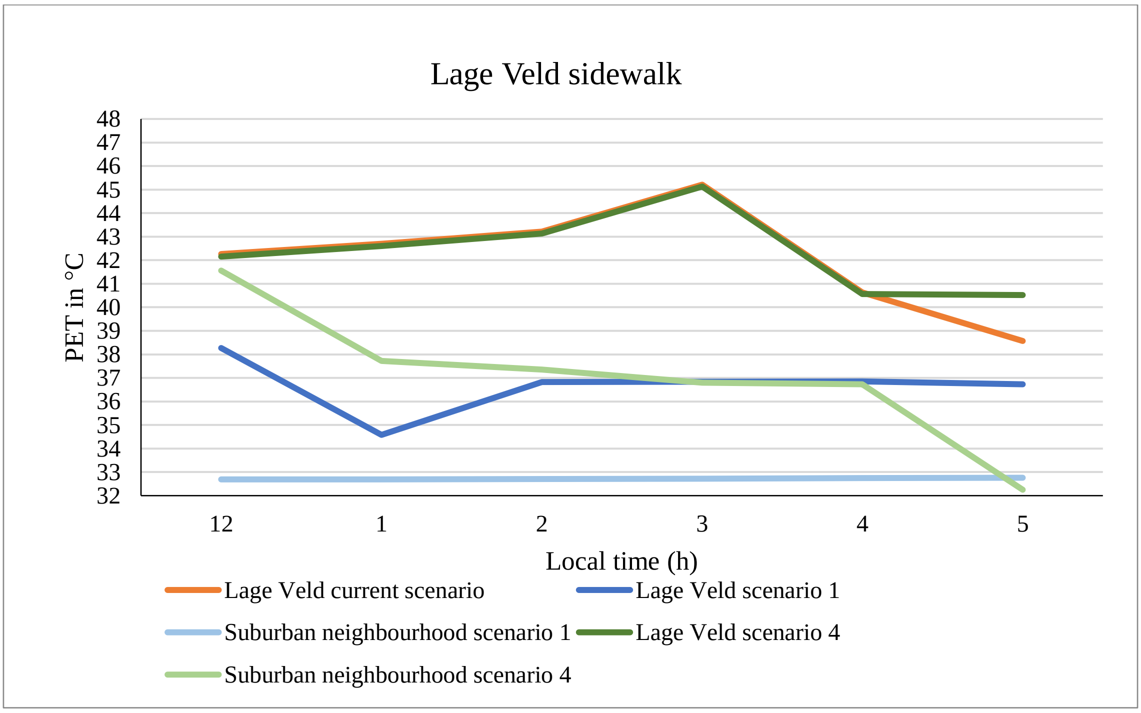


Figure 4.11 PET over time for maple trees sidewalk measurements Lage Veld. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

4.3.3 Kampen (high-rise neighbourhood)

4.3.3.1 Mean PET measurements

In Kampen, the mean PET of the current state is 39,7 °C for road and 40,7 °C for sidewalk measurements (Table 4.13). Scenario 1 results in a decrease of 0,1°C for road measurements and 3,1°C for sidewalk measurements compared to the current state. On the other hand, scenario 4 shows an increase in mean PET for both measures compared to the current state. Figure 4.12 displays the PET results for the current state and scenario 4.

Table 4.13 Mean PET measurements current state Kampen vs scenarios 1 and 4.

	Current state	Scenario 1	Scenario 4
Road mean PET	39,7 °C	39,8 °C	41,6 °C
Sidewalk mean PET	40,7 °C	37,6 °C	41,2 °C

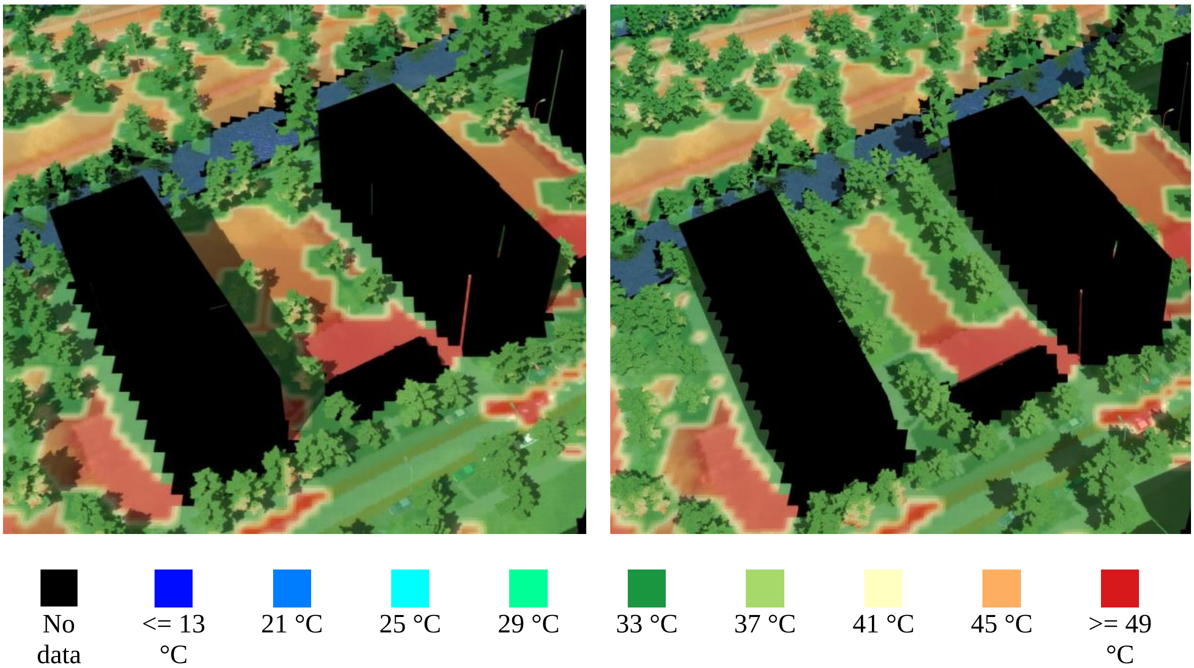


Figure 4.12 Kampen current state(left) and scenario 4(right) on August 2nd 2013, 1 pm.

4.3.3.2 PET measurements over time

Figure 4.13 illustrates the PET results over time for the default high-rise neighbourhood road measurements and Kampen. For scenarios 1 and 4, Kampen exhibits higher PET results than the default high-rise neighbourhood. Additionally, the PET demonstrates different development patterns for Kampen and the high-rise neighbourhood. From 1 to 4 pm, the PET decreases from 44,0 °C to 35,0 °C in scenario 1 for Kampen, while the results indicate a constant PET between 32,0-33,0 °C for the high-rise neighbourhood. Sidewalk measurements reveal PET differences over time for Kampen and the high-rise neighbourhood (Figure 4.14). In scenario 4, the results are comparable between Kampen and the default high-rise neighbourhood, but the PET differs over time by 3,5 °C between 12 to 5 pm. From 1 pm to 5 pm, the current state and scenario 4 show the same PET for Kampen over time. The high-rise neighbourhood shows a PET decrease over time for scenarios 1 and 4. In contrast, Kampen shows a PET increase and eventually exhibits a higher PET between 1 to 5 pm compared to the high-rise neighbourhood for scenarios 1 and 4.

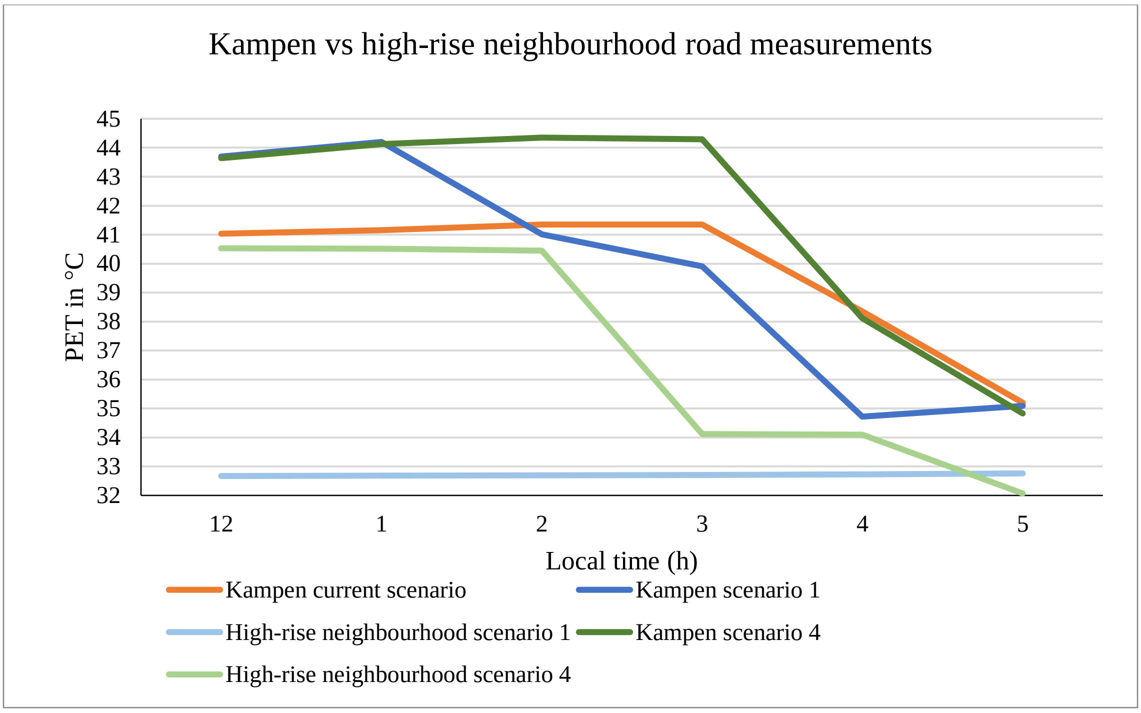


Figure 4.13 PET over time for maple trees road measurements Kampen. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

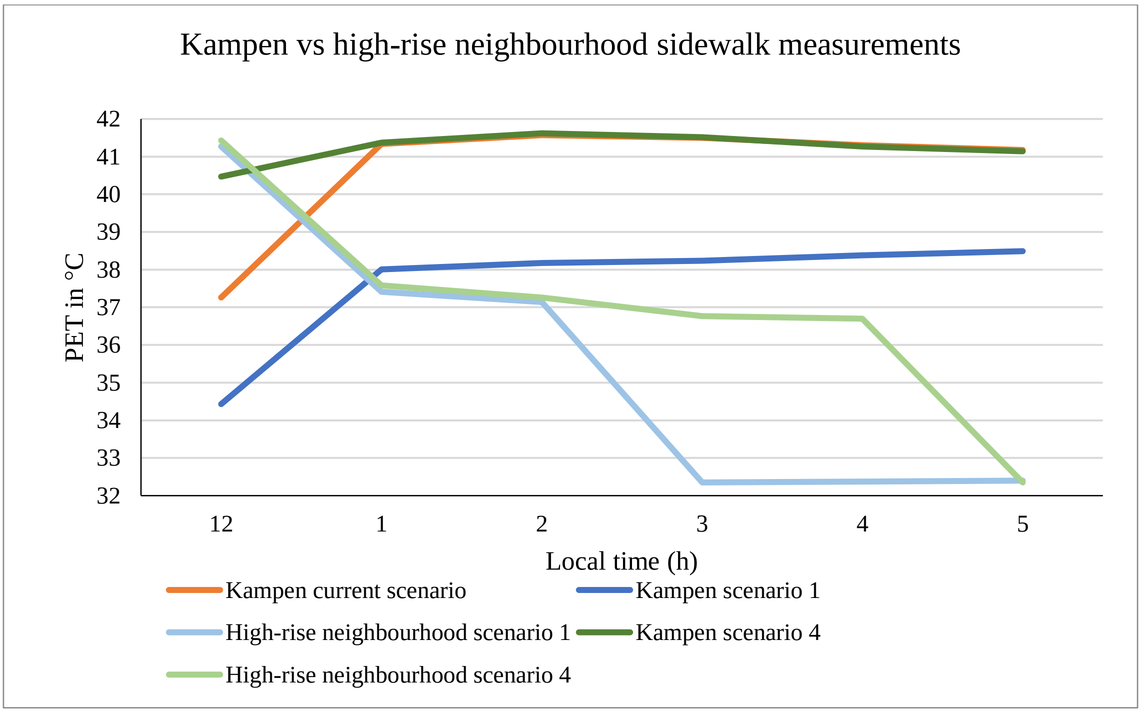


Figure 4.14 PET over time for maple trees sidewalk measurements Kampen. Scenario 1: twelve trees in a single line, Scenario 4: no trees.

4.3.4 Conclusion subchapter 4.3

Overall, the analysis of the different scenarios in the three neighbourhoods (Laakkwartier-Oost, Lage Veld, and Kampen) shows that adding trees as increasing tree cover can reduce the mean PET values. However, there are variations in the PET values and trends over time, depending on the neighbourhood and the measurement location (road or sidewalk). Scenario 1, which involves increasing tree cover, generally produces lower PET results than the current state and scenario 4 involve removing trees. In Laakkwartier-Oost, scenario 1 shows a decrease in mean PET values, while scenario 4 does not affect PET values. In Lage Veld, scenario 1 also shows a decrease in mean PET values, while scenario 4 increases the PET values. In Kampen, scenario 1 leads to a reduction of PET values, while scenario 4 leads to an increase in PET values. The results also show that the PET values in the current state and scenario 4 are generally higher than those in suburban or high-rise neighbourhoods.

In conclusion, the study highlights the importance of urban green in neighbourhoods to mitigate the urban heat island effect and improve the thermal comfort of urban residents. The results can be used to guide urban planning and management practices that prioritise green infrastructure and tree planting to enhance the liveability of urban areas.

Chapter 5

Discussion, Conclusion and Recommendations

5.1 Discussion

While numerous studies have investigated the effects of green spaces on air temperature and Physiological Equivalent Temperature (PET), more research still needs to be conducted on thermal comfort and tree placement. Studies recommend using different building layouts and tree species to maximise more research on height as a variable (Zhang et al., 2018; Rahman et al., 2020). This study aims to evaluate the impact of tree placement strategies on thermal cooling in Dutch urban areas, focusing on the influence of trees on thermal comfort. Previous research in the Netherlands has focused mainly on urban heat islands (UHIs) without distinction between vegetation types or consideration of wind speed and direction (Steenveld et al., 2011; Van Hove et al., 2011). In addition, none of the literature reviewed for this study employed 3D modelling to assess thermal comfort, including the effects of trees and building shadows.

Academic literature revealed that trees positively influence thermal comfort in urban areas. Trees provide shade and reduce air temperature through evapotranspiration. Trees can also block solar radiation and reduce the heat absorbed by buildings and other urban surfaces. However, the specific impact of trees on thermal comfort may depend on factors such as their placement, species, and size, as well as other variables such as wind speed, humidity, and building layout (Hsieh et al., 2016; Hami et al., 2019; Marando et al., 2022; Wang et al., 2022). In this thesis, three distinct urban configurations were modelled with varying building layouts, revealing that despite identical tree placement, different outcomes were obtained. This indicates that the building layout contributes to determining the PET. The reviewed studies used other study areas. Zhang et al. (2018) and Hami et al. (2019) modelled the PET in one study area with multiple building blocks and applied different plating patterns. Abdi et al. (2020) modelled the PET in 3 other parks to compare, whereas Hsieh et al. (2016) modelled the PET at three other locations in one park. Lee et al. (2020) modelled the PET on two different streets. Finally, a similar methodological approach has been applied by Taleghani et al. (2015), modelling the PET in five urban forms based on the building layout.

The placement of trees impacts the cooling ability of trees regarding scientific literature (Zhao et al., 2018; Zhang et al., 2018; Abdi et al., 2020; Lee et al., 2020). Two planting patterns have been studied in this thesis. Differences between the two planting patterns are the distance between trees and a single tree versus a pair of two trees. Zhao et al. (2018) concluded that the two most effective strategies for improving thermal comfort are planting a single tree and planting two trees at equal intervals. Overall, in all three neighbourhoods planting single trees in line with the same interval resulted in a lower PET than when a pair of two trees were planted with an interval of two trees. Additionally, it is recommended by Zhao et al. (2018) and Lee et al. (2020) to avoid tree crown overlap. However, in planting scenario 2, the three trees' crowns overlap, potentially negatively impacting the PET. Therefore, it is possible that planting scenario 1 may show more optimal PET results.

Shadow has a major effect on PET results and is an interesting discussion point in this study. In the urban configuration, buildings and trees are the two factors providing shadow. Therefore, each neighbourhood has different building heights to test the effect of building height on PET. In their findings, Zhang et al. (2018) noted that PET can be affected by building shadows. They found that when trees were placed farther apart, PET results improved compared to scenarios where the same trees were placed closer together but under the same building layout. At 1 pm, the working-class neighbourhood without trees (scenario 4) shows a PET of 42,8 °C for road and 42,3 °C for sidewalk measurements. However, at 5 pm, the same neighbourhood and scenario show a PET decrease of 10,8 °C to 32,0 °C for road and a PET decrease of 9,0 °C to 33,3 °C for sidewalk measurements, while there are no trees added to the neighbourhood (Figure 5.1). This shows that the effect of shadow strongly influences the

PET. Similar results are found for the suburban and high-rise neighbourhoods. Because of this shadow effect, similar PET results are found between the plantation of shrubs versus trees. Shrubs have a less cooling impact than trees. However, when shrubs and trees are placed in the shadow, identical PET results are computed.

Another point of discussion for the urban configuration is the choice of three neighbourhoods. No conclusions can be drawn based on comparing the neighbourhoods since the extent of the neighbourhoods differs. Also, the length of the street and sidewalk is different, and the location of trees is different. In the working-class and suburban neighbourhoods, 12 sidewalk tiles are removed to plant trees, whereas in the high-rise neighbourhood, the trees are placed on grass, and no sidewalk had to be removed. Therefore, between neighbourhoods, there is no distinction made between the coolest or warmest neighbourhoods, and PET results are discussed per neighbourhood.

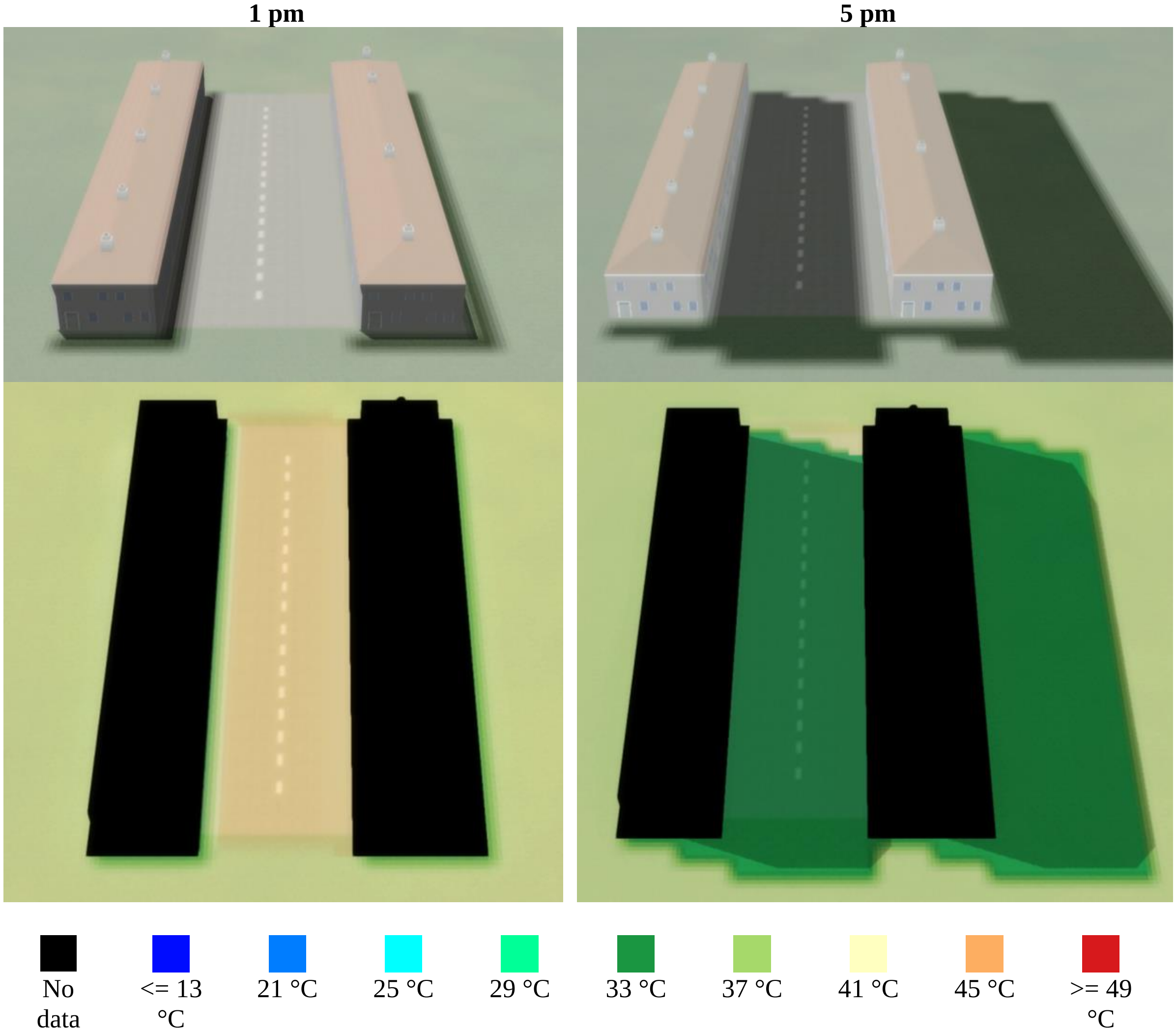


Figure 5.1 PET scenario 4 working-class neighbourhood 1 vs 5 pm.

The Tygron software has been used to model urban configurations, plant trees and calculate the PET. Eight measurement points were used to model the PET (four on the road and four on the sidewalk). These points were placed with a certain distance between them to measure a representative PET. PET results are compared between the road and sidewalk in the three neighbourhoods. The study examines four scenarios for all three tree types in working-class, suburban, and high-rise neighbourhoods. In both working-class and suburban areas, the sidewalk measurements indicate lower PET results than the road measurements. This difference in PET ranges from 0,7-6,4 °C across all tree types. However, the results for the high-rise neighbourhood show a different trend, with road measurements showing lower PET results than sidewalk measurements. It is possible that the positioning of the trees on grass in the high-rise neighbourhood and the layout of the buildings impact this difference. To test the sensitivity of Tygron, eight extra measurement points were added in the urban configurations. Those additional measurements showed different PET results from 0,1 °C up to 1,4 °C, meaning that the location of measurement points influences the (mean)PET results. For example, if a measurement point is located in the shadow from 12 to 5 pm, the mean PET is lower than when the measurement point is located in the sun from 12 to 1 pm and in the shadow from 1 to 5 pm.

Second, the height for all tree types has been set to 10 meters in the Tygron model. There would have been differences between tree type and height to compare PET results for tree types between planting scenarios within neighbourhoods. With this choice, the literature study to select the most optimal tree types is less relevant since the height of the three tree types is equal to ten meters. Furthermore, no changes have been made to adjustable variables such as Bowen ratio, Foliage crown factor and Heat effect. The difference in the default settings between the three tree types is in the Foliage crown factor. The Foliage crown factor for maple is 0,75, and for birch and pine 0,5. This explains the slightly more optimal PET results for maple trees than birch and pine trees. The Heat effect for all three tree types was -10,0 °C, which had not been changed during the modelling process. If, for example, the Heat Stress effect was reduced for maple trees, the outcomes of this study would probably have been different. Additionally, the higher the Leaf Area Index (LAI), the higher the cooling potential (Abdi et al., 2020; Rahman et al., 2020). The leaves of maple trees are bigger than birch and pine trees. However, the LAI is not included as a variable in Tygron, so a specific statement about LAI cannot be made.

Variables have been adjusted to test the model's sensitivity. Trees can direct wind flows and produce a ventilation effect in cities. All four wind flows have been modelled and compared during the modelling process. Overall, the northern wind flow provides the most optimal PET results. Wind flows from the east and west both blow against buildings and is, therefore, most likely to produce higher PET results. Current flows from the north and south blow through the street among the trees in the urban configuration and are expected to show the same PET results. According to Zhang et al. (2018), trees planted parallel to the wind direction provide better airflow in summer. This finding explains why the northern and southern wind directions showed more optimal results than the west and east directions, which experience obstructions from buildings. However, in most modelling configurations, the northern wind flow, compared to the southern, provides the most optimal PET results. Furthermore, increasing the variable wind speed shows a more optimal PET in working-class and suburban neighbourhoods. In the high-rise neighbourhood, increasing the wind speed causes random PET differences, which probably had to do with building height since the buildings in the high-rise neighbourhood are higher than those in the working-class and suburban neighbourhoods. Finally, increasing the humidity variable showed minimal impact on the PET. However, the modelling showed that humidity does influences PET.

The Tygron software is also used to test tree planting patterns and their effect on the PET in the real world. The Tygron software provides insights into complex challenges such as Urban heat islands (UHI). The PET results measured in the three default neighbourhoods are comparable to the real world. The three neighbourhoods in The Hague show similar results to the three default neighbourhoods. In The Hague neighbourhoods, the current state offers a higher PET than scenario 1. This result was expected since more trees were added in scenario 1 than were initially present. Additionally, it is worth noting that in all three neighbourhoods in The Hague, the PET measurements on sidewalks are consistently lower than those on roads. This is because to the fact that sidewalks are often situated in the shadows formed by nearby buildings, which leads to lower PET values compared to measurements taken on roads. The general ambition of The Hague is to enhance its resilience to heat by 2050 by designing public spaces and buildings to be more heat-resistant, green, and balanced with a mix of shade and sun to create a healthy and attractive living environment. In addition, the impact on vulnerable groups' health will be reduced through education and creating more cool spots while ensuring that vital infrastructure and emergency services continue functioning (Van Tongeren et al., 2021). However, no concrete plans have been found to address the heat problem in the three neighbourhoods in The Hague.

5.2 Conclusion

In conclusion, the study provides valuable insights into the impact of tree planting scenarios and tree types on the Physiological Equivalent Temperature (PET) of roads and sidewalks in working-class, suburban, and high-rise neighbourhoods in Dutch urban areas. In this subchapter, the research questions defined in subchapter 1.1.2 are answered.

What may be expected of trees regarding thermal comfort?
The results demonstrate that trees play a crucial role in reducing PET, thereby mitigating the urban heat island effect and enhancing the thermal comfort of urban areas. In all three neighbourhoods, the presence of trees positively affected the PET. A comparison between a scenario without trees and a scenario with trees showed a reduction in PET by 3-5 °C.

How can trees be placed for optimal thermal comfort?
In all three neighbourhoods planting single trees in line with the same interval resulted in a lower PET than when a pair of two trees were planted with an interval of two trees. However, the differences between the two planting strategies are nihil. A greater difference is visible between the scenario where no trees are planted and where there are trees planted.

What form of urban configuration should be used to verify the impact of tree placement on thermal comfort?
The findings indicate that PET results vary across neighbourhoods based on building layout and pavement. Higher buildings exhibit lower PET results due to the shade they provide. A reduction in PET over time was observed in neighbourhoods without trees, indicating that the building layout has an important influence on PET and the potential to mitigate heat in urban areas. Therefore, developing various urban configurations in modelling PET becomes an interesting way to explore its impact on PET outcomes. Findings reveal important differences in PET values between low-rise and high-rise buildings. Specifically, in the absence of trees, a neighbourhood with low-rise buildings models a mean PET value of 39,1 °C, while high-rise buildings present a relatively lower PET value of 37,0 °C.

What is the models' sensitivity by adjusting meteorological data?
The study results indicate that PET results are subject to change when meteorological data is adjusted. Changes in wind direction show a noticeable impact on PET results, with the northern wind direction demonstrating the most optimal PET results. In contrast, wind flows from the east and west lead to higher PET results as they blow against buildings. Furthermore, a higher wind speed in working-class and suburban neighbourhoods results in more optimal PET results. However, increasing wind speed in the high-rise neighbourhood leads to random PET differences, which may be attributed to building height. In terms of humidity, while it does have some impact on PET, the influence is minimal. Furthermore, the results indicate that adding more measurement points generally resulted in slight increases in mean PET values, particularly for sidewalk measurements. Overall, the study concludes that various variables must be considered when modelling PET, as they all contribute to PET outcomes.

How can the model's results be compared and configurated with current tree configurations?
The Tygron software is valuable for modelling complex issues, such as urban heat islands (UHI), and provides clear and accessible results. The three neighbourhoods in The Hague modelled in this study generated outcomes comparable to those of the three default neighbourhoods. Implementing scenario 1 in the Hague neighbourhoods resulted in a decrease in PET, consistent with the findings of the three designed neighbourhoods. Notably, the Tygron software is highly responsive to the planting of trees, resulting in decreased PET. Consequently, this tool is recommended to support policymakers' decisions on tree planting in urban areas.

Overall, the results of this study have important suggestions for urban planning and management practices that prioritise green infrastructure and tree planting to enhance the liveability of urban areas. By understanding the impact of different tree planting scenarios and tree types on PET, policymakers and urban planners can make informed decisions about urban greenery and improve the thermal comfort of urban areas. The findings can also be used to develop strategies targeting different neighbourhoods' specific needs, considering their unique characteristics and environmental conditions. Ultimately, the study contributes to the increasing literature research on the benefits of urban green areas and their role in improving the liveability of cities.

5.3 Recommendations

For further research, it is recommended to obtain field data conforming to PET measurements in The Hague for the appropriate location to test the model's sensitivity. This will allow for correlation analysis with the model outcomes and provide an R2 measurement to evaluate the degree of variation between the two datasets. This will also help to verify the accuracy of the model outcomes and improve the overall quality of the research. Additionally, specifying the technique to be used to obtain the field data would help ensure the consistency and reliability of the data. In this research, the age of trees has not been considered. The growth of trees can also impact thermal comfort. Trees with dense foliage and a high Leaf Area Index (LAI) can provide more shade and cooling than trees with sparse and low LAI. The density and shape of a tree's foliage can affect the amount of shade it provides and the amount of cool air it generates through transpiration. In addition, younger trees may have a lower cooling effect than mature trees as they have smaller canopies and less foliage. For further research, it is interesting to consider the age of trees.

Two tree arrangements were used in this study to model the PET. However, there is potential for further research on different tree arrangements. For instance, while tiny forests were discussed in the theoretical chapter, they were not included in the modelling part. It would be interesting to model trees in clusters or plant them in double rows. Additionally, it would be beneficial to model a mix of tree species instead of just one type. Overall, exploring different tree arrangements can aid in identifying the most effective methods to use trees to improve thermal comfort in urban areas.

It is essential to acknowledge that in Tygron, it is only possible to calculate the thermal comfort for one day at a time. However, it would be interesting to look at the meteorological outcomes over several days for longer heatwaves or consecutive days with high temperatures and calculate a range of possible outcomes. This would allow for assessing the potential accumulation of thermal discomfort over time, an essential aspect of urban heat stress. It is recommended to mention this as a potential study limitation, as it has yet to be discussed. Furthermore, as discussed earlier, the Tygron software does not account for Leaf Area Index (LAI). It would be valuable to incorporate LAI for trees as a specific tree characteristic, in addition to tree height and foliage crown factor.

Finally, it is recommended to expand the scope of the research to include the assessment of how tree locations and arrangements benefit individual parcels and the surrounding area, including both public and private vegetation. This recommendation is in line with the argument made by Zhao et al. (2018) that such research needs to be included. Although the focus of the current research was on public areas only, the use of Tygron can facilitate the assessment of both public and private vegetation and should be mentioned as a potential avenue for future research.

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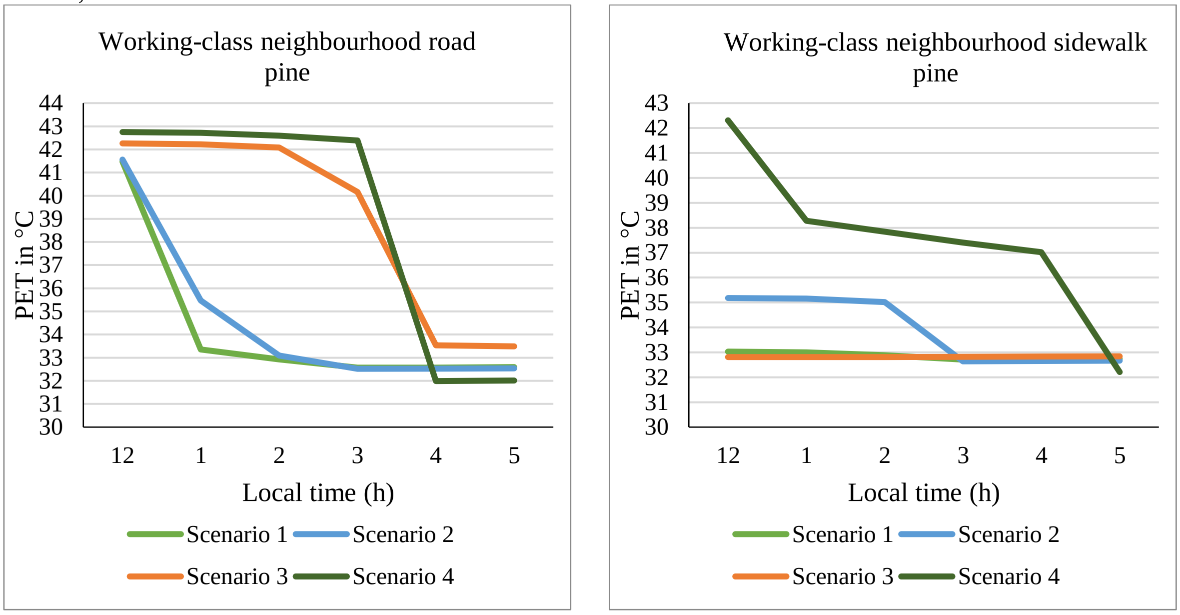
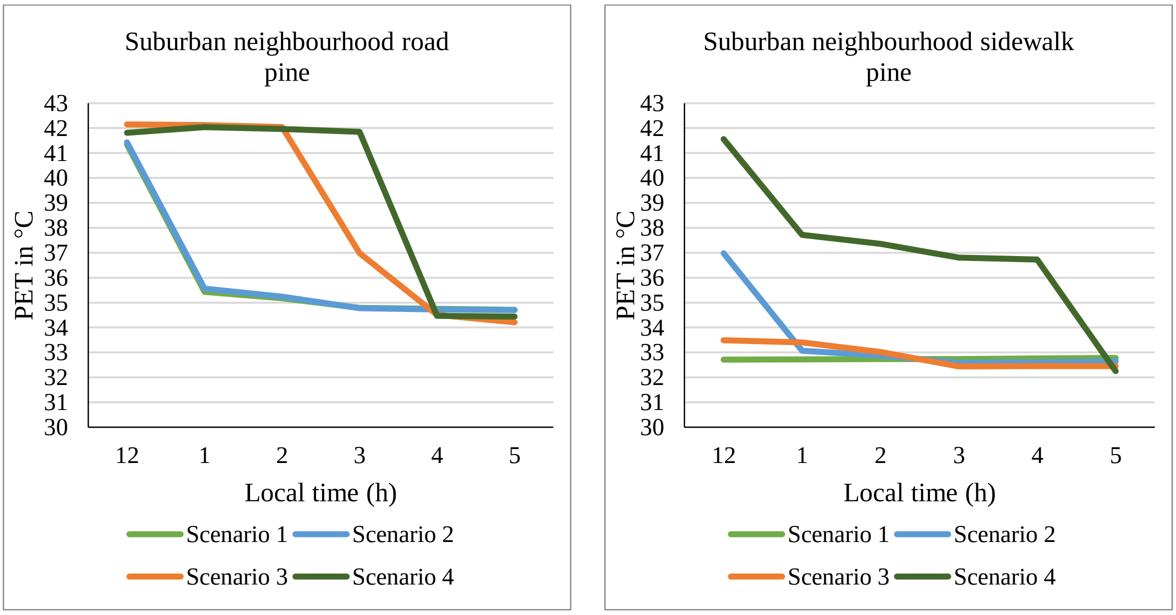
Appendix

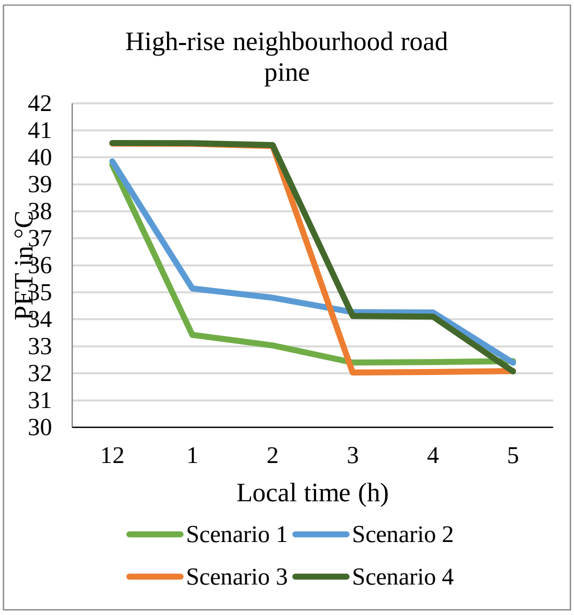
Appendix 1 PET over time for pine tree road vs sidewalk measurements working-class neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.

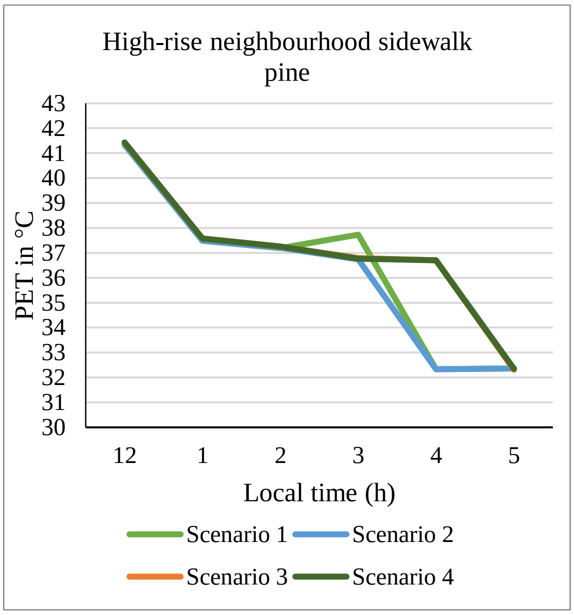


Appendix 2 PET over time for pine tree road vs sidewalk measurements suburban neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.

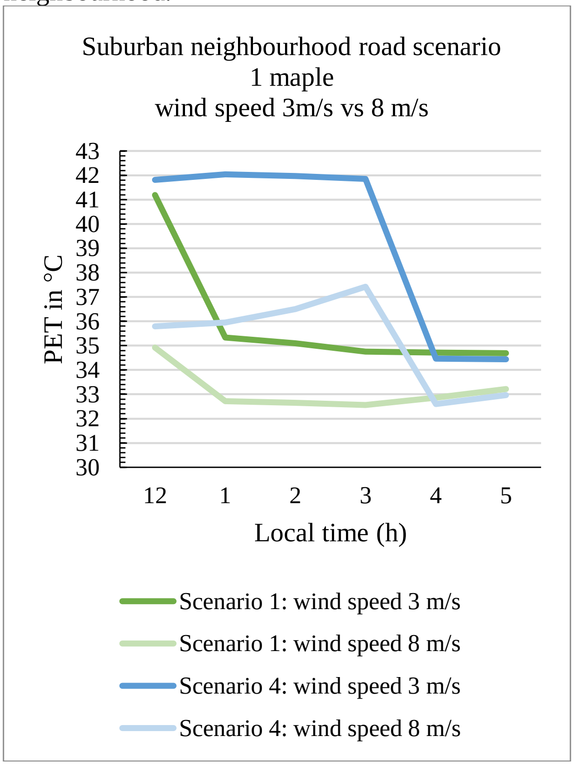


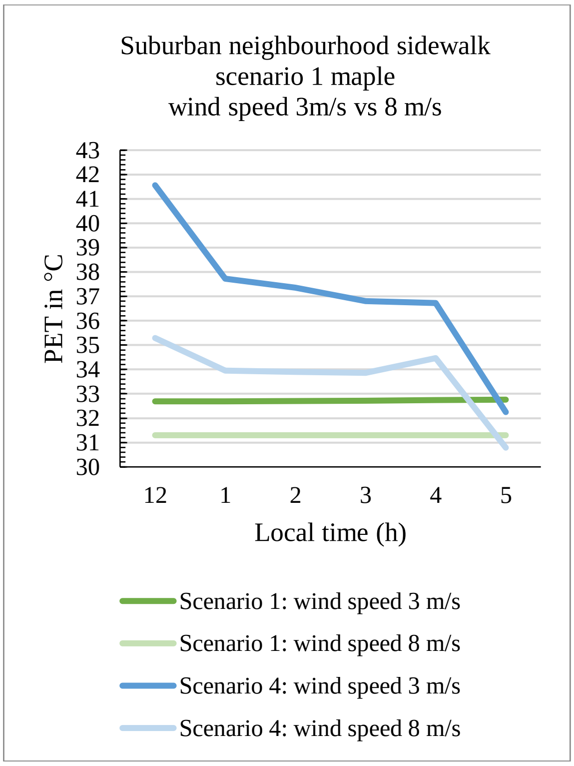
Appendix 3 PET over time for pine tree road vs sidewalk measurements high-rise neighbourhood. Scenario 1: twelve trees in a single line, Scenario 2: twelve trees in pairs of two in a line, Scenario 3: twelve shrubs, Scenario 4: no trees.





Appendix 4 Wind speed 3 m/s vs 8 m/s in scenario 1 maple road and sidewalk measurements suburban neighbourhood.





Appendix 5 Wind directions scenario 4 suburban neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	41,8	42,0	42,0	41,9	34,5	34,4	39,4 °C	
Sidewalk wind direction north	41,6	37,7	37,4	36,8	36,7	32,3	37,1 °C	
Road wind direction east	42,8	42,8	42,6	42,4	34,7	34,6	40,0 °C	+ 0,6 °C
Sidewalk wind direction east	42,3	38,1	37,8	37,1	37,0	32,4	37,5 °C	+ 0,4 °C
Road wind direction south	42,1	42,0	42,0	41,8	34,5	34,3	39,5 °C	+ 0,1 °C
Sidewalk wind direction south	41,6	37,7	37,4	36,8	36,7	32,3	37,1 °C	+-0,0 °C
Road wind direction west	42,8	42,7	42,6	42,4	34,7	34,6	40,0 °C	+ 0,6 °C
Sidewalk wind direction west	42,3	38,0	37,8	37,1	37,0	32,4	37,4 °C	+ 0,3 °C

Appendix 6 Wind directions scenario 1 suburban neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	41,2	35,3	35,1	34,8	34,7	34,7	36,0 °C	
Sidewalk wind direction north	32,7	32,7	32,7	32,7	32,7	32,9	32,7 °C	
Road wind direction east	42,4	35,8	35,6	35,4	35,0	35,0	36,5 °C	+ 0,5 °C
Sidewalk wind direction east	33,0	33,0	33,0	33,0	33,0	33,0	33,0 °C	+ 0,3 °C
Road wind direction south	41,2	35,3	35,1	34,8	34,7	34,7	36,0 °C	+-0,0 °C
Sidewalk wind direction south	32,7	32,7	32,7	32,7	32,7	32,8	32,7 °C	+-0,0 °C
Road wind direction west	42,4	35,8	35,6	35,2	35,1	35	36,5 °C	+ 0,5 °C
Sidewalk wind direction west	33,0	33,0	33,0	33,0	33,0	33,0	33,0 °C	+ 0,3 °C

Appendix 7 Wind directions scenario 4 high-rise neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	40,5	40,5	40,5	34,1	34,1	32,1	37,0 °C	
Sidewalk wind direction north	41,4	37,6	37,3	36,8	36,7	32,4	37,0°C	
Road wind direction east	41,9	41,8	41,6	34,6	34,5	32,4	37,8 °C	+ 0,8 °C
Sidewalk wind direction east	42,8	38,4	38,0	37,4	37,2	32,6	37,7 °C	+ 0,7 °C
Road wind direction south	40,5	40,5	40,5	34,1	34,1	32,1	37,0 °C	+-0,0 °C
Sidewalk wind direction south	41,4	37,6	37,3	36,8	36,7	32,2	37,0 °C	+-0,0 °C
Road wind direction west	41,9	41,8	41,6	34,6	34,5	32,4	37,8 °C	+ 0,8 °C
Sidewalk wind direction west	42,8	38,4	38,0	37,4	37,2	32,6	37,7 °C	+ 0,7 °C

Appendix 8 Wind directions scenario 1 high-rise neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Road wind direction north	32,7	32,7	32,7	32,7	32,7	32,8	32,7 °C	
Sidewalk wind direction north	41,3	37,4	37,1	32,4	32,4	32,4	35,5 °C	
Road wind direction east	42,0	33,9	33,5	32,9	33,0	33,0	34,7 °C	+ 2,0 °C
Sidewalk wind direction east	43,6	38,9	38,5	37,8	32,9	32,9	37,4 °C	+ 1,9 °C
Road wind direction south	39,7	33,4	33,0	32,4	32,4	32,5	33,9 °C	+ 1,2 °C
Sidewalk wind direction south	41,3	37,5	37,2	36,7	32,3	32,4	36,2 °C	+ 0,7 °C
Road wind direction west	42,0	33,9	33,5	32,9	33,0	33,0	34,7 °C	+ 2,0 °C
Sidewalk wind direction west	43,6	38,9	38,5	37,8	32,9	32,9	37,4 °C	+ 1,9 °C

Appendix 9 Humidity working-class neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Scenario 4: road 60%	42,8	42,7	42,6	42,4	32,0	32,0	39,0 °C	
Scenario 4: sidewalk 60%	42,3	38,3	37,8	37,4	37,0	32,2	37,5 °C	
Scenario 4: road 80%	42,9	42,9	42,8	42,5	32,1	32,1	39,2 °C	+ 0,2 °C
Scenario 4: sidewalk 80%	42,5	38,4	38,0	37,3	37,2	32,3	37,6 °C	+ 0,1 °C
Scenario 1: road 60%	41,3	33,3	33,0	32,6	32,6	32,6	34,2 °C	
Scenario 1: sidewalk 60%	33,0	33,0	32,9	32,7	32,7	32,7	32,8 °C	
Scenario 1: road 80%	41,4	33,4	33,1	32,7	32,7	32,7	34,3 °C	+ 0,1 °C
Scenario 1: sidewalk 80%	33,1	33,1	33,0	32,8	32,8	32,8	32,9 °C	+ 0,1 °C

Appendix 10 Humidity suburban neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Scenario 4: road 60%	41,8	42,0	42,0	41,9	34,5	34,4	34,4 °C	
Scenario 4: sidewalk 60%	41,6	37,7	37,4	36,8	36,7	32,3	37,0 °C	
Scenario 4: road 80%	42,2	42,2	42,1	42,0	34,6	34,6	39,6 °C	+ 5,2 °C
Scenario 4: sidewalk 80%	41,7	37,9	37,5	36,9	36,9	32,4	37,2 °C	+ 0,2 °C
Scenario 1: road 60%	41,2	35,3	35,1	34,8	34,7	34,7	36,0 °C	
Scenario 1: sidewalk 60%	32,7	32,7	32,7	32,7	32,7	32,7	32,7 °C	
Scenario 1: road 80%	41,4	35,5	35,2	34,9	34,9	34,8	36,1 °C	+ 0,1 °C
Scenario 1: sidewalk 80%	32,8	32,8	32,8	32,9	32,9	32,9	32,9°C	+ 0,2 °C

Appendix 11 Humidity high-rise neighbourhood.

	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	Mean PET	PET difference
Scenario 4: road 60%	40,5	40,5	40,5	34,1	34,1	32,1	37,0 °C	
Scenario 4: sidewalk 60%	41,4	37,6	37,3	36,8	36,7	32,4	37,0 °C	
Scenario 4: road 80%	40,7	40,7	40,6	34,3	34,2	32,2	37,1 °C	+ 0,1 °C
Scenario 4: sidewalk 80%	41,6	37,7	37,4	36,9	36,8	32,4	37,1 °C	+ 0,1 °C
Scenario 1: road 60%	32,7	32,7	32,7	32,7	32,7	32,8	32,7 °C	
Scenario 1: sidewalk 60%	41,3	37,4	37,1	32,4	32,4	32,4	35,5 °C	
Scenario 1: road 80%	39,9	33,5	33,1	32,5	32,6	32,6	34,0 °C	+ 1,3 °C
Scenario 1: sidewalk 80%	41,5	37,6	37,3	36,9	32,5	32,5	36,4 °C	+ 0,9 °C